WILLEM F. VLOTMAN

Health and Irrigation

Incorporation of disease-control measures in irrigation, a multi-faceted task in design, construction, operation

J.M.V.Oomen
J.de Wolf
W.R.Jobin

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We dedicate this book to the memory of B.B. Waddy, D.M. D.P.H. A pioneer of research into the health problems associated with the development of water resources and industry in the tropics. He died in 1981. From his writings, we quote:

> 'Experience of the problems of human health and welfare raised by the creation of lakes has accumulated by now. Most of these problems are very straightforward, and are common to the disciplines of health, agriculture, and sociology. The cost of resettling displaced communities, always much greater than expected, the long-lasting social distress among such communities, and the economic loss due to the flooding of good farm land, are now well known. But they may not be known by governmental authorities, who are happily – and fecklessly – planning to add one more man-made lake to the map of the developing world, in complete and usually misplaced confidence that it will benefit their economy. Mistakes that are repeated with monotonous regularity could be avoided, perhaps without any extra expense, if the authorities for the project concerned were forewarned of them.'

Source: Research into the Health Problems of Man-Made Lakes, with special reference to Africa. Transactions of the Royal Society of Tropical Medicine and Hygiene 69 (1): 39-50. 1975.

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Preface

At the beginning of the 1980's, the International Institute for Land Reclamation and Improvement/ILRI approached the Dutch Directorate of International Cooperation/ DGIS with a proposal that DGIS assist in financing an ILRI publication entitled *Health and Irrigation*. The origin of this proposal was the contact that had been established between ILRI and Dr J.M.V. Oomen after the publication of Dr Oomen's Ph.D. thesis, *Monitoring Health in African Dams* (prepared under the guidance of Professor Dr H.A. Valkenburg of the Institute of Epidemiology at the Erasmus University in Rotterdam).

It was felt within ILRI that a publication linking elements of Dr Oomen's thesis with features of irrigation could be beneficial to all who are involved in irrigation projects. The book would cover health planning in irrigation projects in areas where water-related diseases (e.g. malaria, schistosomiasis, filariasis, onchocerciasis) were endemic or could become so through the implementation of irrigation projects.

DGIS's response to ILRI's proposal was positive, in principle, but before making a definite decision, it wished to discuss the matter with representatives of the World Health Organization and to hear opinions from Dutch engineering bureaux working in developing countries. The result of these consultations was that, in mid-1983, DGIS made funds available for the preparation of the manuscript of *Health and Irrigation*. In making this decision, DGIS added the provisos that the book give ample attention to practical examples and case studies, and that a Steering Committee be created to advise and guide the authors. The Steering Committee met eight times. Its members were:

- Dr D.C. Faber, Centre for World Food Studies, Wageningen;
- Ir W.C. Hulsbos, Euroconsult, Arnhem;
- Dr J.L.M. Lelijveld, Department of Environmental and Tropical Health, University of Agriculture, Wageningen;
- Drs F. Meyndert, DGIS, later succeeded by
- Drs M. de la Bey, DGIS;
- Dr A.M. Polderman, Institute for Tropical Medicine, University of Leiden;
- Ir K. Roscher, Department of Civil Engineering, University of Agriculture, Wageningen;
- Ir C. Storsbergen, DHV Consultants, Amersfoort.

The Steering Committee's Secretaries were:

- Ir W.T. Lincklaen Arriens, ILRI, later succeeded by
- Ir B.T. Ottow, ILRI.

The authors express their appreciation for the constructive criticism they received from the members of the Steering Committee. The work of the two Secretaries deserves special mention. This went far beyond mere secretarial duties to the Committee; it extended to cover an entire literature survey and the processing of its data. Ir W.T. Lincklaen Arriens was also instrumental in realizing the Sri Lanka case study.

Health and Irrigation is being published in two volumes. The first contains Chapters 1 to 10, and Technical Notes 1 to 3. Chapters 1 to 9 and Technical Note 2 are the work of the main authors. Chapter 10 was written by Dr D.H.H. Bol, an economist with Consultants for Development Programmes, Utrecht. Technical Note 1 was written by Dr L. Molineaux, an epidemiologist with the World Health Organization, Geneva. Technical Note 2 was the work of Dr J.A.M. van Druten of the Department of Medical Statistics at the Medical Faculty of the Catholic University, Nijmegen.

Volume 2 was published in advance of Volume I so that it could be presented at the 12th International Congress for Tropical Medicine and Malaria, held in Amsterdam in 1988. In accordance with the DGIS proviso, it contains practical examples and case studies. Much of this was contributed by Dr W.R. Jobin. The case study in Sri Lanka was taken from the field work of the students J.J. Speelman and G. van den Top of the Department of Irrigation and Civil Engineering at the Wageningen University of Agriculture. Another case study was derived from the literature survey conducted by Ir W.B. Snellen of ILRI on 'Sanitation Works in Java, Indonesia'.

The authors are further indebted to Ir Snellen for his positive criticism of Chapter 10 and for the work he put into completing its final draft.

Data on the geographical distribution of vectors and vector-borne diseases were drawn from publications of the World Health Organization. For schistosomiasis, a separate study was undertaken by Jos L.M. Boeren, a student at the Department of Environmental and Tropical Health, Wageningen University of Agriculture. The support given him by Dr S. Frandsen of the Danish Bilharziasis Laboratory in Charlottlund, and by Dr F.S. McCullough of WHO's Ecology and Vector-Control Unit in Geneva, is gratefully acknowledged.

We would like to express our thanks to:

- Various departments of the World Health Organization for their comments on the manuscript and for the information they so generously gave us.
  In particular, we would like to thank Dr R.J. Tonn and Dr A. Smith of the Division of Vector Biology and Control and Mrs P.L. Rosenfield of the Special Programme for Research and Training in Tropical Diseases.
  For the very useful contacts with Dr R. Bos, Secretary of the WHO/FAO/UNEP Panel of Experts on Environmental Management for Vector Control, we are very grateful;
- Ir E.L.P. Hessing of the IRC International Water and Sanitation Centre, The Hague, for his support on Chapter 9;
- Dr Ir W. Takken of the Department of Entomology of the Wageningen University of Agriculture for his suggestions on various entomological questions;
- The ILRI Drawing Office for the care and expertise that went into the drawings in the book.

Finally, complying with the request of DGIS, we include the following passage:
The research for this publication was financed by The Netherlands Ministry of Development Cooperation.

Section DPO/OT
Ministry of Development Cooperation
P.O. Box 2006,
2500 EB The Hague
The Netherlands

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1 Health and irrigation – Some Basic Issues

In the decades that lie ahead of us, land and water development will have a major role to play in increasing the world's food production – an increase that should primarily take place where food shortages exist or are to be expected, i.e. in the developing countries. It has long been known that by regulating the water supply to a crop, its production can be substantially increased. With the rapid growth of the world's population and the consequent increasing demand for food, the role of irrigation is a vital one.

Although, on a global scale, only 20 per cent of the harvested area is irrigated, it produces 40 per cent of the total crop production and receives more than 60 per cent of all the fertilizer that is applied (Hotes 1982).

Of the total area under irrigation (roughly 270 million ha in 1986), it is estimated that 65 to 70 per cent lies in the developing world, and that more than half of that area lies in India and the People's Republic of China.

Irrigation is the principal means by which man modifies his environment to produce more food. New developments in irrigation technology, plus complementary advances in plant breeding and crop protection, and new agronomy 'packages', have increased the potential productivity and profitability of irrigated agriculture. This increased productivity comes from higher yields, multiple cropping (often two or even three crops a year), and a reduced risk of crop failure.

We can therefore conclude that irrigation is of great significance for the world's food production, that it will continue to be significant, and that it is beneficial for food production and farmers alike. Conversely, whenever irrigation is applied in the tropics and subtropics of the world, it can do great harm to the environment and can have ill effects on human health. This is a cause of grave concern which cannot easily be quantified in value terms.

This publication deals with the harm that irrigation can do to human health and the steps that can be taken to prevent that from happening. One harmful effect of irrigation is that it can spread water-related diseases and thus cause the consequent suffering of millions of human beings (Waddy 1975; Worthington 1976; Hunter et al. 1982; Heyneman 1984). Irrigation schemes have often created or enhanced ecological environments that are favourable for the transmission of malaria and other vector-borne diseases: schistosomiasis (bilharzia), dengue and dengue haemorrhagic fever, liver fluke infections, filariasis, and onchocerciasis (river blindness).

Singling out schistosomiasis from the string above and considering the question 'Bilharzia or Starvation?' (Obeng 1966), one can see that food must be produced, but that the intermediate snail host of bilharzia must be prevented from establishing itself. From the very beginning, irrigation schemes need to be adequately planned and managed, with environmental safeguards incorporated into them to fight bilharzia. And what holds for bilharzia holds for the other diseases.

Techniques that can create disease-free ecological environments in irrigation schemes are available. In this book, we shall discuss these techniques, their effects, and the necessary measures to bring about change in disease-ridden areas.

1.1 Health through Development

Great differences exist between the prevalent health situation in developed and developing countries. The impact of development on health can be illustrated by the health situation some seventy or eighty years ago in countries which have since become developed. Poor health conditions were commonplace in those countries then, as they still are in less fortunate parts of the world. Table 1.1 provides some striking figures.

Table 1.1. Range and weighted average of life expectancy at birth, for three groups of countries

	Industrialized countries	Middle-income countries	Low-income countries
Life expectancy (years) (at birth)	72-76 (74)	39-70 (61)	39-53 (50)

Source: World Development Report 1980. The World Bank, Washington D.C.

There is historical evidence that the decrease in mortality and the increase in life expectancy in the industrialized countries were associated firstly with the falling incidence of infectious diseases and secondly with the improvement of nutrition. Major factors influencing these changes were:

- Improvements in drinking-water supplies, in excreta disposal, and in nutritional hygiene, which reduced the transmission of many infections;
- The growing awareness of what constitutes good nutrition;
- Demographic changes. Fewer children were born, but they could be given better care and stayed alive.

With this evidence before us, we can draw the conclusion that development offers ample opportunities to improve health: by reducing the transmission of common infections, by improving nutrition, and by controlling the growth of populations.

Internationally, this conclusion motivated the Basic Needs Strategy (ILO 1976), the Primary Health Care Strategy (WHO/UNICEF 1978), and the International Water Decade (World Bank 1980). About the same time, the Panel of Experts on Environmental Management for Vector Control (PEEM) was instituted (WHO/FAO/UNEP 1981).

New irrigation projects, and the population resettlement programs that often accompany them, form ideal targets for applying the principles of health promotion through development. Such projects constitute a large section of the development taking place in the tropical and subtropical zones of Africa, Asia, and Latin America. In many of the countries concerned, the burden of infectious diseases is heavy and the prevailing health situation is poor. Under these conditions, any action to promote health could be highly effective.

Irrigation development brings with it profound ecological changes. In tropical and subtropical climates, these changes have a more severe impact on health than in temperate climates. One reason for this is that vector-borne diseases are already a major public-health problem in the tropics and subtropics, while the ecological changes

brought about by irrigation often lead to the explosive propagation of those vectors. A second reason is that the low standard of living is conducive to the transmission of diseases (see Table 1.2). And a third reason is that the health infrastructure, which tends to be only weakly developed anyway, is unable to cope with the increased burden of diseases.

Table 1.2. Number of infections, deaths, and diseased of major infectious diseases in Africa, Asia, and Latin America (1977-78)* (Source: Walsh and Warren 1979)

Infection	Infections (1000's per year)	Deaths (1000's per year)	Disease (in 1000's of cases per year)
Water-related vector-borne:			
Malaria	800,000	1,200	150,000
Filariasis	250,000	low	2-3,000
Dengue	3-4,000	0.1	1-2,000
Schistosomiasis	200,000	500-1,000	20,000
Onchocerciasis (skin)	30,000	low	2-5,000
Onchocerciasis (river blindness)		20-50	200-500
African Trypanosomiasis	1,000	5	10
Gastro-enteric:			
Diarrhoeas	3-5,000,000	5-10,000	3-5,000,000
Typhoid	1,000	25	500
Gastro-intestinal worms:			
Ascariasis	800,000/ 1,000,000	20	1,000
Hookworm	7-900,000	50-60	1,500
Respiratory:			
Acute and chronic respiratory diseases		4-5,000	
Measles	85,000	900	80,000
Tuberculosis	1,000,000	400	7,000

*) Based on estimates from the World Health Organization and its Special Programme for Research and Training in Tropical Diseases, confirmed or modified by extrapolations from published epidemiological studies performed in well-defined populations. Figures do not always match those officially reported, because under-reporting is common.

1.1.1 Planning Irrigation Projects and Disease Control

The incorporation of environmental safeguards to promote health should be envisaged right at the beginning of the planning process. An excellent example of project planning is provided by the Tennessee Valley Authority (TVA) in its integrated plan for the development of water resources in the Tennessee River Valley. Malaria posed a serious health problem in the region, with wide implications for the economic and social well-being of the population. A direct consequence of any impoundments would be an increased transmission of malaria. For this reason, an integrated strategy of malaria control was incorporated into TVA's program. (More details of this will be given

in Chapter 5 and in Volume 2, Annex 3.1.)

Figure 1.1 illustrates the concept of integrated planning. The adoption of a development project is motivated by the desire to improve human welfare, although economic and technical objectives may dominate the plan. The activities necessary to implement the plan can be designated as primary or secondary, according to their relationship to the objectives. Health considerations are most likely to be included in the project if they can be linked to primary activities (direct health effects) and secondary activities (indirect health effects). Direct health effects, particularly in the tropics, will be those related to vector-borne infections, which can form a threat to the realization of the objectives. Indirect health effects are likely to cover a range of infections of varying significance, with diarrhoeal diseases and nutritional problems the most common.

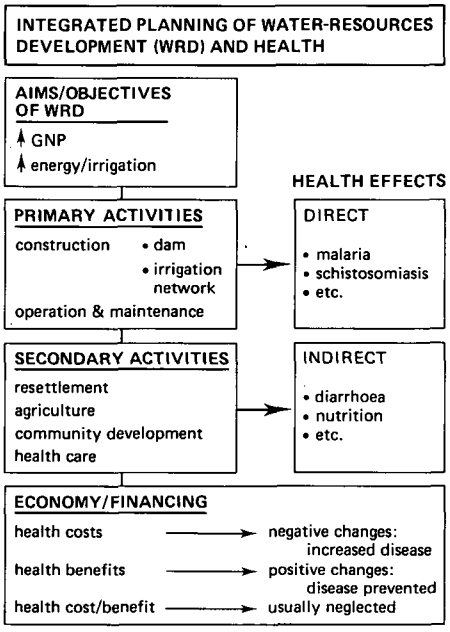


Figure 1.1 Integrated planning of water-resources development and health

1.1.2 Social and Economic Parameters

The social and economic significance of a disease is broadly indicated by an estimate of the number of days of healthy life lost through the disease or premature death. Such estimates make it possible to rank the infections (Table 1.3). This ranking can then be used, for example, to compare the cost-effectiveness of different options for disease prevention. A major difficulty, however, remains the expression of the health impact in an economically tangible, monetary, measure.

Table 1.3 The health impact of vector-borne infections in Ghana, estimated in terms of days of healthy life lost per 1000 persons

	Days of healthy life lost	Lower and upper limits	
Malaria	32,567	27,000	41,000
Schistosomiasis	4,368	750	12,500
Onchocerciasis	1,926	1,540	3,100
Hookworm	1,482	900	3,000
Ascaris	1,222	850	1,800
Trypanosomiasis	195	100	400
Guinea worm	108	45	180

Source: Morrow and Ghana Health Assessment Team (1981)

Cost-benefit and cost-effectiveness analysis are instruments that can be used for the allocation of resources. These analyses will be discussed in Chapter 10.

Applying the cost-benefit method to the health component requires that information be available on the current prevalence[1] and incidence[2] of diseases, and that future trends can be forecast. Epidemiological methods for the collection of this information will be discussed in Chapter 4.

1.2 The Prevention and Control of Diseases

1.2.1 The Natural History of Disease

The natural history of a disease covers both the time that people are at risk of catching the disease, and the course the disease takes in those who are afflicted (see Figure 1.2). Measures to improve health aim at preventing the disease process or its damaging sequelae. On the basis of a disease's natural history, preventive measures can be classified as primary, secondary, and tertiary, according to the stage in which they act on the process. In this epidemiological concept, treatment is also seen as a form of prevention, because it interrupts the process. The degree of success in preventing a disease depends on the completeness of knowledge about its natural history, the opportunities to apply that knowledge, and the actual application of the knowledge.

Primary prevention encompasses any form of health promotion and may be regarded as one of the main factors in producing healthy populations. Health promotion means the creation of healthy and hygienic living conditions in which the basic human needs (food, water, housing, clothing, excreta disposal, and health care) can

[1] Prevalence: Ratio of number of persons with a specified disease at a particular moment in time, to the population in question (e.g. on July 1st 10.000 persons suffer from Schistosomiasis in a population of 100.000; the point prevalence = 0,1).

[2] Incidence: The number of newly diagnosed cases of a disease during a defined period (usually 1 year) divided by the population in question (e.g. from January 1st till December 31st 1000 persons are newly diagnosed as having Schistosomiasis in a population of 100.000; incidence = 0,01).

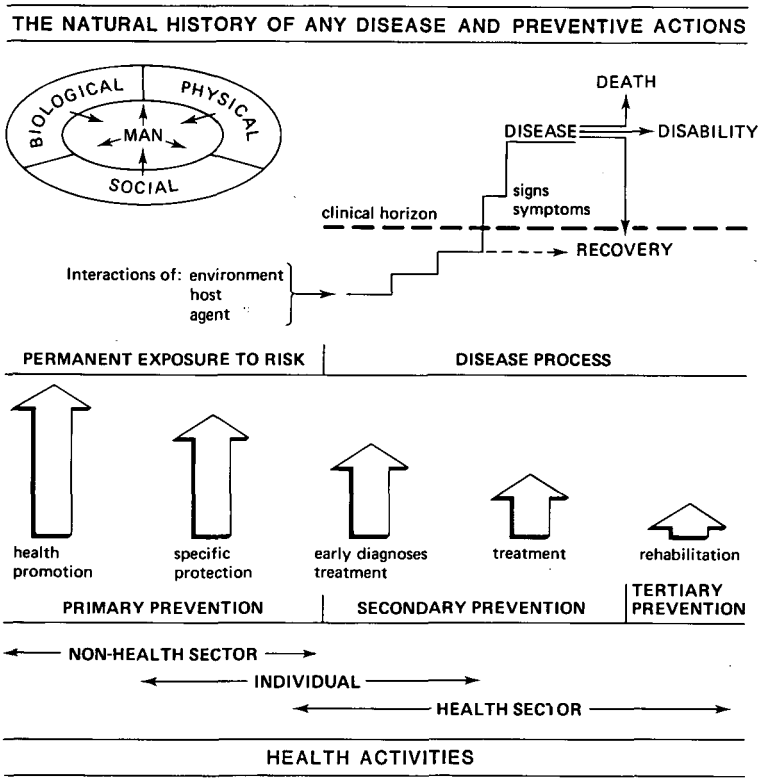


Figure 1.2 The natural history of health and disease in man (Source: Leavell and Clark 1958)

be satisfied. The mere satisfaction of basic needs, however, will not generate an impact on health unless the people use what is provided as it was intended to be used. Health and hygiene education should therefore be a fundamental component in any action to promote health.

Health promotion is not a task for the health sector alone, but for all sectors concerned with social and technical development. The role of the health sector in primary prevention is limited to providing the necessary knowledge and expertise for health promotion, and to providing specific forms of protection through the use of vaccines, prophylactic drugs, disinfectants, insecticides, and other biochemical agents.

Secondary prevention is concerned with the early diagnosis and treatment of people who have the disease, either pre-clinically or clinically. Tertiary prevention aims at limiting the disabling consequences of the disease.

For the control of major infectious diseases, experience has shown that an efficient and reliable control strategy combines both primary and secondary preventive measures.

1.2.2 The Transmission of Infectious Diseases

Infectious diseases are caused by biological agents such as bacteria, viruses, protozoa,

and various types of worms. The diseases are transmitted by the disease agent passing from one person to another, or sometimes, to or from an animal. The carriers of the agent constitute the 'reservoir of infection', and the person (or animal) acquiring the infection the 'susceptible host'. Some of the agents are transmitted by direct bodily contact, but more often they are first expelled into the environment and only reach the susceptible host by some intermediary 'transmission mechanism', which can involve irrigation water, food, etc. In vector-borne infections, the transmission mechanism involves an insect, snail, or an animal (Figure 1.3).

1.2.3 The Integrated Control of Transmission

The burden of infectious diseases in a community can be reduced by the partial or complete disruption of their transmission. There are three ways in which this can be done:

- By interfering with the transmission mechanism;
- By protecting the susceptible host;
- By reducing the reservoir of infection.

Environmental management, or environmental health engineering, can disrupt transmission by eliminating the breeding places of the vectors. This might be supplemented by the use of chemicals, either to kill the disease agents by disinfection, or the vectors with insecticides or molluscides. Biological measures can also be taken. These constitute either genetic manipulation or the introduction of organisms (i.e. predators or toxic plants) which compete ecologically with the disease agents or vectors.

The susceptible host can be made less susceptible through immunization or the pro-

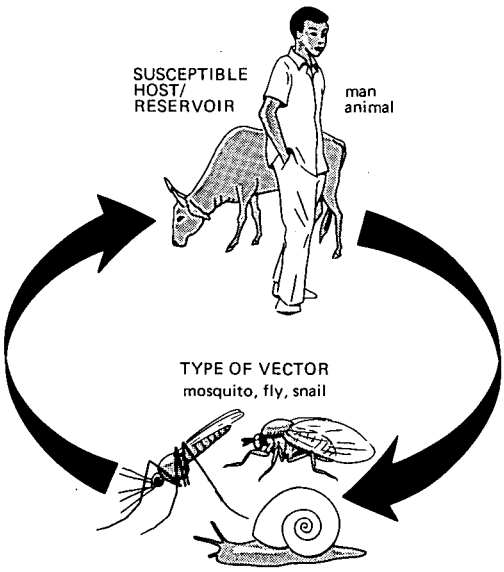


Figure 1.3 Intermediary mechanisms for the transmission of infectious diseases

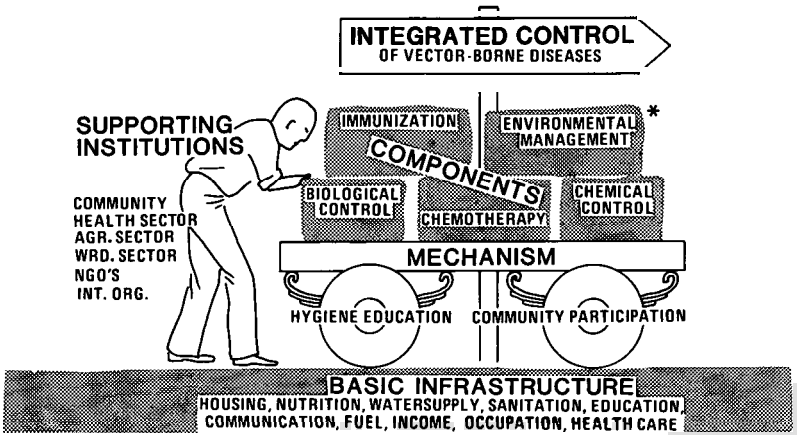
phylactic use of drugs. (This also applies to susceptible animal hosts.) Further, the susceptible host can be protected by reducing his contact with the vector, by his use of repellants against biting insects, and by screening his house. Also, his village can be sited away from vector-breeding habitats, and domestic water facilities can be provided at places where there are no harmful insects.

The reservoir of infection can be reduced by treating infected and ill people, and by treating or eliminating infected animals.

The integrated control of infectious diseases is a control strategy that combines, if relevant, elements of all three of the above approaches (WHO 1983). As a combination of primary and secondary preventive measures, integrated control is illustrated in Figure 1.4.

1.2.4 Engineering Design Components for Integrated Control

The adverse health impact of irrigation in the tropics and subtropics is well documented (Deom 1982; Hunter et al. 1982), revealing that engineers have an important role to play in the integrated control of diseases. The conventional biological classification of diseases is not helpful to the engineer, because it has no bearing on the environmental changes he might make to combat diseases (Bradley 1974). For the engineer, it is more convenient to have the diseases classified in categories that relate to those aspects of the environment which he can change (Cairncross and Feachem 1983; McJunkin 1982).



THE VEHICLE GAINS MOMENTUM THROUGH:

- support by the community
  support by the health sector
  support by the agricultural sector
  support by the water-resources development sector
  support by various organizations
  } the push
- the mechanism of hygiene education
  the mechanism of community participation
  } good lubrication of the wheels

* ENVIRONMENTAL MANAGEMENT
- environmental modification (permanent measures)
- environmental manipulation (recurrent measures)
- man-water-vector contact reduction (screening, zoning, foot bridges)

Figure 1.4 Integrated control of vector-borne diseases

With the basic needs as its starting point, Table 1.4 presents such a classification. In each category of basic needs, it identifies the transmission mechanisms and indicates those engineering design components that are relevant for disease control (Stephens et al. 1985). These will be further discussed in Chapters 5 to 9.

The most common diseases generated by irrigation are vector-borne diseases. Their prevention is thus the main focus of this book. The epidemiology of these diseases will be dealt with in Chapter 2, the vectors themselves in Chapter 3.

Table 1.4 Transmission mechanisms of diseases, and design components for environmental health engineering that contribute to integrated control

Design component	Transmission mechanism	Design feature	Related diseases
Occupation	Insect-vector breeding in water/ biting near water Water-based	Dam construction Irrigation network Agriculture	Malaria, onchocerciasis, trypanosomiasis, other vector infections Schistosomiasis
Water supply	Water-borne Water-washed	Quality and/or quantity of water	Diarrhoeas & dysenteries Enteric fevers Enteric virus infections
		Quantity only	Skin infections Eye infections Louse-borne fevers
	Water-based	Protection of water source	Guinea worm infection
Excreta disposal	Person-person contact Domestic contamination Water contamination Field contamination Crop contamination	Latrine construction Excreta treatment Hygiene environment	Diarrhoeas & dysenteries Enteric fevers Soil transmitted helminths Beef and pork tapeworms Waterbased helminths (Schistosomiasis) Filariasis
Housing	Siting near vector habitat	Siting/screening of houses	Malaria, filariasis, onchocerciasis, trypanosomiasis
	Overcrowding Air pollution	Space and ventilation	Epidemic meningitis Acute & chronic respiratory infections Respiratory malignancies
	Vector breeding	Water storage	Arbo-viral infections (dengue, yellow fever)
	Refuse Construction Fire	Refuse disposal Construction materials Burns	Chagas disease, leishmaniasis Soil transmitted helminths Fire hazards
Nutrition	Lack of calories Lack of proteins Lack of vitamins	Staple crops Home-gardens	Undernutrition Protein-caloric malnutrition Vitamin deficiencies
	Food storage Food preparation	Storage facilities	Food-poisoning: diarrhoeas
Energy	Use of fire-wood Open fire Storage of kerosene	Kitchen stoves Chimneys	Food poisoning: diarrhoeas Burns see: Air pollution
Village infrastructure Health care		Immunizations	Childhood infections, poliomyelitis, yellow fever
		Mother-Child care Education and Communication	Perinatal/infant mortality Treatment Endemic diseases: malaria, diarrhoea respiratory infections, helminths, schistosomiasis etc. Birth regulation

1.3 Outlook for Irrigation Development

The distribution of irrigated land over the continents is roughly as follows:
- Asia: 68 per cent;
- North America: 13 per cent;
- Europe: 10 per cent;
- Africa: 5 per cent;
- Central and South America: 3 per cent;
- Australia and Oceania: 1 per cent.

For the year 1986, the total irrigated area was estimated at 271 million ha. The annual expansion is of the order of 400,000 ha. This annually expanding irrigated area will certainly present a big challenge to the planners, designers, and operators of irrigation schemes because irrigation will, more and more, be introduced in areas where it is not a well-established form of agriculture, where the individual areas of irrigable land are relatively small, where the general level of crop husbandry is low, where project management is poor, and where rainfall (as the source of irrigation water) is highly seasonal. All these factors are conducive to increasing the areas suitable for the habitats of vectors.

Looking in particular at West and Central Africa, we see that irrigation development in that region seems less promising than elsewhere. Areas suitable for irrigation are relatively small and thus make the costs of irrigation higher than almost anywhere else in the world. (Investment costs are in the order of U.S. $10,000 to 15,000 per ha.) Other disadvantages are the generally low standard of rain-fed agriculture, poor project management, low levels of river discharge in the dry season, and the high rates of evaporation.

1.4 Irrigation Schemes

1.4.1 Their Elements

The three principal elements of an irrigation scheme are its water source, the irrigation and drainage network, and the on-farm management of water.

The scheme water source may be one of the following:
- A large storage reservoir created by the construction of a large dam in a river; it provides water the whole year round;
- Small storage reservoirs created by the construction of small dams; these usually supply water on a seasonal basis only;
- Run-of-river diversions for supplying water on a year-round or seasonal basis;
- River pumping stations;
- Well pumping.

The word 'reservoir' to indicate a 'scheme water source' is used here in the sense of an element separate from the irrigation and drainage network. However, there are also reservoirs that form an integral part of the irrigation network (e.g. tanks, night-storage reservoirs).

The layout of an irrigation scheme is shown in Figure 1.5. The terminology used is that advocated by the International Commission for Irrigation and Drainage (Bos 1979).

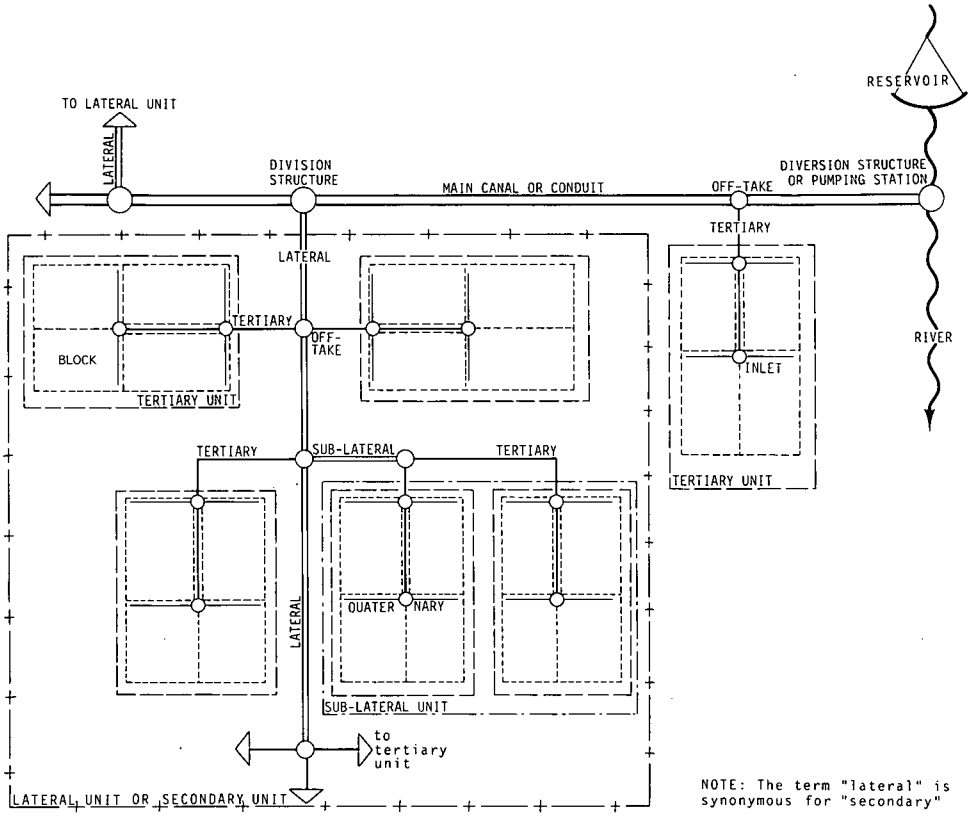


Figure 1.5 The layout of an irrigation scheme (Bos and Nugteren 1974)

In the irrigation network, the water is conveyed from its source through a main canal, from which it may be diverted into secondary canals. It proceeds further until it reaches a tertiary offtake, which is a structure that diverts water from a main or secondary canal to a tertiary unit. Within the tertiary unit, the farmers are responsible for distributing the water among themselves and for the on-farm management of their water. This includes the application of water to the fields and the drainage of any excess water (from rainfall, leaching, or excess applications of irrigation water). The drainage network forms, as it were, the mirror image of the irrigation network.

The task facing the designer of an irrigation scheme is a highly complex one, combining as it does a myriad of technical, economic, agronomic, social, and environmental factors. Basically, however, the designer's task is to create a layout that achieves three things: it must use the available water as efficiently as possible; it must enable an equitable distribution of the water among the farmers; and it must not create or intensify health problems.

1.4.2 Categories of Irrigation Schemes

Mather (1983) distinguishes three categories of irrigation schemes:
- Large-scale formal schemes;
- Small-scale formal schemes;
- Small-scale informal schemes (i.e. the village type).

We could add a fourth category: private irrigation, which has undergone a rapid expansion with the development of cheap pumps.

The four categories of schemes, with their differing characteristics, can be expected to have different social and economic consequences, which in turn will create varying levels of the risk of spreading vector-borne diseases.

A large-scale scheme creates major ecological changes over a wide area. Its effects on human populations will often be considerable, with displacement, resettlement, the mobilization of labour forces for the scheme's construction, the settlement of migrant labour, and the recurring presence of transient, seasonal workers. A large-scale scheme is more likely to multiply the number of pre-project focal points of disease, while the population movement it engenders is more likely to extend the problem beyond the scheme's boundaries.

A large-scale scheme therefore requires a careful design, with built-in safeguards to prevent a high level of risk, and it particularly needs good management. On the other hand, the large population in a large-scale scheme makes it economically more feasible to provide health services and basic sanitary facilities than in dispersed communities.

In a small-scale formal scheme, fewer people are involved, but disease foci can easily spread diseases beyond the scheme's boundaries. If the peripheral environment is also suited to vector production, the task of disease control and its cost may prove onerous in relation to the population benefitting. Similarly, the costs of providing community services and health facilities will be relatively high, or, alternatively, may have to be provided at a reduced level. Even so, the combination of good management and farmer participation in schemes of this category offers good prospects for the control and containment of diseases.

What will happen in small informal schemes is less predictable. They are less disruptive of the traditional social and economic status and hardly involve any population movement. By their very nature, they will not introduce major or rapid ecological changes. They will, however, induce changes in the local environment, which may be significant in terms of vector habitat, with a consequent shift in species distribution and numbers. The size of the scheme and the usually minimal infrastructural and institutional support it receives leave it vulnerable to the build-up of adverse health conditions to a point where emergency intervention may be needed.

Private irrigation usually takes the form of multiple small developments, often clustered near population centres with their markets and communities, or possibly even inducing the creation of such centres. This type of irrigation also changes the hydrological environment and the associated ecology. The large numbers of individual enterprises can be a source of risk in endemic disease areas in the absence of proper water management and without a responsive and adequate health service.

The rehabilitation of existing irrigation schemes also deserves mention. Since the 1970's, rehabilitation has greatly increased in significance, particularly in India, Pakis-

tan, and Indonesia. The aims of rehabilitation are to improve and modernize the irrigation infrastructure and its operation and maintenance, but rehabilitation without the incorporation of health safeguards is not worthy of its name.

1.4.3 Dams

The recent history of dams – large and small – has revealed that the construction of each dam was followed by untoward or unforeseen effects (Oomen 1981; Obeng 1977; Worthington 1976; Stanley and Alpers 1975; Ackermann et al. 1973; Rubin and Warren 1968; Lowe-McConnell 1966; ECAFE 1962).

Large Dams

The development of concrete technology since 1900, the use of experimental models for design since 1945, the improvements in hydro-electric engineering, and the invention of giant earthmoving equipment had the combined effect that after 1950 a generation of superdams were constructed.

The World Register of Dams (Brown 1964), after a world-wide survey, lists 10,000 dams of at least 15 m height, even though several countries, one of which was China, could not be included in the survey. Between 1964 and 1971, 2,000 more large dams were added to the list.

Fels and Keller (1973) compiled data on 41 man-made lakes with a surface area in excess of 1,000 km^2. Seven of these are located in Africa and were constructed after 1950. Of 315 smaller reservoirs, but with a surface area exceeding 10 km^2, 17 are in Africa. Lake Volta in Ghana, with a surface area of 8,500 km^2, is at present the largest man-made lake in the world. (The High Dam Lake has a maximum surface area of 6,118 km^2.)

Small dams

Although precise figures are not available, there are multitudes of small dams in the developing countries. Their effect on agriculture is probably less than that of the large dams, but their impact on disease is probably more severe (Hunter, Rey, and Scott 1982; Obeng 1977). A contributing factor is the ease with which small dams can be constructed at relatively low cost with the now generally available equipment, so that small groups of people (e.g. village communities, farmers' cooperatives, voluntary agencies) can build them. Unfortunately, the undoubted benefit to the community can be offset by adverse effects on health because such developments are usually without any provision for health.

1.4.4 Migration and Resettlement

Population movements as a result of development can increase the transmission of diseases or can introduce new diseases. On the other hand, when resettlement schemes

are being planned, they offer the opportunity to include health promotional measures in the plans (Chambers 1969). The successful implementation of schemes depends to a large extent on the settlers, their sense of well-being, and their willingness to participate. Their active participation in decision-making, both before and after the move, is essential to success.

An important indicator of successful implementation is the duration of the transition period. This is the period from the time of the move until full selfsufficiency, at least in food supplies, is regained. A minimum of two years is considered necessary under optimum conditions.

When resettlement schemes are being planned, the main factors to be considered for the promotion of health and social well-being are those shown in Figure 1.6.

When groups of people move into a new location, there is considerable risk that they will be exposed to diseases for which they have no acquired immunity (Fernando 1984). These may be diseases that are already prevalent in the area (but were absent in the home area) or that will be introduced to the resettlement population by newly-arrived settlers. In any case, resettlement implies that groups with varying degrees of immunity to diseases are being brought together. In this situation, epidemic outbreaks of dysentery or malaria easily flare up. Moreover, resettlement usually means an increase in population density, which in itself facilitates the transmission of diseases.

Resettlement also adds stress to the, often already precarious, health of the settlers. The stress can be physiological, psychological, and socio-cultural, each aggravating the others. Physiological stress is accompanied by a temporary increase of disease incidence and death. Psychological stress has two components: one is grief for the loss of home, lands, and former habitat; the other is the uncertainty as to what the future will bring. The socio-cultural stress mainly concerns a temporary disruption of social relationships and of the efficacy of leadership. Informing the communities beforehand of what they can expect after their move, and soundly organizing the operation itself, will help a great deal in alleviating stress (Scudder 1975).

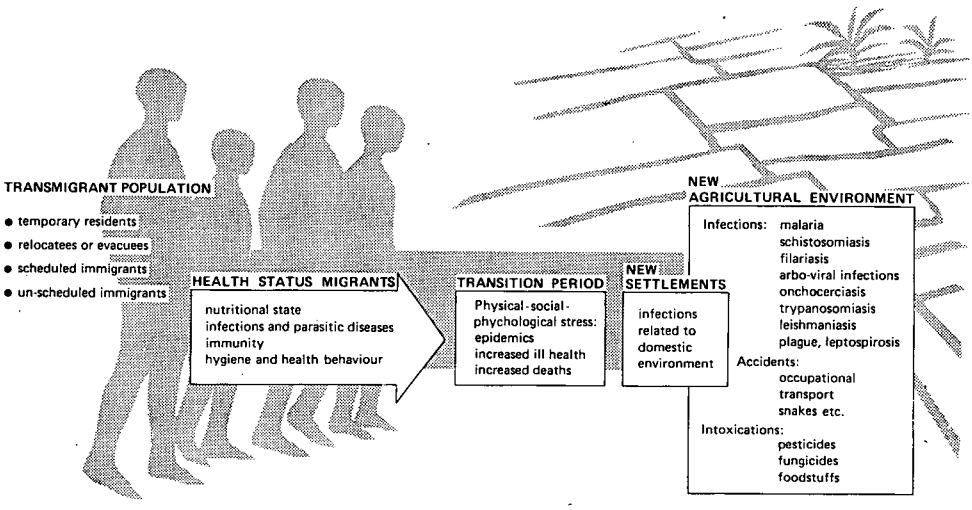


Figure 1.6 Health determinants of resettlement

Health problems associated with resettlement can arise shortly after the move, or may need more time to develop their full impact. Short-term health problems (common diarrhoeal and respiratory diseases, malnutrition) are mostly related to the forced migration; their impact will be felt in the transition period. Vector-borne diseases may be responsible for epidemics in the beginning, but are more likely to become endemic as time passes.

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2 Vector-borne Diseases

Many infections diseases are transmitted by a vector. Vector-borne infections differ from other diseases in that one, or sometimes more than one, intermediate host is necessary for the transmission to occur (see Figure 2.1). The hosts may be insects or aquatic animals. If the intermediate host is an insect, it will acquire disease parasites by biting an infected man or animal and may transmit the parasites to any man or animal it bites afterwards. If the intermediate host is an aquatic animal, it acquires disease parasites passively from infected water and, after the parasites have completed part of their life cycle within the animal's body, they are released back into the water where they may penetrate the skin of any new host, man or animal, that happens to be in the water.

Vector-borne transmission can be mechanical or biological. In mechanical transmission, the vector simply carries the parasite in or on its body from one host to another; viruses and bacteria are transmitted mechanically. In biological transmission, the parasite passes through a stage of its life-cycle in the host's body, usually multiplying whilst there; most protozoa and helminths are transmitted biologically and, with the exception of microfilariae, all multiply in the host's body.

The diseases that will be described in this chapter are listed in Table 2.1. Not all of them have a direct relation to irrigation, but we thought it would be useful to discuss them as well because anyone working in land and water development may come across them.

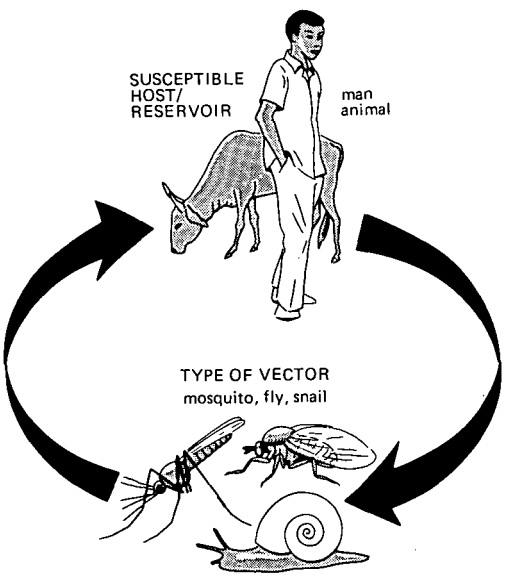

Figure 2.1 Transmission of vector-borne infections

For each disease, some possible control measures are suggested. These will be elaborated in later chapters.

Table 2.1 Type of vector infection, diseases, and disease organism

Type of vector infection	Disease	Disease organism
Mosquito-borne	Malaria	Protozoon
	Filariasis	Nematode
	Yellow fever	Viruses
	Dengue	(arbo viruses =
	Encephalitis	arthropod-borne
	Other arbo-viral infections	viruses)
Snail-borne	Schistosomiasis (bilharzia)	Trematode
	Clonorchiasis	Trematode
	Opisthorchiasis	Trematode
	Paragoniamiasis	Trematode
	Fascioliasis	Trematode
	Fasciolopsiasis	Trematode
Fly-borne	African trypanosomiasis (sleeping sickness)	Protozoon
	Onchocerciasis (river blindness)	Nematode
	Leishmaniasis (kala azar, oriental sore)	Protozoon
	Loiasis (various types)	Nematode
Miscellaneous		
Water flea	Dracontiasis (guinea worm)	Nematode
Bug	American trypanosomiasis (Chagas' disease)	Protozoon
Louse/tick	Plague, louse-borne fevers, and other fevers (tick-borne, mite-borne)	Bacteria, spirochete, rickettsiae

2.1 Malaria

2.1.1 Definition

Malaria is a complex disease, clinically characterized by fever, anaemia, and enlargement of the spleen. Protozoan organisms of the genus *Plasmodium* (*P.*) are responsible for the malaria infection. *P. falciparum* (malignant subtertian malaria) and *P. vivax* (so-called benign tertian malaria) occur solely in man; *P. malariae* (quartan malaria) occurs in man and chimpanzees. A fourth species, *P. ovale*, is so rare that it forms little risk to public health. Some hundred other species of *Plasmodium* are found in reptiles, birds, and lower and higher primates. Plasmodial organisms go through a cycle of asexual development and multiplication in the susceptible host, and complete

their sexual development in mosquitoes of the genus *Anopheles*. Of the more than 300 Anopheles species described, only some 25 species are significant vectors of malaria. Important malaria vectors are listed in Volume 2 (page 15, Table 1.1).

2.1.2 Distribution

Malaria occurs or has occurred on all continents, in latitudes extending roughly from 60°N to 40°S. The distribution of the parasite species is not uniform as it is influenced by climate and the vector species. Throughout the world, there are approximately 150 million clinical cases of malaria annually, although, of course, the number of people infected is considerably higher.

In tropical Africa alone, where malaria affects practically the entire population, it has been estimated that every year the disease causes the death of close to a million children under the age of fifteen. The disease remains highly endemic – and therefore a major public health problem – in virtually all of tropical Africa and in several countries in Asia and Central and South America. A resurgence of the disease is taking place on the Indian Subcontinent, with the occurrence of several million cases.

2.1.3 Symptoms

Malaria is clinically characterized by:

- Fever, which may have a characteristic periodicity. Once the infection is established, fever paroxysms will occur every 48 hours in *P. vivax* infections and every 72 hours in *P. malariae* infections. In *P. falciparum*, the periodicity of paroxysms is less synchronized and more prolonged, or even continuous;
- Anaemia, which results from the destruction of red blood cells;
- Enlargement of the spleen.

Various complications resulting from the involvement of the liver, kidneys, and brain can influence the course of the infection.

Malaria due to *P. falciparum* is the most serious form. Cerebral complications and involvement of the kidneys and other organs are common in the non-immune and are responsible for the high case fatality (1 to 15 per cent) associated with the infection in its epidemic form. Under endemic conditions, the high-risk groups are infants, young children, and pregnant women. Case fatality in each of these groups is equally high. In non-immunes and high-risk groups, it is a danger to life; in immunes and the partially protected, the chronic form lowers physical well-being and working capacity and is accompanied by periods of debility.

Vivax malaria is infrequently followed by serious complications. *Vivax* malaria is a problem, not because of its fatality rate, but because of the debility it produces during its initial phase and in relapses. *P. malariae* symptoms resemble those of *P. vivax*. In African children, *P. malariae* is commonly followed by a chronic and ultimately fatal kidney condition (nephrosis). In both forms, the chronic stage affects physical well-being and working capacity.

So far, we have only considered the direct effects of malaria. But in areas where it is endemic, the mortality and morbidity attributable to it exceed its direct impact.

Chronic malaria negatively affects the nutritional status of children and consequently their growth. Intercurrent other infections often cause a reciprocal stimulation and a more severe form of the disease. Indeed, if the general balance of health is upset in any way (by a common cold, diarrhoea, or minor accident), the *falciparum* infection can react with lightning speed and kill the patient within days.

2.1.4 Diagnosis

The only certain means of diagnosing malaria is to detect the plasmodial parasites by microscopic examination of the blood. For epidemiological diagnosis, the species of parasite is significant, whereas parasite counts are mainly relevant for clinical diagnosis. Various serological tests are now available. They are valuable for certain types of epidemiological studies.

2.1.5 Life Cycle

Figure 2.2 shows the life cycle of mammalian malaria parasites (Mons 1986). Plasmodial sporozoites are introduced into the human body by an infected mosquito and make their way to the liver, where they mature into tissue schizonts that contain large numbers of merozoites. The mature schizonts burst, releasing the tissue merozoites, many of which enter the bloodstream and attach themselves to red blood cells (erythrocytes). These merozoites mature into another generation of schizonts. On maturing, these schizonts release their erythrocytic merozoites into the bloodstream, together with foreign proteins, which are responsible for the malarial fevers. If the infection is not treated, erythrocytic merozoites will continue to enter red blood cells and maintain the erythrocytic cycle for many generations. In severe infections, 10,000 to 50,000 merozoites of *P. vivax* or *P. malariae* can be found per cubic millilitre of blood and as many as 100,000 to 500,000 of *P. falciparum*.

In *P. vivax* and *P. malariae* infections, some of the sporozoites that parasitize liver cells mature only after many weeks, months, or sometimes even years. This delayed maturation is not synchronized. Upon maturation, each of these 'delayed' liver schizonts (hypnozoites) is capable of initiating a new erythrocytic cycle and a 'relapse' of the malaria attack. A single *vivax* infection may therefore be followed by several of these relapses, months or even years apart. *P. falciparum* does not exhibit this phenomenon. Hence, to understand the epidemiological behaviour of the malaria caused by the different parasite species, one has to consider the delayed liver schizonts.

Upon completion of the erythrocytic cycle in all three species, a few merozoites will not enter red cells again, but will develop into male and female forms. These are 'gametocytes'. In *P. vivax* and *P. malariae* infections, gametocytes may appear immediately after the first erythrocytic cycle. In *P. falciparum* infections, however, gametocytes form only after several erythrocytic cycles have been completed, about 14 days later. This is a second feature that differentiates the epidemiological behaviour of *falciparum* from that of the other species.

If gametocytes are picked up by an anopheline mosquito taking a bloodmeal from an 'infectious' host, male and female gametocytes will mate in the mosquito's stomach

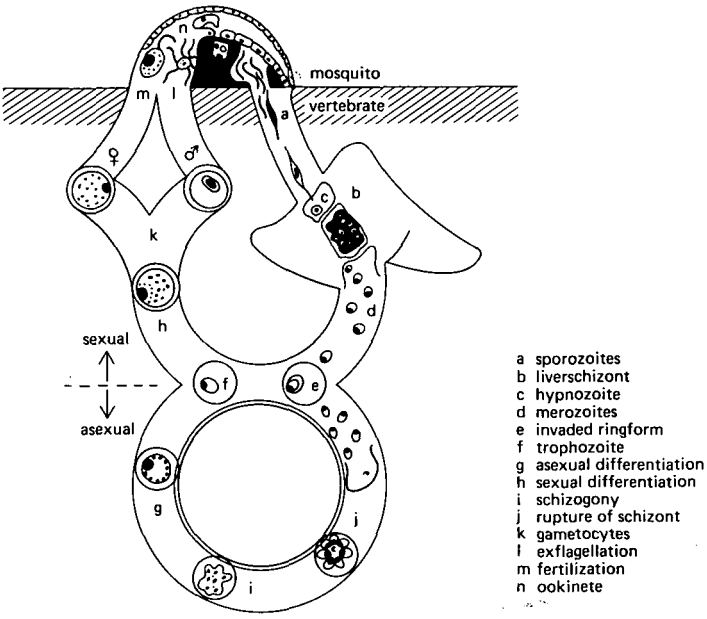

Figure 2.2 Life cycle of malaria parasites (after Mons 1986)

and eventually develop into sporozoites in its salivary gland. The mosquito, upon taking another bloodmeal from a susceptible victim, completes the plasmodial life cycle by injecting these sporozoites into the new host's bloodstream.

2.1.6 Epidemiology

The epidemiological behaviour of malaria is determined by factors related to the parasite, the mosquito vector, and the host. The factors related to the mosquito are discussed in Chapter 3. In a specific region, of all Anopheles species present, only 1 or 2 actually act as a vector of malaria (see Volume 2). Measuring the incidence and prevalence of the disease is complicated by the immunity that the human host develops after repeated infection. For measuring epidemic malaria, the blood parasite rate is the main parameter; for endemic malaria, parameters are the prevalence of spleen enlargement and the blood parasite rate.

The term 'endemicity' refers to the number of cases of malaria in a community or area. Any precise information on the degree of endemicity must be based on quantitative and statistical concepts. Malaria is described as endemic if it has a constant incidence of cases over a period of many years. Epidemic malaria refers to occasional or periodic sharp increases in the incidence of the disease in a community.

A different classification is used for malaria transmission. In 'stable' malaria, transmission is high, without any marked fluctuations over the years, though seasonal fluctuations may exist. In 'unstable' malaria, transmission varies from year to year. In stable malaria, collective immunity is high and epidemics are unlikely. In unstable malaria, collective immunity is low and epidemics may occur from time to time.

There is no sharp distinction between endemic and epidemic malaria, nor between stable and unstable malaria. Splenic enlargement in population samples has proved to be a useful indicator of endemicity. The World Health Organization/WHO has adopted the following classification of endemicity, based on spleen and blood parasite rates in sufficiently large population samples:

- Hypoendemic malaria: spleen rate in children (2 to 9 years) does not exceed 10 per cent. Blood parasite rates are variable in all age groups. There is little transmission;
- Mesoendemic malaria: spleen rate in children (2 to 9 years) is between 11 and 50 per cent. Blood parasite rates tend to be higher in children than in adults. This degree of infection is found typically in small rural communities in sub-tropical zones. The intensity of transmission varies;
- Hyperendemic malaria: spleen rate in children (2 to 9 years) is constantly above 50 per cent; spleen rate in adults is also high (over 25 per cent). The parasite rate is high in young children, but declines in older age groups. This degree of infection is seen in areas with intense – but seasonal – transmission, where immunity remains insufficient to fully prevent the effects of malaria in older age groups;
- Holoendemic malaria: spleen rate in children (2 to 9 years) is constantly above 75 per cent, but low in adults. The parasite rate is very high in under-fives, but low in adults. Holoendemic malaria is found in areas with perennially stable transmission, resulting in a high degree of immune response in all age groups, particularly in adults.

The tissue cycle of *P. vivax* and *P. malariae* may last longer than the erythrocytic cycles, and may represent a dormant phase in the life cycle. Some tissue schizonts burst some 6 months later, allowing the parasite to survive a winter or a dry season when mosquitoes are not biting and transmission is suspended. *P. vivax* and *P. malariae* infections can thus maintain themselves much longer than *P. falciparum* infections. *P. malariae* has been known to persist for 50 years.

The delayed appearance of gametocytes in *falciparum* infections affects the epidemiological incubation period. The incubation period of malaria is the interval between a mosquito's taking up of gametocytes and the appearance of the next generation of gametocytes. For *P. vivax* and *P. malariae*, in ideal circumstances, this is about 3 weeks, but for *P. falciparum*, it is at least 5 weeks.

These factors favour *P. vivax*, but *P. falciparum* has one extremely great advantage: it exists in a very wide variety of immunological strains, so that re-infections continue to take place indefinitely. Hence, even the elderly African, subjected to constant infective challenge since childhood, has parasites in his blood from time to time. In contrast, *P. vivax* induces a much more lasting immunity.

If, therefore, because of a winter or a dry season, the transmission of malaria is seasonal, *P. vivax* will be favoured. There will be an epidemic of spring relapses and, because of the short incubation period, the summer epidemic will build up briskly. *P. falciparum*, starting from a small reservoir of persistent cases, failing to develop in mosquitoes until the weather becomes hot, and having a longer incubation period, increases much more slowly and reaches a peak only late in summer or in the autumn. In areas where both infections are prevalent and seasonal, the summer epidemic will show a predominance of *vivax* in its early phase and a gradual shift to *falciparum*

in its later phases. More importantly, if the transmission season is prolonged because of a hot and wet autumn, there will be a disproportionately severe epidemic, particularly of *falciparum*, with a high case fatality. If transmission continues throughout the year, *P. falciparum* will be the predominant species.

2.1.7 Control

Malaria control aims at reducing the reservoir of infection in the community, and/or reducing the number of malaria vectors biting man. Providing adequate and accessible treatment facilities will significantly reduce the mortality and morbidity of the disease. In its present strategy of malaria control, WHO is specifically recommending the indiscriminate treatment of all fever cases in endemic regions.

A control strategy needs to take into account the type of malaria (epidemic or endemic) and the individual factors affecting the size of vector populations. Depending on environmental and socio-economic conditions in the community, a control strategy can employ a combination of the following:
- Prevent mosquitoes from feeding on man;
- Prevent or reduce mosquito breeding by eliminating collections of water or by altering the environment;
- Destroy mosquito larvae;
- Destroy adult mosquitoes;
- Eliminate malaria parasites in the human host.

When considering measures to control mosquito breeding, one can choose between indiscriminately preventing the breeding of all anophelines, or selectively preventing the breeding of the species known to be the vector, a practice called 'species sanitation'. Species sanitation implies that the efficiency of control measures is greatly improved by concentrating the attack on the vector species, rather than dispersing the effort over all the species in the area. Species sanitation was one of the great advances made in malaria control around the start of this century. Before it can be applied, however, one must know which species is the vector and which breeding places it prefers.

2.2 Filariasis

2.2.1 Definition

Filarial disease in man causes inflammations and obstructive lesions in the lymphatic system. Filarial parasites are tissue-inhabiting nematode worms that need an insect vector to complete their life cycle. Of these, *Wuchereria bancrofti* and *Brugia malayi* are transmitted by mosquitoes. A third species, *Brugia timori*, is closely allied to *B. malayi*. Filarial nematodes have a single sexual life cycle. Their larvae can only develop if ingested by a suitable intermediate host, after which they must enter a final, susceptible host, where they mature into adult filarial worms.

W. bancrofti has its reservoir of infection in the human community; that of *B. malayi*

includes a wide range of animals (cats, dogs, monkeys, and many others).

Mosquito vectors of filariasis belong to the genera Anopheles, Aedes, Culex and Mansonia. Also here a restricted number of species actually are important vectors (see Volume 2).

2.2.2 Distribution

The most widespread mosquito-borne filarial parasite is *W. bancrofti*, with which some 82 million people are infected throughout China, the Indian Subcontinent, Southeast Asia, the Pacific islands, tropical Africa, and South and Central America. *B. malayi*, with which about 9 million people are infected, has a much more limited distribution in Southeast Asia, as does its allied species *B. timori*. About two-thirds of those infected live in China, India, and Indonesia. It is further estimated that 905 million people live in areas where there is a risk of infection.

2.2.3 Symptoms

Lymphatic filariasis is a chronic disease and – particularly in its later stage – a debilitating and disfiguring one. The number of worms with which a person is infected and the duration of the infection are the main determinants of the clinical signs and symptoms. Bancroftian and malayan filariasis are characterized by:

- Early lesions due to inflammation of the lymphatic vessels and glands. Attacks are painful and recur often;
- Late lesions due to lymphedema and chronic obstruction of the lymphatics. Elephantiasis is the disfiguring and incapacitating outcome of the infection. In endemic communities, 5 per cent or more of the population may have elephantiasis.

2.2.4 Diagnosis

The only certain means of diagnosing infection by *W. bancrofti* and *B. malayi* is to detect the microfilariae by a microscopic examination of the blood. The density of microfilariae gives a rough indication of the number of infecting worms.

In most places, a practical problem in conducting epidemiological surveys is the nocturnal periodicity of the parasite, which makes it necessary to collect blood after 9:00 p.m.

2.2.5 Filarial Life Cycle

In the life cycle of the filarial worm, humans or vertebrate animals are the worm's definitive hosts. After copulating, the female gives birth to numerous microfilariae, which enter the host's bloodstream. A mosquito feeding on an infective host may pick up one or a number of microfilariae, depending on their density in the blood (up to $15/mm^3$ in a serious human infection). Inside the mosquito, the microfilariae develop into larvae, which, upon becoming infective (7 to 14 days), enter the mosqui-

to's proboscis. When an infected mosquito bites a human, one or several of these infective-stage larvae (filariae) may wriggle out of the proboscis onto the skin. Subsequently, they may penetrate the wound inflicted by the mosquito bite. After penetration, the male and female filariae enter the lymphatics (lymph vessels and lymph glands) anywhere in the host's body, and mature there. Common sites include the tissues of the external genitals, the female breasts, the lower extremities, and the lower abdominal cavity. Maturation in the host takes 6 to 8 months. Adult filarial worms may live up to 15 years, but microfilarial shedding declines after about 3 years. Microfilariae remain viable for about 2 years.

2.2.6 Epidemiology

Endemicity is usually expressed as the prevalence in a community of people with microfilariae in their blood. In endemic situations, filariasis – because of its epidemiological determinants – has a focal distribution. Highly endemic situations tend to occur when a sedentary and stable community lives in close contact with an abundant vector population. Infected migrants can carry the disease to other places and become the source of an occasional new case.

The microfilariae in the peripheral blood circulation exhibit a typical daily periodicity. In *W. bancrofti* infections, this periodicity is nocturnal throughout most of its geographical distribution. High densities of microfilariae appear in the bloodstream at night and very low densities, or none, appear during the day. In some places, the microfilarial periodicity in *W. bancrofti* infections is less marked and is subperiodic or even diurnal.

A second point, central to an understanding of the epidemiological behaviour of filariasis, is the limited number of parasites that are transmitted by the bite of an infective mosquito. Microfilarial density in the blood depends directly on the number of adult female worms present. In its turn, the worm-load depends on the number of infective mosquito bites that a host is expected to receive over a period of time. In a highly endemic West African focus of bancroftian filariasis, 5 to 7 per cent of the anopheline vectors were infected and 1 to 2 per cent were infective. Under these conditions, an individual could receive about 130 infective bites in a year, but this number could be as high as 1000.

Little is known about the effect of immunity on the transmission of the infection. Nevertheless, people with long-term serious infections and suffering from late lesions generally have few or no microfilariae in their blood.

Four epidemiological types of filariasis have been differentiated:

- Rural bancroftian filariasis, whose principal vectors are *Anopheles sp.* and *Aedes sp.*. This type is often associated with stable ecological conditions (e.g. rice cultivation);
- Urban bancroftian filariasis, which is typically associated with unplanned urban development such as the growth of urban slums. Its principal vector is *Culex quinquefasciatus* (*fatigans*), which breeds in the polluted waters of cesspits, ditches, drains, tanks, barrels, and all sorts of containers. We have only recently begun to appreciate the potential problems of urban filariasis;

- Essentially non-zoonotic brugian filariasis, which resembles rural bancroftian filariasis;
- Zoonotic brugian filariasis, which is largely rural and is dependent on vectors with very specialized breeding requirements in swamp habitats (*Mansonia sp.*). Clearing and draining the swamp forests will increasingly restrict this type in its geographical range.

2.2.7 Control

The principles of control by measures aimed at the vector are essentially the same for filariasis as they are for malaria. In regions where *Culex quinquefasciatus* is the vector, destroying the mosquito larvae (chemically with larvicides or biologically with *B. sphaericus*) is particularly effective. Filarial disease on the whole is more susceptible to control than malaria. This is because the worm-burden of the individual patient is the main determinant of the severity of the case, particularly of the late lesions, and any reduction of transmission will help to reduce the incidence of severe lesions. Drug therapy depends largely on diethyl-carbamazine, which kills microfilariae but does not affect adult worms.

2.3 Mosquito-Borne Viral Infections

2.3.1 Definition

Viruses that are transmitted by mosquitoes belong to the family of arthropod-borne (arbo) viruses. Arboviruses usually have a zoonotic reservoir of infection. There are approximately 300 arboviruses belonging to 41 antigenic groups. Other vectors besides mosquitoes are ticks and sandflies. The major mosquito-borne viral infections are yellow fever, dengue, and several forms of encephalitis.

Mosquito vectors of arbo-viral infections either belong to the genus Aedes or the genus Culex (see Volume 2).

2.3.2 Distribution

For the distribution of the major arboviral infections, see below (Section 2.3.4, The Diseases) and Volume 2, Annex 1.

2.3.3 Arboviral Life Cycle

Viruses are small pathogenic agents that go through an obligatory intracellular phase. Specific arboviruses, after having been introduced into the host's bloodstream by the bite of a mosquito, invade the body through the cells of the lympho-reticular system. From there, they spread to specific target organs. They are ingested with the bloodmeal when a mosquito feeds on an infected vertebrate host. Within the mosquito, the virus

undergoes multiplication and/or cyclical development (5 to 30 days), after which it can be transmitted to another host when the mosquito takes another bloodmeal. Mosquitoes remain infected and infective for life, but do not suffer any apparent ill effects. Female mosquitoes infect their offspring through the transovarian route.

2.3.4 The Diseases

Yellow Fever

Yellow fever is an acute, often fatal, disease. It is characterized by severe head and body aches, fever, and jaundice, followed by internal haemorrhages and vomiting. Death in fulminating cases occurs as early as the third day after the patient has fallen ill. Case fatality is usually 5 to 15 per cent.

The zoonotic reservoir of infection is in jungle monkeys. In South and Central America, the *Haemagogus* mosquito, which occasionally bites man, is the monkey-to-monkey vector. In Africa, the monkey-to-monkey vector is a gallery-forest mosquito, *Aedes africanus*; the monkey-to-man vector is typically *Ae. simpsoni*, which breeds profusely at the periphery of forests in the vicinity of man. Subsequent man-to-man transmission can occur through the vector *Ae. aegypti*, which breeds near human habitation in plant axils, potholes, and containers of all sorts and sizes. When this is allowed to happen, the infection, which is normally confined to monkeys in tropical forests, can become a rural and urban health problem, causing epidemics with a high case fatality.

Yellow fever has never been reported in Asia, although potential vectors (especially *Ae. aegypti*) abound.

Dengue Haemorrhagic Fever

Dengue haemorrhagic fever is an acute disease, characterized by high fever, intense muscular and joint pains, and prolonged incapacitation. A more serious form of the disease, frequently complicated by haemorrhagic shock and leading to death unless treated early, is found in Southeast Asia. Although it is known as a disease of low fatality, dengue haemorrhagic fever has in recent years caused more deaths than any other arboviral infection except yellow fever. The agent is a virus that is closely related to the one responsible for yellow fever. No reservoir other than man is known. The primary vector is the cosmopolitan *Ae. aegypti*, but other *Aedes* species have been incriminated. Explosive epidemics, with tens of thousands of cases, have occurred in the recent past, especially in urban areas.

Viral Encephalitis

Several other mosquito-borne viruses have a special affinity for the central nervous system of the human host, causing encephalitis, an inflammatory disease of the brain and spinal cord. The symptoms are high fever, stupor, disorientation, coma, and spastic paralysis. Encephalitis is a very serious disease, which can leave survivors (especially

children and old people) mentally retarded and with motoric disturbances. The Japanese B virus, in particular, can have a high case fatality.

In the Americas, the arboviruses Western equine, St. Louis, Eastern equine, and Venezuelan equine primarily infect birds. The California viruses primarily infect rodents. Various species of *Culex* and *Aedes* mosquitoes are the vectors. *C. tarsalis*, which breeds in rice fields, plays a significant role in transmitting the infections among birds, and to horses and man.

Japanese B virus is prevalent in the Far East. It is primarily an infection of mammals. Pigs, both domestic and wild, play an important role in the epidemiology. *Culex tritaeniorrhynchus*, which breeds in rice fields, has been the vector in human outbreaks. *C. gelidus* probably maintains the virus in pig-to-pig transmission.

All these encephalitic viruses have a complex epidemiology, involving several different transmission cycles, with different animal reservoirs and different mosquito vectors. The viraemia produced in human infections is in most cases so low that the disease cannot be transmitted from man to man or from man to animal. Thus man is a 'dead-end' host in the life-cycle. Horses are also dead-end hosts.

Chikungunya Fever

The virus that causes Chikungunya fever (O'nyong nyong fever) is particularly associated with irrigation schemes. It has been responsible for large-scale epidemics of a non-fatal febrile disease in East Africa and is also prevalent in Southeast Asia. The animal reservoir includes monkeys and baboons. Its vectors include *Ae. aegypti* and *A. gambiae* and *funestus*.

2.3.5 Control of Arboviral Infections

The development of effective vaccines against yellow fever and their massive application in endemic areas, together with successful mosquito control programs in the recent past, have reduced the threat of yellow fever to a fraction of what it was half a century ago. The vaccination of travellers between endemic and non-endemic areas is enforced by international regulations. The authorities in charge of development projects in areas where yellow fever is enzootic have a special responsibility to ensure that workers and their families have been vaccinated before they settle in such areas.

Vaccines are also available for several encephalitic infections, but their application is usually limited to occupational groups with a high risk of exposure (e.g. laboratory workers).

Vector control has been successful in some cases. The classic example for yellow fever (and malaria) was furnished by Gorgas during the construction of the Panama Canal from 1904 to 1912. Responsible for the health of the workers, Gorgas enforced strict discipline in removing all collections of water where *Aedes* and *Anopheles* could breed. Similar methods were applied in South American cities and towns that were under threat from yellow fever.

In recent times, insecticides have been used successfully, but their application is now being hampered by the resistance that mosquitoes have aquired and by the exophi-

lic behaviour of mosquito vectors. Forest mosquitoes require a special approach. There is a need to develop alternative methods of control, including environmental management, especially for mosquitoes that breed in tree holes.

2.4 Schistosomiasis (Bilharzia)

2.4.1 Definition

Schistosomiasis is a complex parasitic infection that is transmitted to man in a variety of freshwater habitats. The infection is caused by five species of parasitic worm of the genus *Schistosoma: S. haematobium, S. mansoni, S. japonicum, S. intercalatum,* and *S. mekongi.* All five species are epidemiologically distinct and affect different organ systems. Schistosome worms do not multiply inside the human host; the parasite load is acquired by multiple infections.

Snails belonging to the sub-classes of *Pulmonata* and *Prosobranchiata* are the intermediate hosts needed by the parasite to complete its life cycle. The reservoir of infection for *S. haematobium* appears to be wholly in humans. *S. mansoni* infections are found in monkeys, baboons, and rodents, but there is no evidence that animals play any significant role in transmitting *S. mansoni* to humans. Many animals, both domestic and wild, are infected with *S. japonicum*, and these animal reservoirs contribute significantly to the transmission of *S. japonicum* to humans.

With few exceptions snail hosts of S.haematobium belong to the genus Bulinus, of S.mansoni to the genus Biomphalaria, and of S.japonicum the genus Oncomelania.

2.4.2 Distribution

An estimated 200 million people are infected with schistosomiasis, and 500 to 600 million are exposed to it. Details of the distribution of the different parasites are presented in Volume 2, Annex 1.

2.4.3 Symptoms

The disease that develops in many of the people infected by the schistosomal parasite follows a chronic and complicated course. The main determinant of the severity of the disease is the number of worms with which the patient is infected. The parasites themselves appear to play a minor role in causing pathological lesions. While the schistosome eggs excreted by the host maintain the life cycle of the parasite, it is the host's reaction to those he retains in his tissues that is mainly responsible for the disease. The exact proportion of eggs retained is not known, but in view of the vast numbers found at autopsy, it may be as high as 50 per cent in infections by *S. haematobium*, and it has been estimated that one-third of any *S. mansoni* eggs reach the patient's liver.

Four stages of the disease have been identified:
- Invasion: cercarial skin reaction and possibly some fever;

- Development: acute febrile illness, which is not always recognized;
- Established infection: early chronic disease with haematuria or intestinal symptoms;
- Late infection: chronic disease of the bladder/kidneys, intestinal tract, and liver.

In *S. haematobium* infections (urinary schistosomiasis), the target organs are in the urinary tract: the bladder, ureters, and kidneys. The clinical disease is characterized by micturition of bloody urine, accompanied by bladder irritation (painful micturition). If the ureters are involved, obstruction of the urinary flow can result. The proximal part of the ureter and the adjacent kidney can become grossly dilated and dysfunctional. In some countries where urinary schistosomiasis is endemic (Egypt, Mozambique), cancer of the bladder occurs frequently and a causal relationship is claimed.

In *S. mansoni* infections (gastro-intestinal schistosomiasis), the principal target organs are the liver, intestines (rectum, colon, but also the small intestine), and spleen. In contrast to *S. haematobium* eggs, *S. mansoni* eggs are less often laid in clusters and they degenerate rather than calcify. Lesions of organs other than the target organs are more common (lungs, lymphatic glands, pancreas). Clinically, the disease presents more serious constitutional symptoms in the initial acute stage, followed in the chronic stage by intermittent diarrhoea, dysentery, and vomiting of blood. The chronic stage ultimately causes extensive destruction and fibrosis of the liver, spleen, and large intestine. Emaciation, hepatic coma, and massive bleeding from the upper gastro-intestinal tract may lead to the death of the patient.

The disease caused by *S. japonicum* resembles that caused by *S. mansoni*, but is generally more severe. In addition, it is thought that in endemic areas there is a causal relationship between *S. japonicum* infections and carcinoma of the liver and the rectum. Another distinctive feature is the more frequent occurrence of lesions in the central nervous system. In *S. haematobium* and *S. mansoni* infections, these lesions occur in the spinal cord. The high incidence of epilepsy in endemic areas of the Philippines is attributed to *S. japonicum*.

S. intercalatum infections combine features of *S. haematobium* and *S. mansoni* infections. *S. mekongi* infections resemble those of *S. japonicum*.

2.4.4 Diagnosis

All parasitological diagnostic techniques are relatively insensitive because of variations in egg output during the day (in urine) and from day to day (in stool). This is a particular problem if incidence data are to be calculated. However, quantitative techniques have the added advantage of providing reproducible data, which qualitative techniques cannot.

For epidemiological and community studies, the preferred method of diagnosis is to detect worm eggs by a microscopic examination of the sediment of a urine sample (*S. haematobium*) or the sediment of a suspended (and sieved) faeces sample (*S. mansoni*, *S. japonicum*, *S. intercalatum*, and *S. mekongi*). This is a simple and cheap way to demonstrate the qualitative presence of the infection.

The quantitative diagnosis of the infection and the parasite-load requires more equipment, but simple and reliable methods have recently become available. Quantita-

tive diagnosis is necessary for a correct epidemiological interpretation of the disease situation and for evaluating the effect of control measures.

Urine is examined in samples of 10 ml, and the egg-count per sample is interpreted as in Table 2.2.

Table 2.2 Interpretation of urine examinations

Number of eggs per 10 ml of urine	Degree of infection
1–49	
50+	Severe
500+	Very severe

Stool is examined in different quantities, depending on the technique used, but the result is expressed in the number of eggs per gram of faeces, as in Table 2.3. In the often used Kato-smear method, a 50 milligram stool sample is examined and the result extrapolated to the number of eggs per gram faeces.

Table 2.3 Interpretation of stool examinations

Number of eggs per Kato smear	Number of eggs per gram of faeces	Degree of infection
1– 4	24– 96	Mild
5–33	120–792	Moderate
34+	816+	Severe

In epidemiological studies, where many thousands of specimens are examined by semi-skilled workers, high standards of microscopy must be maintained.

2.4.5 Life Cycle

As they develop, schistosome worms go through alternate stages of parasitism and searching for a host: the egg, miracidium, first-stage sporocyst, second-stage sporocyst, cercaria, schistosomulum, and adult schistosome (see Figure 2.3).

The eggs of each species have a characteristic shape. The embryo (miracidium) develops inside the egg for 6 days. If the egg remains in the host's tissues, the miracidium lives for another 15 days, dying approximately 21 days after oviposition. Ova that pass through the bladder or intestinal wall (less than 50 per cent of the total egg production) are voided into the environment. Under suitable watery conditions, the miracidia become active and emerge from the egg.

Miracidia swim vigorously (about 2 mm/second), and their behavioural pattern matches that of the intermediate snail host. They remain active and infective for 8 to 12 hours, swimming in long sweeping lines until they locate a snail host. Flowing

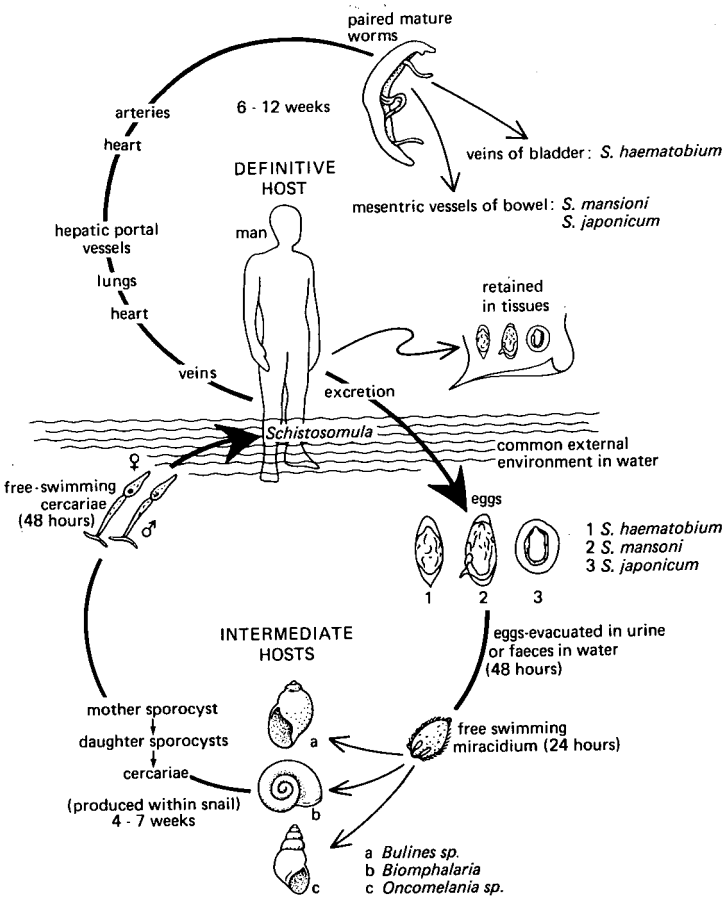

Figure 2.3 The life cycle of schistosomes

water helps to disperse the infective miracidia over a larger area, thereby increasing their chance of finding a snail host. Upon contact with a snail, the miracidia attach themselves and penetrate it with boring movements.

Although a number of miracidia may enter the same snail, only a small proportion of them survive to mature, first into mother sporocysts, and then into daughter sporocysts. Each daughter sporocyst will produce thousands of cercariae (starting 4 to 7 weeks after the miracidia have penetrated the snail). When mature, the cercariae escape from the daughter sporocyst and emerge from the snail. The shedding of cercariae may continue until the snail dies. The snail's schistosomal infection can influence its growth rate, reproductive capacity, and its life expectancy, which is otherwise up to 130 days. Some snails cure themselves spontaneously of the infection.

All the cercariae that develop from the same miracidium are of the same sex. Cercariae are about 1 mm long and swim vigorously. The principle stimulus to their emergence from the snail is light, and usually at temperatures ranging from 10 to 30 °C. Cercariae of *S. haematobium* and *S. mansoni* are released over a period of several

hours towards the middle of the day; those of *S. japonicum* are most abundant in the early hours of darkness. The number of cercariae produced by a snail varies from day to day, depending on environmental conditions, and from snail species to snail species, depending on the susceptibility of the species to the strain of infecting schistosomes. The output of cercariae from *Biomphalaria sp.* and *Bulinus sp.* may vary from 400 to 3,000 per snail per day (25,000 to 100,000 during the course of an infection). The snail hosts of *S. japonicum* are much smaller and shed considerably fewer cercariae (100 to 150 per day). Shedding by this species can be interrupted for many days.

Cercariae are non-feeding organisms and are relatively short-lived (up to 48 hours, but usually 8 to 12 hours under field conditions). It has been suggested that cercariae become fatigued in fast-flowing, turbulent water. When they come into contact with man (or another suitable vertebrate host), they attach themselves with their suckers and penetrate the intact skin within a few minutes. A considerable proportion (probably 25 to 75 per cent) die in the process.

After entering the definitive host, the cercarial larva becomes a worm-like creature – the schistosomula – which migrates to the liver, where it matures. Most sexually mature worms leave the liver when they have mated and migrate to the blood vessels of the target organs, where they begin producing eggs. The period between successful cercarial penetration and the appearance of eggs in the stool or urine of the definitive host may be 30 to 40 days, but is often longer.

The adult worms live in mated pairs in the blood vessels of the target organs. They may live for 20 to 30 years, but their mean life span is 3 to 8 years. Each pair produces 300 to 3,000 eggs per day. The adult schistomes do not multiply in the definitive host's body. An individual's parasite load depends on the number of infections he has acquired. In the host population, most individuals will carry a few parasites; a few may be heavily parasitized.

2.4.6 Epidemiology

The epidemiological behaviour of schistosomiasis is influenced by variables related to the parasite, the intermediate host, and the definitive host. Variables relating to the intermediate snail hosts are discussed in Chapter 3. The dynamics of transmission are complicated, and the resulting pattern of incidence can be astonishing to the uninitiated. One of the main characteristics of incidence is that it is focal. Within a confined geographical area, certain communities can have high prevalence rates, whereas a few kilometres away others can be practically free of the disease (e.g. villages along a lake or stream, compared with inland villages).

The endemic level is commonly described in terms of age-specific prevalence rates. For schistosomiasis, there is no generally accepted classification of levels of endemicity as there is for malaria. As schistosomal disease is mostly associated with a high parasite-load, information on the prevalence of infection gains much in significance if it is supplemented by information on the intensity of infection (see Figure 2.4). In endemic communities, both the prevalence of infection and its intensity generally increase with age in children until they reach adolescence, and then decline in adulthood. Variations in this general pattern do occur – with peak rates in younger age groups in areas of high transmission, and varying degrees of decline in older age groups – but such

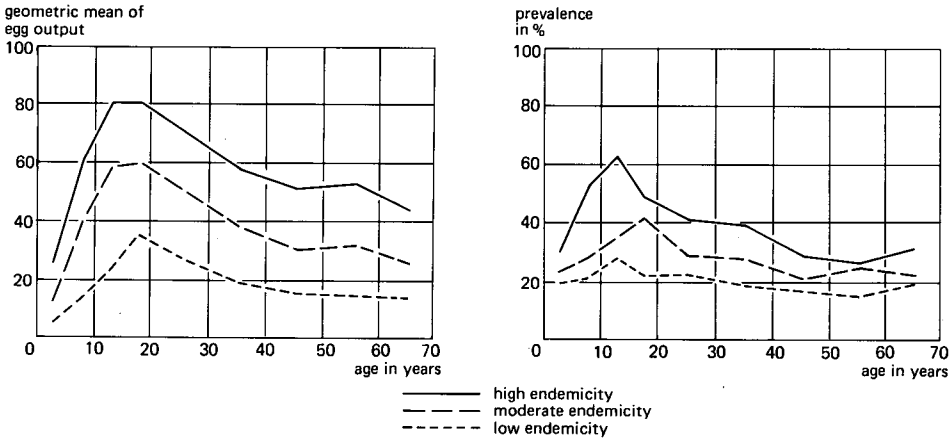

Figure 2.4 Age-specific prevalence data from communities in areas of high, moderate, and low endemicity, and the corresponding geometric mean of egg counts from those infected

variations usually depend on the extent of water contact and the species of parasite. The declining prevalence of infection in adults is attributed, among other things, to the development of immunity, which is assumed to take 15 years or more.

Measuring the incidence of new infections is hampered by the uncertainties of parasitological diagnosis and by the natural duration of the disease. In endemic areas, virtually every child will eventually become infected. Incidence studies are troublesome because of the considerable number of falsely-negative test results. For this reason, incidence studies are usually confined to young children, among whom such false results are less likely.

Human behaviour is an important factor in the transmission of schistosomiasis. Human excreta-related behaviour governs the release of schistosome eggs into the environment via urine and faeces, and human water-contact behaviour governs exposure to the disease.

A measure of the potential level of environmental contamination by schistosome eggs can be obtained from figures on the prevalence of the disease in a community and on the egg output of its victims. As these parameters vary with the age of the host, some age groups will contribute more eggs than others. In areas of high transmission, young children will be mainly responsible for the bulk of contamination. In areas of lower transmission, it will be older children and young adults.

The excretory behaviour of children is less discriminate than that of adults, and can be less well controlled. In rural communities in the tropics, defecation and urination often take place in the open. Urination, in particular, is often directly into water. Excreta may be deposited in flowing water, or near water – on river banks, in tall grass, or behind bushes. Excreta deposited near water may subsequently be washed into the water during rainfall.

Transmission ultimately depends on a community's having contact with infectious surface water. Studies on water-contact behaviour can provide important information

for planning the control of schistosomiasis. Combined studies of the intermediate snail host and human contact with water can indicate when and where transmission takes place. (This knowledge is critical for focal snail control.) As part of an integrated control strategy, information on the different types of water contact could lead to the provision of alternative facilities (standpipes, laundry units, bathing and swimming facilities).

Various studies of human/water-contact behaviour have been made. These support the broad classification of water contacts as being domestic, recreational, religious, and occupational. Although religious and occupational contacts will vary in different endemic regions, the main domestic contacts (collecting water, washing utensils, laundering, bathing) and recreational contacts (playing, swimming) are universally similar. Age plays an important role in human-water contact (see Figure 2.5).

The main water-contact parameters are the number of contacts, their duration, and the extent of body immersion. Contacts with water for specific purposes usually occur at specific sites. Drinking water, for example, may be obtained at one site, and washing clothes or bathing may be done at another. Contact is not limited to the water site. In Ethiopia, sentinel mice became infected when exposed to surface water stored in houses. The pattern of contacts may follow daily, weekly, monthly, or seasonal cycles, depending on the type of activity. Religious rules and practices can be important determinants. Occupational contacts will depend on the type of work done or the form of agriculture that is practised.

2.4.7 Control

The human host, the snail host, and the free-swimming stages of the parasite all offer

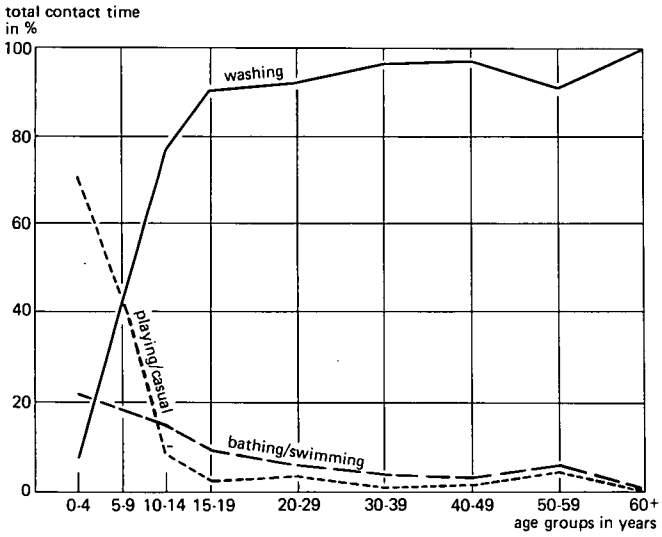

Figure 2.5 The total time spent in contact with water varies according to age group

opportunities to control transmission. The complete eradication of the disease may be the ultimate objective of control efforts, but it will be difficult to achieve in the tropics, except in a few situations (e.g. at oases or on islands). More realistically, control measures should aim at reducing and preventing schistosomal disease. The present knowledge of the relationship between reduction and prevention is incomplete and offers only general guidance. With intensive control measures, it is comparatively easy, in highly endemic areas, to reduce high prevalence to low; but attempting to reduce low prevalence further becomes increasingly difficult and costly. And what constitutes a 'low level' depends on the nature and seriousness of other health problems in the area. It must be appreciated that long-term planning and recurrent expenditures are required.

Reducing transmission involves reducing a potential victim's exposure to infected water, and reducing the numbers of schistosome ova in the environment. Specific measures (e.g. chemotherapy and snail control) directly attack the parasite and the snail vector. Mass chemotherapy, in particular, which has only recently become possible, can rapidly reduce the prevalence and intensity of infection. Other, less specific measures are associated with improving the standard of living, which will provide additional social and health benefits. If effective, they will gradually reduce infection and disease. But, for the successful implementation of any control measure, behavioural changes are essential, so hygiene education should constitute an important element in any control programs.

A strategy for schistosomiasis control could be a combination of the following:

- Mass treatment, primarily to alleviate the suffering of those infected, and secondarily to reduce the output of schistosome eggs by the infected community. The development of simple and reliable diagnostic methods for case detection, and the advent of single-dose oral drugs, have made mass treatment feasible and effective. (The drugs are Oxamniquine for *S. mansoni*, Metrifonate for *S. haematobium*, and Praziquantel for all species.) A rapid decline in prevalence can be expected if participation is good. The uncooperative – and migrants – are major sources of re-infection;
- Control of the intermediate snail host. A knowledge of the ecology and bionomics of the local species is essential for any of the control methods (e.g. environmental modification and manipulation, biological and chemical control);
- Reduction of contact with contaminated water. The basic element in this is to change human behaviour and so make transmission less likely. In addition to providing hygiene education, one can site villages away from water, improve domestic water supplies, and build bridges, fishing ramps, fences, and so on;
- Reduction of environmental contamination. A change in human excretory habits is fundamental, as are improvements in excreta disposal.

2.5 Other Snail-Borne Diseases

2.5.1 Definition and Distribution

Several species of trematode worms other than schistosomes have man as their final host. Despite individual differences in their life cycles, these trematodes all enter man

through his digestive tract. Each first parasitizes a snail, then encysts on vegetation or in some aquatic animal that man subsequently ingests. Besides man, all these infections have sizeable animal reservoirs.

2.5.2 Life Cycle

Worm eggs enter the water in faeces, except for those of the worms that cause paragonimiasis, which mainly enter the water in sputum. The initial part of the trematode life cycle is similar to that of the schistosomes: the eggs hatch and the miracidia find an intermediate snail host in which the next stage of development takes place. Before they can infect a new definitive host, however, the cercariae that emerge from the snail must pass through an additional developmental stage (the metacercarial, or resting, stage). Cercariae must therefore reach a suitable plant or aquatic animal (fish or crustacean) if they are to survive. There they encyst, mature, and lie dormant until ingested by man or another definitive host.

2.5.3 The Diseases

Clonorchiasis and Opisthorchiasis

Liver fluke disease caused by *Clonorchis sp.* and *Opisthorchis sp.* is widespread in parts of Asia and Europe. Man is most commonly infected by *Clonorchis sinensis*, of which many millions of cases are reported in China, Japan, the Koreas, and Southeast Asia.

Opisthorchis infections have been reported in Asia and Eastern Europe. It is said that 3.5 million Thais are infected, and that prevalence in the U.S.S.R. has increased as a result of the construction of dams on the Rivers Volga and Dnieper.

Man is infected by eating raw fish that contain encysted metacercariae. Raw fish is a common food in all endemic areas. Fish culture in ponds that are contaminated by infected faeces fosters transmission.

Light infections are asymptomatic, but infections with hundreds of worms may be associated with varying degrees of abdominal discomfort, inflammation of the gall bladder, and obstructive jaundice. In endemic areas, carcinoma of the gall bladder is more frequent than elsewhere, and is believed to be associated with the infection.

Paragonimiasis

The disease is a significant health problem in southern China, Japan, the Philippines, Korea, and some other Southeast Asian countries. Three-and-a-half million people are believed to be infected. Small foci of the disease exist in Latin America (e.g. Peru) and Central Africa (e.g. Cameroon). The intermediate snail hosts are often found in swift mountain streams.

The disease is acquired by eating raw or inadequately cooked freshwater crabs and crayfish. The adult worms usually migrate to the lungs, where they cause a chronic inflammation whose symptoms (e.g bloodstained sputum) may be confused with tuberculosis.

Fascioliasis

Liver fluke disease is also caused by the relatively large trematode *Fasciola sp.* This form of the disease, fascioliasis, has been reported in many countries and is particularly associated with cattle-raising. Most reports of human infections are of single cases. Under certain conditions, the infection may occur in endemic foci. In a specific area of Malawi, 2.4 per cent of the population were infected; in Peru, 5 to 34 per cent of children under the age of 15 were infected. The intensity of the infection is usually low, and the resulting disease is characterized by symptoms involving the liver. The infection is acquired from eating raw watercress (*Nasturtium officinale*), dandelions, and other plants that grow in wet areas.

Fasciolopsiasis

The disease is caused by *Fasciolopsis buski*, a large trematode. Highly endemic foci are found in China, India, and other parts of South Asia. The adult worms settle in the small intestine, where they cause inflammation and ulceration. Heavy worm-loads are not uncommon. Fasciolopsiasis can be accompanied by abdominal pain and diarrhoea, alternating with constipation. The infection is acquired by eating raw water caltrop (*Trapa sp.*), water chestnut (*Eliocharis tuberosa*), and water hyacinth (*Eichhornia crassipes*).

2.5.4 Control

All these infections could be prevented if fish and crustaceans were cooked and if various vegetables were not consumed raw. But eating habits are difficult to change and the energy costs for cooking may be prohibitive.

A second line of control is the sanitary disposal of excreta, including sputum in areas where paragonimiasis is prevalent. This is particularly important where ponds are used for pisciculture and aquaculture. Ponds should be protected from contamination by human and animal (pig) sewage. If sewage water is used to fertilize fish ponds, it should be investigated with great care.

Because these infections occur over such extensive areas, snail control by engineering or chemical measures would be neither practicable nor financially feasible. Snail control measures should therefore be confined to clearly recognizable sources of infection (e.g. ponds). Some infections can be controlled by mass treatment of the community (paragonimiasis) and chemotherapy of its cattle (fascioliasis).

2.6 African Trypanosomiasis (Sleeping Sickness)

2.6.1 Definition

African trypanosomiasis is a fatal disease of complex symptomatology. It is caused by protozoan parasites of the genus *Trypanosoma* (subgenus *Trypanozoon*), which

includes *Trypanosoma brucei gambiense* and *T.b. rhodesiense* (the causative agents of sleeping sickness in man) and *T.b. brucei* (a trypanosome that affects domestic animals). The parasites are transmitted by flies of the genus *Glossina* (the tsetse flies).

In man, the onset of the disease is characterized by recurrent bouts of fever. Eventually, the central nervous system is affected. Gambian sleeping sickness runs a chronic course, with death often not occurring for several years. Rhodesian sleeping sickness runs a more acute course, with death supervening within months.

T.b. gambiense is transmitted by *Glossina palpalis spp.* and *G. tachinoides* in West Africa, and by *G. fuscipes spp.* in Central and East Africa. The reservoir of infection was believed to be man, but in recent years *T.b. gambiense* has been isolated from domestic pigs, dogs, and forest antelopes, suggesting that a reservoir exists in the wild.

T.b. rhodesiense is transmitted mainly by *G. morsitans morsitans*, *G.m. centralis*, *G. pallidipes*, *G. swynnertoni*, and *G.f. fuscipes* in East Africa – from the north of Lake Victoria to Zimbabwe, Botswana, and Mozambique. The main reservoir of infection is in bushbucks, wild pigs, and bovids. Normally, man becomes infected only accidentally. Nevertheless, if *G. pallipides* and *G.f. fuscipes* establish themselves close to human habitation and domestic livestock, man-to-man transmission is likely to occur.

T.b. gambiense, *T.b. rhodesiense*, and *T.b. brucei* are morphologically indistinguishable, but they can be characterized with isoenzyme techniques. *T.b. brucei* does not infect man.

Animal trypanosomiasis is closely allied to the human form. Known as 'nagana', it has often been a major obstacle to development in Africa. The disease affects cattle, goats, sheep, horses, and camels. It occurs throughout the tsetse-infested areas of Africa, but also in Asia and South America, where it is transmitted by flies living in association with livestock. Animal trypanosomiasis can be caused by *T. vivax* (subgenus *Dutonella*), *T. congolense* (subgenus *Nannomonas*), and *T.b. brucei* (subgenus *Trypanozoon*). In addition to these are *T. evansi* (subgenus *Trypanozzon*), which causes 'surra' in camels, and *T. simiae* (subgenus *Nannomonas*), which causes a fatal disease in domestic pigs.

2.6.2 Distribution

Tsetse flies are found in an area of 10 million km^2 in Africa, south of the Sahara. Within this area, sleeping sickness occurs in fairly discrete pockets, from 15°N to 20°S on the west coast, and extending to 30°S on the east coast. It is estimated that 35 million people in 36 countries are continuously at risk of infection. Although some of these countries maintain tsetse and trypanosomiasis control services, all the classical foci of the disease persist, albeit with transmission at a low level. Occasionally, epidemics break out as a result of the interruption of medical surveillance, changes in climate and vegetation, population movements, or changes in land use. Despite its relatively low incidence in many countries, the disease remains a major public-health problem, especially when the established methods of surveillance and control break down because of economic difficulties or civil strife.

2.6.3 Symptoms

During the first stage of the disease, essential trypanosomal activity is in the lymph glands and the spleen. The visibly enlarged lymph glands at the back of the neck (Winterbottom's sign) are particularly characteristic of the Gambian form of the disease.

Trypanosomiasis enters its second stage when the central nervous system and the heart are invaded. Irritability, sleeplessness, and personality changes are early signs of this stage. These are gradually followed by a further disintegration of the central nervous functions. Patients walk stiffly and unsteadily and become apathetic and drowsy. Daytime somnolence becomes more regular and pronounced. Death follows, usually because of an intercurrent infection, which, in more than 50 per cent of the cases, is pneumonia.

2.6.4 Diagnosis

Except in the advanced stage, the clinical features of sleeping sickness are not typical, and diagnosis must be made by parasitological demonstration of trypanosomes in the blood, in lymphatic fluid, or in cerebro-spinal fluid. In addition, serological tests are used to screen population groups. A simple field test, the Card Agglutination Test for Trypanosomiasis (CATT), is currently being evaluated. So far, the results are promising.

2.6.5 Life Cycle

Trypanosomes show a complicated sequence of morphologically different forms during their life cycle in fly and man. A full discussion of the life cycle is beyond the scope of this book.

An infected fly remains infective all its life. The proportion of flies found to be infective under field conditions is usually 1 per cent or less, but may, in certain situations, be as high as 5 per cent. Moreover, when infectious flies bite man or other hosts, only 50 per cent of the bites will successfully transmit the infection. With so many hurdles to overcome, the trypanosome appears to be highly vulnerable. Yet, after 50 years of intense control efforts, experience shows that its ability to survive is tenacious.

2.6.6 Epidemiology

The epidemiology of sleeping sickness is complex and is determined by the interrelationship between the hosts, the parasite, and the vector. All these elements behave dynamically in response to internal and external factors, and variation in one element creates changes in the others.

Sleeping sickness does not occur in all the parts of Africa that are infested with tsetse flies. The two types of the disease occur in distinct isolated foci scattered over the 'tsetse belt'. Most of the foci have been known for a long time and are geographi-

cally stable. Newly infected areas are discovered from time to time. The epidemic potential of either type of disease is enormous, as past records testify. Since the introduction of effective control measures, the vast epidemics of the past no longer occur. Epidemic outbreaks, however, flare up regularly in the established foci. The recorded data on the prevalence and mortality of sleeping sickness are incomplete because an unknown number of patients go undetected or unreported.

Population movements have been – and still are – an important factor in the distribution of sleeping sickness. In earlier times, these movements were often connected with warfare between tribal groups, and later with the conscription of Africans into the colonial armies. Malnutrition is known to increase the susceptibility of the population, and an epidemic may follow in the wake of a famine. At present, the movements of labourers and the peregrinations of nomadic fisherman are still regularly responsible for epidemic outbreaks in foci where the disease is under control. For instance, the infection is regularly re-introduced into old foci in Burkina Faso after the return of migrants who had gone to work in endemic areas of the Ivory Coast.

Until recently, man-to-man transmission was considered the only cause of the spread of *T.b. gambiense*, but domestic pigs are now recognized as possible agents of transmission as well.

For the zoophilic tsetse flies of the *morsitans* group, which are responsible for transmitting *T.b. rhodesiense*, man is merely an incidental substitute host who becomes infected when he enters the natural enzootic foci. Accordingly, hunters and fishermen are the main victims of the disease.

A different pattern of transmission has been noted where vegetation and humidity near homesteads and domestic animals favour the establishment of *morsitans* flies. In such cases, man-fly contact becomes a regular occurrence, transmission is more likely to be man-to-man, and all members of the community are exposed to infection.

Recently, *G.f. fuscipes*, a member of the riverine group of tsetse, was identified as the vector of *T.b. rhodesiense* in Busoga, Uganda. There, because of a change in land use and habitation, *G.f. fuscipes* is assumed to have taken over as vector from *G. pallidipes*.

The acute nature of the disease and the permanent risk of the infection being introduced from an independent enzootic focus make the epidemiology of *rhodesiense* trypanosomiasis more capricious than that of *gambiense*, and imply that a resurgence is always possible.

2.6.7 Control

The distribution and ecology of the different species of tsetse fly are closely linked with vegetation. Any modification in vegetational cover can therefore affect the dynamic behaviour of tsetse populations and the transmission of trypanosomiasis. Water impoundment, irrigation and rural development programs, and the establishment of large plantations and animal-husbandry centres often drastically change the natural vegetation over vast areas, resulting in changes in the local epidemiology of sleeping sickness. Fundamental for the establishment of control programs is therefore an understanding of the population dynamics of tsetse flies in the natural foci of trypanosomiasis and of the impact of land use.

Any control program must be a continuing process. Two approaches have proven effective: medical surveillance and treatment, and vector control. (Vector control will be discussed in the next chapter.)

Medical surveillance and treatment aim at the timely detection of cases of trypanosomiasis and a reduction of the parasite reservoir. In endemic *T. gambiense* areas, the appropriate form of surveillance is to have mobile teams screen the population once or twice yearly. This permits the early recognition of a focus that shows signs of becoming reactivated. In endemic *T. rhodesiense* areas, there is little point in screening the population. As this form of the disease is more acute, patients tend to present themselves at medical centres. For this reason and for this form of the disease, it is more appropriate to reinforce primary health care facilities.

Treatment, which requires hospitalization for an average of 30 days, is difficult and not without risk. In some areas where *T. gambiense* is endemic, the drugs suramin or pentamidine have been used prophylactically. These are administered at 6-month intervals, and great care must be taken to make sure that recipients are free from infection.

The available methods of controlling the parasite reservoir and the vectors are far from ideal. Research is in progress to develop diagnostic tests and new and safer drugs.

2.7 Onchocerciasis (River Blindness)

2.7.1 Definition

Onchocerciasis (river blindness) is a filarial infection caused by the nematode worm *Onchocerca volvulus*. The parasite is transmitted by several species of blackfly belonging to the genus *Simulium*. The adult worm normally lives in the subcutaneous tissues, where it may be enveloped in a nodule. The microfilarial larvae live in the skin and may be picked up from there by a biting *Simulium*. The main pathogenic effects are to the skin and the eyes.

2.7.2 Distribution

It is estimated that 20 million people are infected with *O. volvulus*. This estimate, however, has remained unchanged since 1947, despite considerable population growth in the affected areas, the availability of better diagnostic methods, and the discovery of new foci. It is therefore reasonable to assume that the actual number of people infected is considerably higher. The great majority of these (99 per cent) live in Africa.

Endemic foci of onchocerciasis exist in tropical Africa, Yemen, Mexico, and Central and South America. In Africa, the northern boundary of endemic onchocerciasis lies between 15°and 19°N, and the southern boundary between 14° and 8°S. One of the largest endemic areas is in the Volta River basin. (See also Volume 2, Annex 1.)

2.7.3 Symptoms

Onchocercal infection in man produces a wide variety of skin changes, nodules, pathol-

ogy of the lymphatics, and some systemic effects. The most dangerous lesions are those of the eye, which may lead to impaired vision and blindness. There are considerable regional differences in the disease, especially in the frequency and severity of particular lesions. The worm-load is an important determinant of the severity of lesions, particularly of the eye.

The most common symptom is itching, which may be localized or may affect the whole body. In long-standing onchocerciasis, the affected skin commonly becomes atrophic and paper-thin. Changes in pigmentation cause patches of lighter-coloured skin ('leopard skin').

The presence of subcutaneous nodules containing a varying number of adult worms is another diagnostic sign. The diameter of these nodules ranges from a few millimetres to some centimetres. They cluster in places where the skin closely overlies the bones. In the forms of the disease that occur in Africa, nodules can be very small and difficult to detect, particularly those on the head. These can be dangerous as they produce abundant microfilariae near the eye.

Living microfilariae can invade all parts of the eye and, living or dead, they can damage the eye structure. Both eyes tend to be affected. Permanent ocular lesions develop only in response to heavier and more prolonged invasion by microfilariae. This level of ocular infection can take years to build up, but it is likely to be reached earlier in the severely afflicted. In West Africa, the risk of blindness is higher in communities in savanna areas than in those in rain forests. There is evidence to suggest that some strains of *O. volvulus* are more pathogenic to the eye than others.

Other, more chronic, consequences of the infection include elephantiasis and hanging groin, sometimes associated with an incapacitating hernia.

Onchocerciasis is a chronic disease that causes serious discomfort and severe incapacitation of its victims. In the conditions prevailing in most parts of Africa, blindness can shorten the victims' life expectancy.

In hyperendemic areas, 5 to 10 per cent of the total population, or even more, may be blind. A closer look at the age and sex of those affected may reveal that 30 to 50 per cent of the adult male population is incapacitated by blindness.

2.7.4 Diagnosis

For epidemiological studies, onchocerciasis can be diagnosed in one of two ways. Historically, the common method has been to check for the characteristic nodules produced by adult worms. This method is relatively insensitive because nodules may be absent during the early stages of the infection, or too small or deep-seated to be detected later on. Currently, the most common diagnostic procedure is to examine small, bloodless 'skin snip' biopsies. This is a safe and fast method that causes very little inconvenience to the patient and has proved to be of great value in mass surveys. The microfilariae emerging from the skin snip can easily be recognized under the low power of a microscope, and the microfilarial density (an indicator of the worm-load) can be estimated by counting them.

2.7.5 Life Cycle

The routes followed by the infective larvae after entering the definitive host's skin through a *Simulium's* bite wound are not known. Immature worms may reach adult size within 2 months of being introduced, but maturation requires 8 to 12 months. Mature worms (males are 2 to 4 cm long, females 30 to 50 cm long) live mainly under the skin, frequently forming visible and palpable nodules that contain one or more coiled-up pairs of worms. It seems that maturing worms can locate each other and congregate. As has been stated, nodules tend to form near bony prominences (hips, chest, scalp). Patients probably have more deep-seated impalpable nodules than palpable subcutaneous nodules.

During its life of up to 15 years, the female worm produces millions of embryos (microfilariae), 150 to 300 microns long. The microfilariae invade the skin, but may also be found in the blood and in various organs. It has been estimated that heavily infected patients may harbour some 50 to 200 million microfilariae at any one time. Microfilariae do not develop in the original host; if they are not ingested by a biting blackfly, they will die after some 30 months (see Figure 2.6).

When a female blackfly bites an infected person, it may take up one or several microfilariae. Within 6 to 13 days, if the temperature is favourable, some of these (15 to 44 per cent of *S. damnosum* in the West African forest, but only 0.3 to 7 per cent in the savanna) will develop into infective larvae in the fly, and will pass through

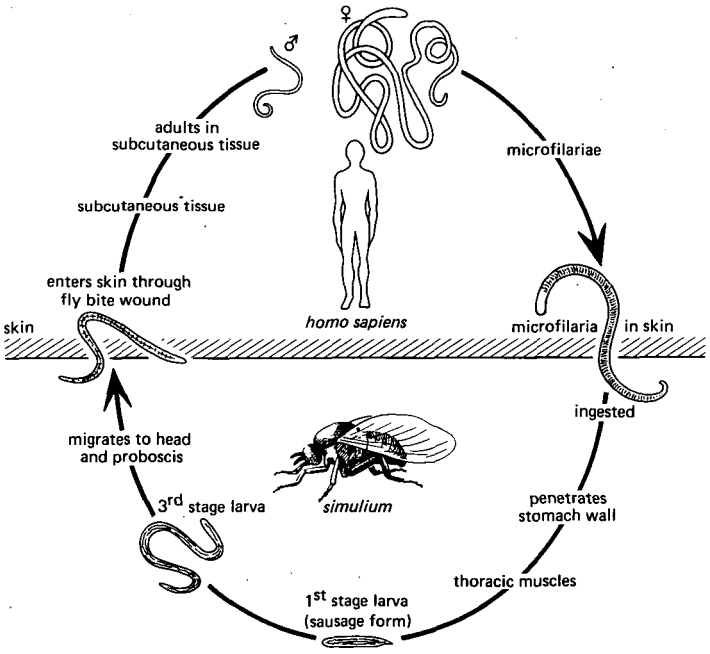

Figure 2.6 Life cycle of *Onchocerca volvulus*

its head into its proboscis. When the fly feeds again, it deposits these larvae on the skin of its victim, where they may penetrate and create a new host. Flies that ingest microfilariae at their first bloodmeal will be carrying developing larvae when they feed a second time, but they will not usually be infective until the third bloodmeal.

Low temperatures are a limiting factor in transmission. In Tanzania, a critical value, below which transmission does not take place, was found to be 18 °C.

2.7.6 Epidemiology

To compare transmission in different areas or at various seasons, or to evaluate control measures, the 'transmission potential' is used as a parameter. It is defined as the number of infective larvae of *O. volvulus* which are carried by the blackflies that may bite one person during a certain period of time. The transmission potential does not indicate the actual number of larvae transmitted to any one person.

For epidemiological investigations, the Annual Transmission Potential (ATP) is used as a parameter. In the forest zone of West Africa, the ATP's recorded for different places have reached values ranging from 50,000 to 90,000 infective larvae per person. In this bioclimatic zone, however, even the highest figures are not associated with high blindness rates. Paradoxically, in the Sudan-savanna zone of West Africa, ATP values ranging from 500 to 18,000 have been recorded near villages where onchocerciasis prevalence rates in the human population are nearly 100 per cent. There, values above 1500 are associated with a high prevalence of blindness; values of 2500 and above cause such severe blindness problems that whole villages may be deserted.

The level of endemicity is positively associated with the intensity of infection and the occurrence of blindness. Great differences in endemicity are found, even between villages only a few kilometres apart. These differences are directly related to the relative proximity of fast-flowing streams in which the blackfly breeds. Swarms of female flies usually seek the nearest source of animal or human blood.

On the basis of these observations, communities are classified as being first-, second-, or third-line villages. The most striking differences between the three lie in the patterns of disease prevalence by age in children and teenagers, and in the frequency of eye lesions and blindness in adults (Figure 2.7).

In Burkina Faso, levels of endemicity in the Red Volta focus are described as:

- Hyperendemic if the prevalence of infection is 70 per cent or more in first-line villages and the prevalence of blindess is about 10 per cent of the total population. Hyperendemic villages usually have less than 200 inhabitants;
- Mesoendemic if the prevalence of infection is 33 to 66 per cent and the prevalence of blindness is about 5 per cent;
- Hypoendemic if the prevalence of infection is less than 33 per cent and serious ocular problems are rare.

In endemic areas, the general pattern of infection shows an increasing prevalence and severity with age. And while the incidence of infection in males and females is similar, more men than women have nodules and eye damage. These differences may be due to the heavier infections that men incur in the course of their work.

Factors that influence exposure to infection are often related to the cultural, social,

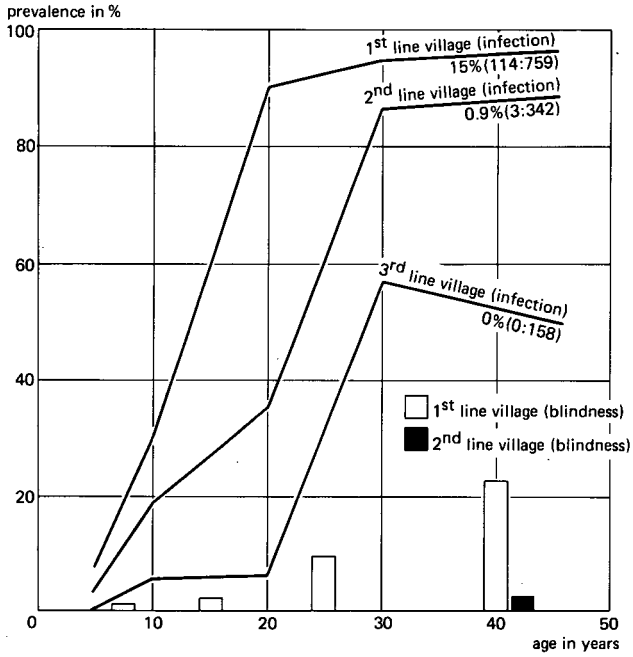

Figure 2.7 The prevalence of onchocerciasis varies according to age

and behavioural characteristics of individuals and groups. Exposure is highest for families who live and work near the banks of the rivers in which the vector breeds. The location of a house may be influenced by the occupation of the head of the household, the traditional pattern of land distribution, and the availability and accessibility of water for domestic use. People whose work brings them into close contact with blackflies include fishermen, ferrymen, workers on coffee plantations, and farmers with holdings near breeding sites.

2.7.7 Control

Onchocerciasis, like other vector-borne diseases, can be controlled with campaigns against the parasite, or the vector, or both. Because of the limitations of chemotherapy, however, the mainstay of control is reducing the vector population.

Various features of onchoceriasis control distinguish it from the control of other vector-borne diseases. The control program in Western Kenya, for instance, which succeeded in eradicating *S. naevi*, showed that the cumulative life span of adult *O. volvulus* and its microfilariae is 16 to 18 years. It follows that, in the absence of effective chemotherapy, control efforts will have to be continued over a period of about 20 years to achieve permanent results.

A second feature is the extraordinary ability of *S. damnosum*, in particular, to disperse over long distances. As a consequence, control efforts must cover large areas

to avoid re-invasion from adjacent foci. Of special concern in this respect is the question whether the parasite-vector complexes of the forest are able to colonize the savanna.

Finally, control of *Simulium* may require unusual physical efforts, as in the case of WHO's Ochocerciasis Control Programme against *S. damnosum* in the Volta Basin. *S. damnosum* breeds in large and medium-sized rivers and streams that provide suitable conditions. Numerous breeding sites, spread over an entire river basin, must be reached and dosed every 7 days, which gives rise to problems that may be insuperable without facilities for spraying from the air.

Drugs are available to control the parasite. Nevertheless, suramin, which kills the adult worms, is unsuitable for use in mass campaigns because of its toxicity, and diethyl-carbamazine is only effective against the microfilarial larvae. A new drug (Ivermectine) has proven extremely effective against the microfilaria: a single tablet kills virtually all the larvae in the body, and it needs to be taken only once a year. The drug could offer a fast, cheap method of controlling the disease. The challenge now is making sure it reaches the people who need it (TRD 1988).

As an alternative to drug therapy, the surgical removal of nodules is being practised in Guatemala, both curatively and prophylactically.

2.8 Other Fly-Borne Diseases

2.8.1 Leishmaniasis (Kala Azar, Espundia, Oriental Sore)

In both the Old and the New World, sandflies of the genera *Phlebotomus*, *Lutzomiya*, and *Sergentomiya* are vectors of leishmanial infections. Although some species of sandflies, especially of the genus *Phlebotomus*, occur in semi-arid areas, the actual larval habitat must have a high degree of humidity. Eggs are deposited in small cracks and holes in the ground, in the ventilation shafts of termite mounds, in cracks of mud walls and masonry, and in other places that provide the required shelter and humidity. Sandflies that transmit the disease to man have become infected either by man or – more usually – by animals. In most infected areas, the disease is a zoonosis (the reservoirs are dogs and other mammals, or sylvatic rodents), and man is an occasional host.

Three groups of leishmanial infections that affect man are generally recognized. They differ in localization and clinical pattern, in the role of certain species of sandflies as vectors, and in geographical distribution. The infections are:

- Visceral leishmaniasis (kala azar), which is endemic in East Africa, the Indian Subcontinent, and Latin America. It occurs sporadically in China, the Mediterranean Basin, Southwest Asia, and the southern parts of the Soviet Union. The parasite, *Leishmania donovani*, invades the internal organs (spleen, liver) and bone marrow. The disease is usually lethal if left untreated;
- Mucocutaneous leishmaniasis (espundia), which is found primarily in South America, but cases have been reported from Africa (Sudan, Ethiopia). The parasite, *Leishmania braziliensis*, invades the skin and mucosal tissues. The disease begins with a primary skin lesion, followed several years later by other lesions in the mouth, nose, or pharynx. These destructive mucocataneous lesions carry a social stigma;

- Cutaneous leishmaniasis (oriental sore), the most prevalent form, which is found in Africa, Latin America, the Indian Subcontinent, Southwest Asia, the Mediterranean Basin, and parts of the Soviet Union. The parasite, *L. tropica*, invades the skin, causing ulcers that are slow to heal. Uncomplicated ulcers heal within 9 to 24 months. Non-healing lesions occur as diffuse cutaneous leishmaniasis. Even if uncomplicated, the disease leads to high morbidity, a disfiguring lesion, and permanent scarring. In new development projects in forest and desert areas, loss of work time because of the disease can have significant economic consequences.

Sandflies are highly susceptible to insecticides. No resistance problems have yet been reported. Control programs that rely on insecticides and are directed primarily against malaria vectors have been very effective against leishmanial infections. This is illustrated by the epidemic of kala azar that broke out in 1977 in Bihar State, India, after the insecticidal malaria control program had ceased.

2.8.2 Loiasis

Loiasis is a filarial disease caused by the Loa Loa worm. It is transmitted from man to man by mangrove flies (*Chrysops spp.*). These tabanid flies inhabit woods and forests, and breed in low-lying swampy places. The disease occurs in West and Central Africa. The life cycle of the Loa Loa worm resembles that of *O. volvulus*. In man, the adult worms live under the skin, but the microfilariae are found in the peripheral blood.

2.9 Miscellaneous Diseases

2.9.1 Dracontiasis (Guinea Worm)

Guinea worm infection has great social and economic consequences where it occurs: in West, Central, and East Africa (Sahelian Zone), the Eastern Mediterranean countries, the Arabian Peninsula, Iran, Pakistan, and the Indian Subcontinent. The parasite is the fialrial worm *Dracunculus medinensis* (length 30 to 120 cm), which inhabits the subcutaneous tissues of its human host. The mature female guinea worm produces a localized sore in the skin of the host, through which it expels numerous microfilarial larvae when the host comes into contact with water. Once water-borne, the microfilariae infect a microscopic, intermediate crustacean host (cyclops or water flea). Man becomes infected by drinking water that contains these infected cyclops.

Dracontiasis sores are painful and often give rise to abscesses, or they involve joints. Not a killing disease, except when tetanus causes complications, dracontiasis can be severely incapacitating for a prolonged period. In West Africa, the average is 100 days per case. Most of the incapacity occurs during the farming seasons, and annual reinfections are not uncommon.

The transmission of guinea-worm infection can be totally stopped by the provision of safe drinking water. Effective control of the disease is therefore based on improving drinking water supplies (i.e. protecting them from contamination).

2.9.2 American Trypanosomiasis (Chagas' Disease)

The distribution of American trypanosomiasis, or Chagas' disease, is confined to the tropical and subtropical countries of Latin America. The infection is caused by *Trypanosoma cruzi*, a protozoan parasite transmitted to man by reduviid bugs (*Triatomine spp.*), which are also referred to as kissing bugs because of their habit of biting the faces of their sleeping victims.

Many species of this bug, with different habits, can transmit the organism to man and animal alike. The infection is essentially a zoonosis. There are two independent cycles of parasite transmission: a persistent sylvatic cycle in numerous wild animals (e.g. armadillos, opossums, rodents, bats), and an intradomiciliary and/or peridomiciliary cycle in man and domestic animals.

The parasite can also be transmitted by blood transfusions from infected donors. This is becoming more of a problem because of the increasing migration of infected people from rural areas to urban centres.

The triatomine vectors breed near their hosts in the cracks and crevices of walls, floors, ceilings, and furniture. They especially favour old dilapidated mud-walled and thatched-roofed houses in rural areas or urban slums. In the sylvatic cycle, they breed in rodent burrows and a variety of peridomestic shelters that are used by their avaian and mammalian hosts. Immature and adult bugs of both sexes feed on their hosts at night, and may acquire the infection from them. Ingested parasites develop in the gut of the bug. Within 6 to 15 days, the bug begins to excrete infective intermediate forms of *T. cruzi* while feeding. Man becomes infected by scratching the excreta into the site of the bug's bite or into skin abrasions.

Once the infective forms have entered the new host, they multiply near the site of penetration. In about 5 days, hundreds of new parasites are released and spread through tissue fluids and blood to various organs. The disease has two stages: acute (occurring shortly after the initial infection) and chronic (in which the heart, esophagus, lower intestines, and peripheral nervous system are affected). As many as 15 to 20 years may elapse between the stages, during which time the infection is present without causing overt illness. The disease is a cause of serious chronic morbidity and disability, as well as mortality.

Spraying houses with residual insecticides has been used to control the infection. This method, however, does not kill bugs resting in natural outdoor shelters. Similar spraying of houses during malaria control campaigns has frequently reduced triatomine populations and, hence, the incidence of Chagas' disease. More lasting effects, however, can be achieved if housing is improved. Replacing mud-walled houses with those built of brick or cement blocks, and thatched roofs with corrugated metal roofs, will contribute significantly towards the elimination of domestic bugs.

2.9.3 Plague

Plague, or Black Death, has a wide distribution. Until the recent past, it broke out in disastrous world-wide epidemics. At present, small outbreaks occur from year to year. The causative agent is the bacteria *Pasteurella* (*Yersinia*) *pestis*. The disease is essentially a zoonosis of a wide variety of sylvatic rodents. In the urban cycle, domestic

rats (*Rattus norvegicus*, *Rattus rattus*) form the reservoir of the infection. Various fleas are responsible for transmitting the infection among animals and, occasionally, to man. The most common disease vector is the rat-flea *Xenopsylla cheopis*. The control of plague is based on rodent and rat control, with the careful use of rodenticides and insecticides.

2.9.4 Louse-Borne Fevers

Louse-borne epidemic typhus has appeared on all continents except Australia. It is prevalent chiefly in cooler areas, including the higher altitudes of tropical zones, where heavier clothing is worn. The disease is caused by *Rickettsia prowazecki*. Transmission is from man to body louse to man. Man is considered the reservoir of the infection.

Louse-borne epidemic relapsing fever occurs under the same conditions as epidemic typhus, and the two diseases may appear together. The causative agent is *Borrelia* (*Treponema*) *recurrentis*, a spirochete. Transmission is effected by body lice; man is the reservoir of infection.

Control hinges on improving hygienic practices and the availability of water. In epidemic situations, however, such measures can be impractical because immediate re-infestation can occur. In these situations, insecticides (DDT dust) are employed to reduce the louse population.

2.9.5 Tick-Borne Fevers

Tick-borne relapsing fever occurs throughout the tropics, the subtropics, and in some temperate regions. The causative agent is the spirochete *Borrelia* (*Treponema*) *duttoni*. Man becomes infected through the bite of an immature or adult soft tick (*Ornithodoros spp.*). Besides man, various animals (mainly rodents) can be the reservoir of infection. The vector breeds in the cracks and crevices of walls, floors, and furniture, in rodent holes, and in the nests of animals and birds.

Control depends on improved housing (of bricks, cement, corrugated iron) and the careful use of insecticides.

2.9.6 Mite-Borne Fevers

Scrub typhus, or Tsutsugamushi disease, is widely distributed throughout Eastern and Southern Asia and on the islands of the South Pacific. Most reported cases are from low-lying areas, but infections can appear at altitudes of up to 1000 m. The causative agent, *Rickettsia tsutusgamushi*, is transmitted by trombiculid mites. People are bitten by the vector mites while visiting or working in areas with so-called 'mite islands' (i.e. patches of vegetation that harbour large numbers of immature host-seeking mites). Control is difficult.

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3 Vectors of Disease

The four major vectors of disease are mosquitoes, snails, tsetse flies, and blackflies. For each of them, information will be presented on their taxonomy, types, life cycle, and bionomics.

An understanding of a vector's bionomics is important in establishing the relationship between the epidemiology of a disease and the ecological status of its vector. It is impossible to devise effective measures to control the vector without understanding this relationship.

3.1 Mosquitoes

3.1.1 Taxonomy

Mosquitoes are two-winged insects belonging to the order of the *Diptera* and the family of *Culicidae*. They are characterized by a long needle-shaped proboscis. The number of mosquito species exceeds 3000. These are classified in three sub-families: the *Toxorhynchitinae*, the *Anophelinae*, and the *Culicinae*. The *Anophelinae* sub-family includes the vectors of human malaria and filariasis. The *Culicinae* include the vectors of human viral and filarial diseases. The three sub-families are further divided into 34 genera.

An important genus of the *Anophelinae* is *Anopheles*. Important genera of the *Culininae* are *Aedes*, *Culex*, *Mansonia*, and *Haemagogus*. In Volume 2, Annex 1 the individual vector species are listed and linked to the disease which they transmit.

3.1.2 Life Cycle

Like all highly evolved insect groups, the individual mosquito passes through a series of stages in the course of its development. The immature stages require an aquatic environment, and the adult stage an aerial or terrestrial one. For all *Culicidae*, the sequence of development is the same: egg, larva, pupa, adult. The stages of development are illustrated in Figure 3.1.

Egg deposition (oviposition) is either terrestrial or aquatic, depending on the species. For hatching, all species require contact with water. The egg is neither active, nor is it capable of ingesting food. Eggs generally hatch after 2 or 3 days of contact with water.

The larva that emerges is about 1.5 mm long when newly hatched, and is 10 mm when fully grown. The larva grows in four stages, after each of which the old cuticle is moulted (larval instar 1 to 4). The larva, in all stages, is an active feeder and swims freely by a peculiar twisting motion of its body. Its food consists largely of microscopic plant life that develops near the surface of the water.

A mosquito larva breathes through two orifices, called spiracles. Those of the anopheline are situated on the eighth abdominal segment so that, in order to breathe,

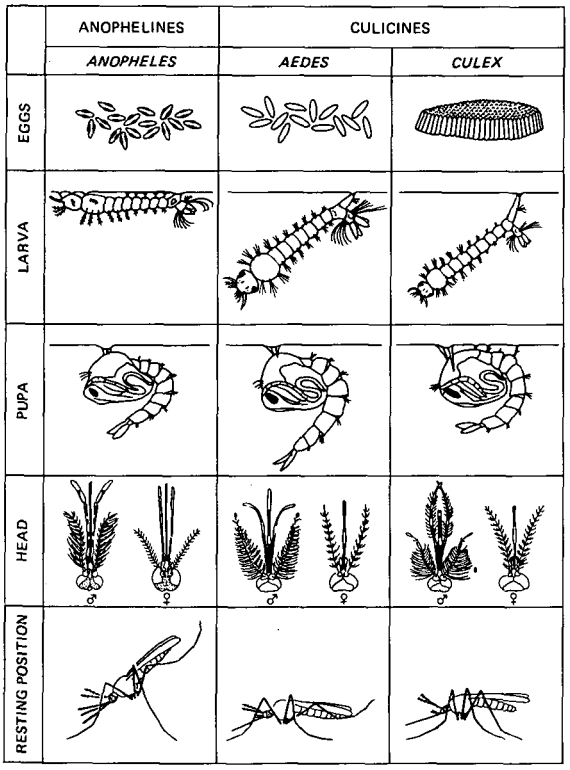


Figure 3.1 Differentiation of *Anopheles*, *Aedes*, and *Culex* mosquitoes at various stages of their development (Source: Bruce-Chwatt 1980)

the larva rests in a horizontal position at the surface of the water. In the culicine larva, the spiracles are situated at the end of a tubular organ, called a siphon. Since the spiracles must lie on the plane of the water surface, the culicine larva, in order to breathe, must hang down from the water surface by the tip of its siphon. An exception is formed by the genus *Mansonia*, in which the siphon is modified for piercing and adhering to the stem of aquatic plants, from which it draws air.

Maturation takes 7 to 14 days, after which the larva becomes a pupa. Maturation time is a direct function of water temperature (7 days at 30-32 °C; 14 days at 20-25 °C). The pupa, like those of other insects, takes no food. Unlike most insect pupas, however, those of mosquitoes are active swimmers, leaving the surface if disturbed and seeking safety in deeper water. At the water surface, the pupa breathes through a pair of respiratory trumpets that extend from the thorax. After 2 to 3 days, the adult mosquito struggles out of its pupa.

Adult mosquitoes are aerial and terrestrial, have moderate powers of flight, and usually live for several weeks. Both sexes feed on plant juices, but only the female feeds on blood. For almost all anophelines and culicines, egg development is dependent on a bloodmeal.

Anophelines can generally be distinguished from culicines by the appearance of

their wings. With some exceptions, the anopheline wing is patterned with dark and pale areas, whereas the culicine wing is unpatterned. Another visual distinction is the resting position. At rest, the body of an anopheline mosquito forms an angle halfway vertical to the surface, whereas the culicine mosquito holds its body almost parallel to the surface.

3.1.3 Bionomics

Bionomics deals with the relationship between a given species and its environment. Among the 3000 or so mosquito species, each single species occupies a separate ecological habitat, and has specific requirements to be able to breed, emerge from the pupal skin, fly, feed, mate, and lay eggs. An understanding of mosquito bionomics is therefore of key importance in planning methods of mosquito control.

Climatic factors play an important role in species distribution, behaviour, survival, and vectorial status. Water is an essential component of the mosquito environment, but the aquatic, terrestrial, and aerial environments are interdependent. Adult mosquitoes need an aquatic environment to lay their eggs, whereas they need the aerial environment for mating and dispersal, and the terrestrial environment for feeding, resting, and completing the cycle of ovarian development from bloodmeal to egg laying.

For the larval and pupal stages (i.e. in the aquatic environment), the following factors are of special significance:

- Temperature: Between species, variations exist in temperature tolerance and in the optimum temperature for development;
- Sunlight and shade: Some species are sun-loving while others prefer shade;
- Water movement: Species differ in their tolerance of current and wave action;
- Salinity: Some species are fresh-water species; others prefer brackish water;
- Pollution: Some species react differently to oxygen tension and the presence of organic matter;
- Turbidity: The depth to which sunlight penetrates can be a factor;
- Microflora: Different species prefer different compositions of microscopic plant life as the source of larval food, which must be present in abundance;
- Macroflora: Emerging adults have specific requirements of shade, protection, and resting places;
- Fauna: The presence of predators and parasitizing organisms reduce the number of immature forms, which would otherwise have developed into healthy adult mosquitoes.

Figure 3.2 illustrates the influence of some environmental factors on the distribution of mosquito species.

Environmental factors also govern the habitual behaviour of adult mosquitoes, particularly the following:

- Mating: This occurs within the first 24 to 48 hours of adult life. In some species, the males form swarms at dawn or in the evening. Females entering the swarm are seized and mated with. Females only need to be inseminated once during their lifetime;
- Hybridization: Only sexes of the same species mate;

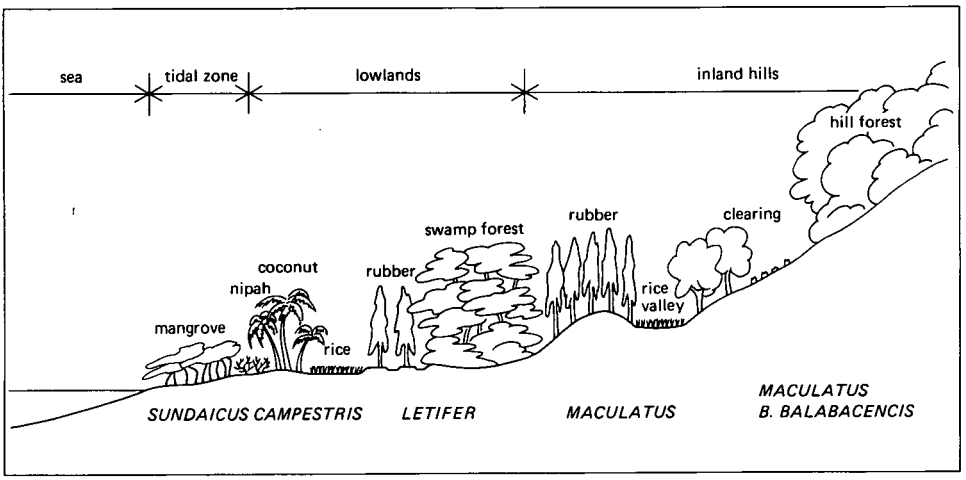


Figure 3.2 Ecological distribution of habitats of several species of *Anopheles* in a coastal area of West Malaysia (Source: Bruce-Chwatt 1980)

- Oviposition: Many species deposit their eggs at night, shortly before sunrise. Eggs (30 to 300 in one batch) are laid on the water surface (Anophelines, Culicines), or near water on a damp substrate (Aedes);
- Gonotrophic cycle: This is the cycle in the life of the adult female, from taking a bloodmeal to oviposition. After feeding, gorged with blood, females rest from 24 to 48 hours until the meal has been digested and mature eggs have formed in the ovary. The gonotrophic cycle is repeated periodically until the mosquito dies;
- Dispersal: Under normal atmospheric circumstances, flights range from 1 to 5 km. Dispersal is mostly downwind, and strong winds may carry mosquitoes much further. Passive dispersion through boats, buses, trains, and aircraft is common nowadays;
- Biting behaviour: Flight, host-seeking, and feeding generally take place in a warm and humid environment. Many species, including the principal malaria vectors, bite in the latter half of the night when relative humidity is high. Species associated with dense vegetation may bite during daytime or at dusk. Some mosquitoes prefer biting inside houses (endophagic); others bite outdoors (exophagic). A single bloodmeal may amount to 0.2 or 0.3 ml;
- Host preference: The preferred vertebrate host may be man (anthropophilic) or animal (zoophilic). Some species have no fixed preference. In the absence of the preferred host, species may feed on other hosts;
- Resting places: The terms endophilic and exophilic indicate whether female mosquitoes prefer resting inside or outside houses. The design and construction of houses can greatly influence the extent to which they are entered by mosquitoes. Outdoor resting places tend to be sheltered, shaded, and humid. The extent to which mosquitoes are endo/exophilic and endo/exophagic greatly influences their vectorial status, and varies according to environmental and seasonal conditions;
- Seasonal prevalence: Some species hibernate to survive winter temperatures, either in the egg or the larval stage. Some adults may hibernate in sheltered places. In

Africa, some tropical species, including *An. gambiae*, are able to survive hot, dry, and apparently waterless periods (aestivation);

- Longevity: Climatic factors greatly influence mosquito longevity and mortality. Heavy parasitic infections (malaria, filariasis) shorten their life expectancy. In mosquito-borne infections, the interval between the mosquito becoming infected and its first infective bloodmeal is called the extrinsic incubation period. The vectorial status of mosquito species depends on the margin by which longevity exceeds the extrinsic incubation period;
- Susceptibility to insecticides: Insecticide resistance is induced through the selection of individual insects that survive dosages of insecticides which kill susceptible individuals. Once induced, resistance is inherited by the next generation. Various mechanisms of inheritance are possible with different mosquito species and different insecticides.

3.1.4 Breeding and Vegetation

The presence of vegetation and/or floatage in water is important for the breeding of certain mosquito species – vegetation being associated with the presence of larval food. A second, perhaps more important reason is the protection vegetation affords against wave action and predation.

Distinguishing different ecological plant types facilitates the understanding of the relation between mosquito production and vegetation. Not all types of vegetation create the same favourable habitat for mosquito breeding. As an example, Figure 3.3

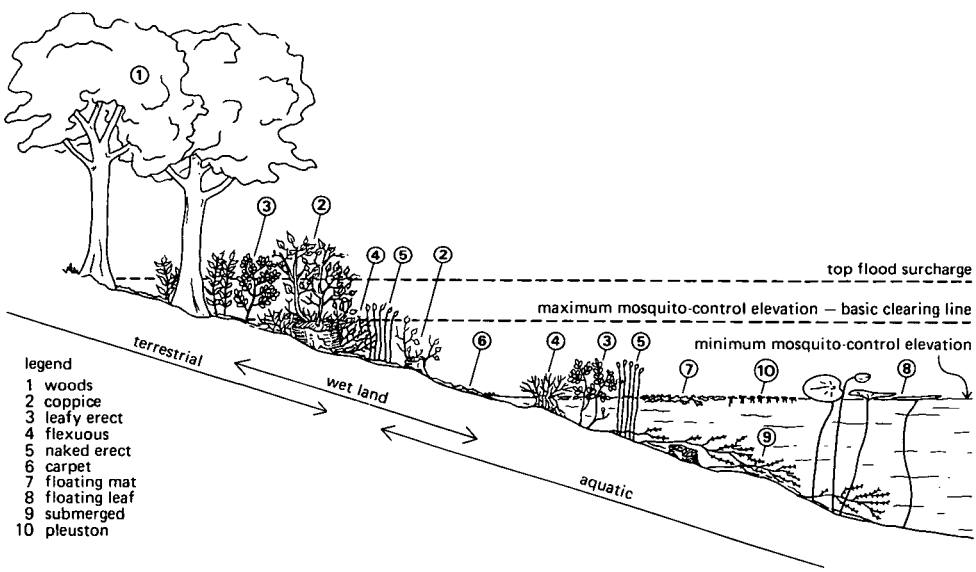


Figure 3.3 Generalized contour distribution of basic plant types on the shore line of a main-river reservoir (Source: Tennessee Valley Authority 1984)

presents a classification of the basic plant types distinguished on the shore line of a reservoir in the Tennessee Valley.

As the mosquito depends not only on vegetation, but even more on water and air, it is where these three elements meet that the requirements for mosquito breeding are fulfilled. This situation occurs where plant parts intersect the water surface. The 'intersection line' (or the length of this intersection) is a valuable concept which can be used to express the suitability of a water body for quantitative breeding. For vegetation of the naked erect type (see Figure 3.3), the intersection line is equal to the sum of the circumferences of all the stems. In other types of vegetation, the formula becomes more complex.

According to investigations done by the Tennessee Valley Authority, the production potential of *A. quadrimaculatus* (the predominant mosquito in that area) appears to be directly proportional to the length of the intersection line, other factors being equal. Figure 3.4 shows that the intersection line increases as plant cover increases, up to a certain maximum, after which it decreases. The explanation for this is that when plant cover is nearly 100 per cent, there is little or no free water surface, and consequently no intersection line. The relative mosquito production potentials of different plant types are in direct proportion to their relative amount of intersection line per unit area of water surface.

Only those portions of a plant that intersect the water surface are relevant to mosquito production. For example, submerged species are not relevant, except during periods of low water or flowering, when they may intersect the water surface. Likewise, leafy erect species may have low mosquito production potentials at normal pool levels when the water surface intersects the naked lower portions of the stems; but, if the water rises into the upper leafy portions of the plants, the production of mosquitoes may be greatly increased. Figure 3.5 illustrates some typical quantitative records on the relative mosquito production potential of *A. quadrimaculatus* and types of vegetation.

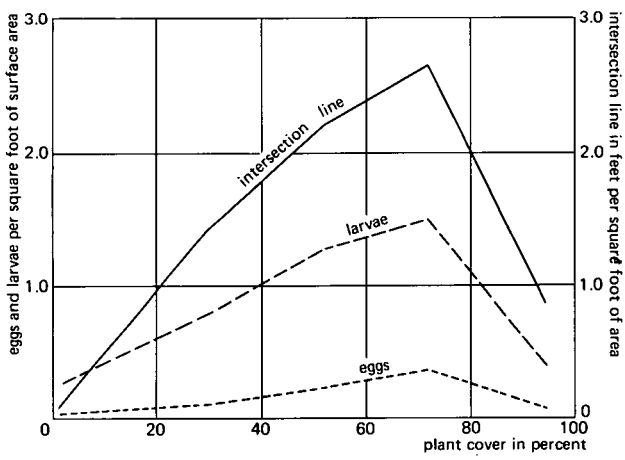


Figure 3.4 Relation of intersection line to the production of *Anopheles quadrimaculatus* mosquitoes in lotus (Source: Tennessee Valley Authority 1984)

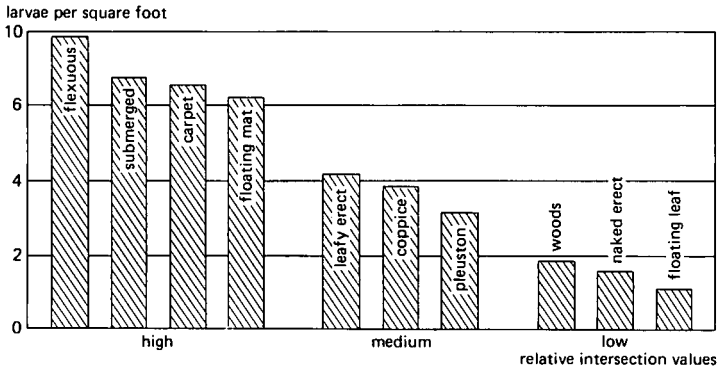


Figure 3.5 *Anopheles quadrimaculatus* production potentials of basic plant types (Source: Tennessee Valley Authority 1984)

Microscopic plants do not produce an intersection line, except in some situations such as during the formation of surface mats by certain species of filamentous algae. Such mats have fairly high intersection values and may produce considerable numbers of mosquitoes.

3.1.5 Breeding Habitats and Measures to Control Them

A classification of the breeding habitats of mosquitoes was presented in the *Manual on Environmental Management for Vector Control* (WHO 1982). This classification, together with suggested control measures, is presented in Table 3.1.
In the case study in Sri Lanka presented in Volume 2, Annex 5.3, the above classification was adapted to classify potential breeding places.

For the geographical distribution of the most important mosquitoes and the diseases of which they are the vectors, see Volume 2, Annex 1.

3.2 Snails

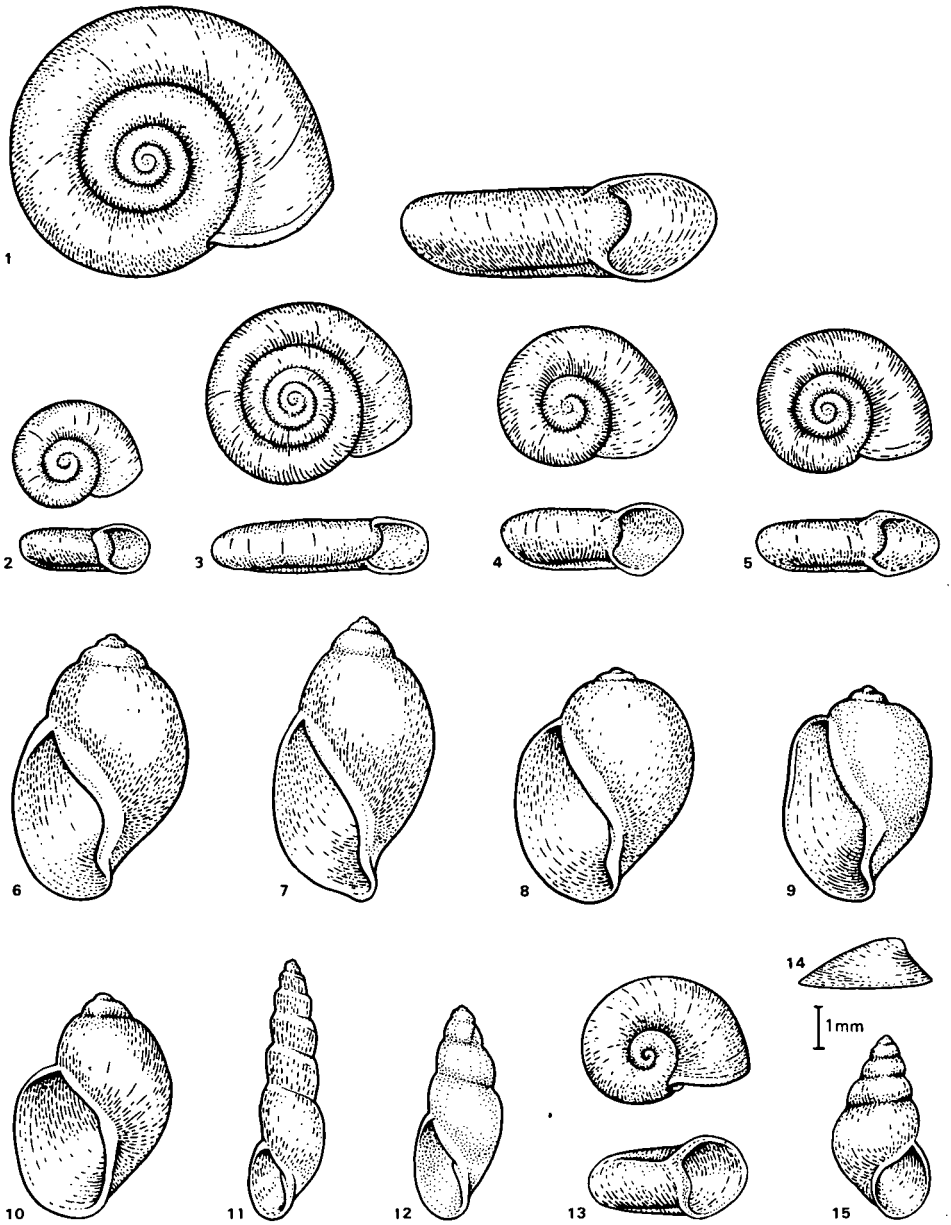
3.2.1 Taxonomy

The intermediate snail hosts of schistosomiasis (see Figure 3.6) are molluscs belonging to the class *Gastropoda* and the subclasses *Pulmonata* and *Prosobrachia*. For the medical profession, the taxonomic status and classification of snails on the basis of morphological criteria leave many problems unresolved. Genetic, biochemical, and immunological methodologies are therefore now being applied to study doubtful affinities and identify variations between and within different populations.

Following the revision by Mandall-Barth in 1958, nearly all the (bulinid) snail hosts of *S. haematobium* belong to the genus *Bulinus*, which has been divided into four species groups, three of which belong to the subgenus *Bulinus*, and one to the subgenus *Physopsis*. Exceptions are the snail species *Ferrissia tenuis*, which is believed to have been

Table 3.1 Breeding habitats of mosquitoes and suggested control measures (Source: WHO 1982)

Breeding sites	Control measures
Large bodies of fresh water in full or partial sunlight. Larvae occur in floating or emergent vegetation or floatage near the edges. Impoundments, lakes, pools, bays, large borrow pits, slow rivers, pools in drying beds of rivers and major streams. Marshes.	Shoreline straightening by cutting, deepening, and filling; shoreline levelling, grading, and clearing of vegetation; filling or draining side-pockets; water-level management; introducing natural enemies and predators; draining, filling, and ponding or canalizing marshes and swamps.
Small collections of seepage water, stagnant and often muddy, but not polluted; full to partial sunlight. Vegetation present or absent; Semi-permanent rain pools or overflow water; roadside ditches, clogged drainage ditches, small borrow pits, wheel ruts, hoofprints, natural depressions in the ground, puddles at the edge of rice fields. Desert saline pools.	Filling and grading; drainage.
Rice fields.	Intermittent irrigation of paddy fields, with periods of flooding and drying; grading paddies and ditches for rapid dewatering; clearing vegetation.
Brackish or saltwater marshes and lagoons; saltwater fish ponds; full or partial sunlight.	Draining, deepening and filling, ponding, canalizing; changing salinity by using floodgates and dikes; reclaiming marshland; clearing vegetation.
Partially or heavily shaded water in forests or jungles.	Draining, filling, canalizing; removing vegetation, clearing jungle.
Running water courses, clear fresh water, direct sunlight; shallow gravelly stream beds with emergent grass and weeds; margins of foothill streams; small irrigation channels of upland rice fields. Lowland grassy or weedy streams and irrigation ditches. Stream-bed pools and side pockets with abundant algae mats. Pools in drying stream beds. Rock holes in stream beds.	Stream-bed correction and clearance; channelling, sluicing and flushing, shading; vegetation and debris clearance.
Springs; seepages from streams, irrigation channels, and tanks; clear water; direct sunlight.	Draining, filling, repairing leaks in dams and embankments, clearing vegetation.
Plant hollows and cavities: epiphytic arboreal and terrestrial bromeliads.	Destroying water-holding plants.
Man-made containers: wells, cisterns, water-storage tanks, ornamental basins, tins, plastic packages, etc.	Tight covers or screens for essential water-storage cisterns, barrels, etc., and emptying, piercing, or destroying unnecessary water containers.



1 *Australorbis glabratus*, Brazil
2 *Tropicorbis stramineus*, Brazil
3 *Biomphalaria sudanica*, Uganda
4 *B. pfeifferi*, Zimbabwe
5 *B. alexandrina*, Egypt
6 *Bulinus (Physopsis) africanus*, Kenya
7 *B. (Phys.) nasutus*, Tanzania
8 *B. (Phys.) globosus*, Angola
9 *B. (Phys.) abyssinicus*, Somalia
10 *B. (Bulinus) truncatus*, Egypt
11 *B. (B.) forskalii*, Sudan
12 *B. (B.) senegalensis*, Gambia
13 *Planorbarius metidjensis*, Portugal
14 *Ferissia tenuis*, India
15 *Oncomelania quadrasi*, Philippines

magnification: nrs 1–5: 1.5x natural size; nrs 6–10, 13: 2x nat. size; nrs 11–12: 2.3x nat. size; nrs 14–15: 5x nat. size

Figure 3.6 Intermediate hosts of *S. mansoni*, *haematobium*, and *japonicum*

the intermediate host of *S. haematobium* in a small focus in the Bombay area of India, and the species *Planorbarius metidjensis*, which was the host in the Algarve Province focus in Portugal.

The (planorbid) snail hosts of *S. mansoni* all belong to the genus *Biomphalaria*. In Latin America, the genus *Biomphalaria* is represented by 20 species, but only a few have been found naturally infected.

The (oncomelanid) snail hosts of *S. japonicum* belong to the genus *Oncomelania* and to the genus *Tricula*.

It has generally been found that sub-populations of the above-mentioned species and sub-species have specific affinities with different strains of the parasite species.

3.2.2 Life Cycle and Bionomics

Bulinid and planorbid snails are aquatic; they spend their entire lives in a watery environment. They are also hermaphroditic and capable of self-fertilization, although cross-fertilization is more usual. Eggs are deposited in water in batches of 5 to 25. Depending on the environmental temperature, oviposition continues throughout the year, although a considerable increase in young snails may be observed at the beginning of the rainy season. The snails hatch some 9 to 11 days after oviposition. Young snails grow at a rate of approximately 0.5 mm per week for the first 6 to 8 weeks, by which time most of them are mature. The rate of growth then progressively diminishes. Maximum size may not be attained until about 12 months after hatching, but only a small fraction of a snail population will live that long.

In contrast, the oncomelanid snails are amphibious and are sexually distinct. Depending on the sub-species, eggs are mostly laid above the water on a solid substrate. Once fertilized, females continue to lay viable eggs for several months, either singly or in small batches of 1 to 4 eggs. The eggs hatch 10 to 25 days after oviposition. Young amphibious snails pass through an aquatic phase of 2 to 3 weeks, after which they spend a large proportion of their time on moist surfaces out of the water. The young snails grow at a rate of approximately 0.25 mm per week until reaching maturity after 10 to 16 weeks. Oncomelanid snails have been known to survive for several years, but the average life span may be only a few months.

In general, all these snail species have an enormous capacity for reproduction, which is controlled by extrinsic factors related to season and food supply, but also by intrinsic factors related to the size and composition of a particular snail population.

Migratory movements of snail populations are, obviously, slow. Snails, however, can be carried passively in flowing water. They can also be transported by many types of animals, particularly birds. Passive transport undoubtedly accounts for the early appearance of snail hosts in newly developed impoundments, thereby reducing the long-term effectiveness of mollusciciding. This is especially true of the hermaphroditic species, of which a single specimen may rapidly reproduce to become a sizable colony.

Decaying vegetable debris and micro-organisms form the principal food of the snails. Most aquatic habitats amply provide these foodstuffs. Habitats without higher plant life, but rich in algae and diatoms, may support thriving snail populations. Dense populations of certain species are found in water contaminated by sewage. This has

led to the conclusion that the snails are attracted by the increased food supply from organic waste matter. In contrast, observations elsewhere have indicated that streams receiving sewage effluent are free of snails.

As with mosquitoes, there is an association between snails and aquatic plant species – the plants providing shelter, protection, and surfaces for oviposition, and supplying snail food when decomposing.

Aquatic snails have the capacity to withstand desiccation, being able to survive out of water for weeks and months. (Drying affects amphibious snails far less than it does aquatic snails.) Aquatic snails may burrow up to some 10 cm deep into the soil for aestivation. This capacity for aestivation is an important factor in epidemiology, and needs to be taken into account when control strategies are being designed. Snails infected with Schistosome appear to be less tolerant to aestivation. Mature schistosome infections in snails tend to degenerate within a few weeks, but immature infections may be retained. It is therefore mainly immature infections that can be carried by aestivating snails from one rainy season to the next.

3.2.3 Habitat Characteristics

With the restriction of the obligatory aquatic habitat, the snail hosts of schistosomiasis have adapted to a wide range of environmental conditions, both in naturally-occurring, flowing or standing water bodies as in man-made ones. Bulinid snails are generally found in naturally-occurring or impounded still waters, but also in slowly flowing water and in irrigation networks. Planorbid snails prefer shallow water in streams with a moderate organic content, little turbidity, a muddy substratum with submerged or emergent vegetation, and moderate light penetration. Oncomelanid snails inhabit floodplains and many man-made habitats created by irrigation and agricultural development.

The following environmental factors are of particular significance for the habitats of snails:

- Temperature: Snails tolerate a wide range of water temperatures. Low temperatures tend to reduce activity and breeding. Optimum temperatures are generally between 20 and 30 °C. Of the planorbid snails, *B. pfeifferi* are less tolerant of higher temperatures, and are absent where temperatures of more than 27 °C last for more than 120 hours per week. On the other hand, bulinid snails appear better adapted to the higher temperatures;
- Rainfall: In areas with snail populations, seasonal rainfall is followed by a period of intense breeding. In contrast, rainfall may also sharply reduce population densities because of the flushing out of streams and a temporary suppression of breeding;
- Light: Particularly the locomotion of snails is considered to be influenced by light. Light may be more important than temperature in this respect;
- Population density: High densities of snails in a given volume of standing impounded water may result in reduced reproduction;
- Chemical and physical factors: In general, snails tolerate wide limits of chemical and physical environmental conditions. Salinity, electrical conductivity, concentration of calcium and magnesium ions, and oxygen tension appear to be of significance.

For the geographical distribution of the intermediate snail hosts of human schistosomes and their habitat requirements, see Volume 2, Annex 1.

3.2.4 Control of the Vector

As the measures that can be taken to control the snail vector will be discussed in later chapters, they will merely be touched upon here.

Of all the organisms that play a role in transmitting tropical diseases in irrigation systems, the bilharzia snail will be the most affected by the design velocity selected for the canals. If sediment is deposited in the canals, velocities will drop and the growth of vegetation will be encouraged. The vegetation will then provide food, shelter, and habitat sites for snails. A program of canal maintenance for silt removal and vegetation clearance will avoid this. The judicious drying of canals for short periods (intermittent flow) is another important point. Canal lining can be of great help.

In spite of these control measures, mollusciciding may still have to be considered.

3.3 Tsetse flies

3.3.1 Taxonomy

Tsetse flies are insects belonging to the order of the *Diptera*, family *Glossinidae*, and genus *Glossina*. They are larger (6 to 15 mm) than houseflies, yellowish to brown-black in color, have a rigid and forward-pointing proboscis, and wings folded in a scissorlike way and reaching just over the tip of the abdomen. In the centre of the wings, the veins form a closed cell with the shape of a hatchet – a characteristic that serves to identify a fly as a tsetse (Figure 3.7).

There are 30 named species and subspecies of tsetse flies, which have been divided into three well-marked groups based on the form of the genitals. These are:

- *Fusca*: The *fusca* rarely feed on man, and none of the species is a vector of sleeping sickness;
- *Palpalis*: The *palpalis* essentially inhabit vegetation along rivers and lake shores from the forest zone to the drier savannah regions. In this group, important vectors of sleeping sickness are *G. palpalis*, *G. tachinoides*, and *G. fuscipes*;

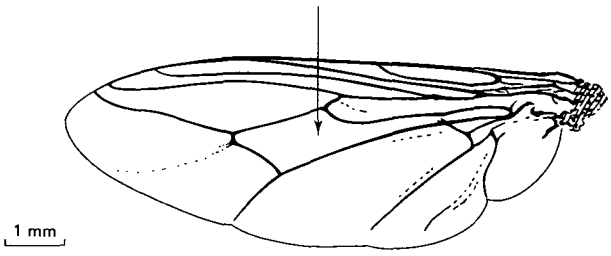


Figure 3.7 Diagnostic feature of the genus *Glossina*: the 'hatchet cell' (arrowed) is in the centre of the wing

- *Morsitans*. The *mortisans* typically inhabit the savannah regions of Africa, which may extend from the coast or the edges of forests to dry and semi-desert regions. In the rainy season, the flies disperse over a vast area, but in the dry season they retire to places with green trees. Important sleeping-sickness vectors in this group are *G. morsitans, G. pallidipes*, and *G. swynnertoni*.

3.3.2 Life Cycle and Bionomics

Both male and female flies bite man and a large variety of domesticated and wild animals, as well as reptiles and birds. Although no species feeds exclusively on one type of host, most species show a definite host preference.

Flies take bloodmeals on the average every 2 to 3 days, and always in daylight. They are attracted by dark, moving objects. In between feedings, the flies rest in dark, usually humid, resting sites. They avoid high temperatures, above 36 °C. The environmental conditions permitting tsetse to settle are found at altitudes below 1800 m, and must provide a combination of an average temperature between 20 and 30 °C, high humidity (except for the *Morsitans* group), the presence of shade, and suitable sources of food.

Unlike many other flies, the tsetse are viviparous and deposit their larvae one at a time. After having mated, the female remains fertile for the rest of her life. Eggs are fertilized in the uterus and hatch within it after 3 or 4 days. The larva then develops over a period of 4 to 5 days until it is mature and about 8 or 9 mm long. The mature larva actively wriggles out of the genital orifice and is deposited by the female on loose friable soil or humus in cool shaded places. Immediately after it is deposited, the larva starts to bury itself under 2 to 5 cm of soil, after which it transforms into a pupa. The duration of the pupal period lasts from 3 to 5 weeks, depending on the environmental temperature. The fly that emerges from the pupa forces its way to the surface, where it unfolds and pumps its wings for 15 to 20 minutes before taking flight to find its first bloodmeal and become a mature adult.

3.3.3 Habitat Characteristics

The transmission of *T. gambiense* is by tsetse species whose principal habitat is dense vegetation along rivers and forests. It has been shown that flies of the *Palpalis* group will feed on man in 8 to 40 per cent of cases, and even more frequently where man-fly contact is intense (i.e. at water-collection points and rivers).

Tsetse flies of the *Morsitans* group and also *G. fuscipes*, which transmit *T. rhodesiense*, have their habitat principally in the low woodland and thickets of the East African savanna and lake shores. They are inclined to take animals as their primary source of food, and are less flexible in their host preference. *G. morsitans* feeds on bovids (25 to 40%) and suids (30 to 45%). *G. pallidipes* is typically associated with the bushbuck (80 to 90%), and *G. swynnertoni* has a strong preference for suids (65%, mainly warthogs). For these zoophilic species, man is merely an incidental substitute host.

3.3.4 Control of the Vector

An overview of vector-control methods is given in Table 3.2.

Table 3.2 Vector-control methods for human and animal trypanosomiasis (after Jordan 1986)

Application of insecticides*)	From ground or air
Clearing of vegetation and destruction of wild animals**)	Removal of habitats and host of tsetse
Traps and insecticide-impregnated targets***)	Promising recent developments
Genetic/biological/physiological control	Possibilities for the future

*) The most favoured method of tsetse control is still ground spraying, usually with Endosulfan and Dieldrin. (WHO does not recommend DDT.) Tsetse populations can be satisfactorily controlled in this way, provided that natural barriers are present to prevent re-infestation. So far, no problems of vector resistance have come up. It has been shown, however, that the commonly used practices of pesticide application cause a high mortality among many non-target organisms. Such undesirable environmental side effects have not yet been satisfactorily defined

**) The biology of the different species of tsetse is closely linked with vegetation. Any modification in vegetational cover can affect the dynamic behaviour of tsetse populations and the transmission of trypanosomiasis

***) Until recently, traps had mainly been used in ecological studies of *Glossina spp.* Nowadays, the design, portability, and efficiency of traps have been improved to such an extent that they can be realistically used, in some circumstances, to control tsetse populations. The biconical trap (Challier and Laveissière 1973) is portable, sturdy, easily assembled, and is highly effective in catching species of the *palpalis* group (Figure 3.8)

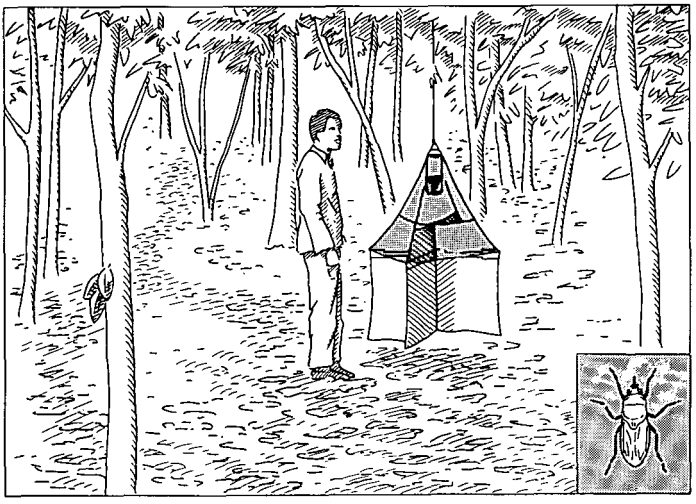


Figure 3.8 Inspecting *G. palpalis palpalis* caught in a biconical trap in a cocoa plantation in southern Ivory Coast (after Jordan 1986)

3.4 Blackflies

3.4.1 Taxonomy

Blackflies belong to the order of the *Diptera*, and the family of the *Simuliidae*. This family contains twelve genera, of which only three are regular man-biting species. *Simuliidae* are small (2 to 5 mm long) dark-coloured flies with a typical 'hump' (Figure 3.9), reminiscent of the American buffalo. (They are also known as 'buffalo gnats'.) They can occur in great swarms, not only in Africa and Latin America, but also in Northern America, Europe, and other temperate or arctic climatic zones, where they may be a severe pest for man and beast. Blackflies of the genus *Simulium* are of special medical importance because they contain three species that are vectors of *Onchocerca volvulus*. These are:

- The *Simulium damnosum* complex (Africa and South Arabia): *S. damnosum* was formerly considered to be a fairly uniform species, but chromosomal investigations have shown it to be a complex of subgroups. From the criteria produced by these investigations, eight species have been identified in West Africa, and a further eleven in East Africa. *S. damnosum* breeds in a wide variety of watercourses in different climatic zones: from very large rivers to medium-sized streams. The main factors governing its breeding places are adequate water velocity (0.70 to 1.50 m/sec), which is linked with oxygenation and food supply, and the presence of suitable supports, which may be rocks, stones, sills, sidewalls of structures, spillways, gates;
- The *S. naevi* group (East Africa): This group includes species which all have a phoretic association: larvae and pupae attach themselves to riverine crabs (*Potomonautes sp.*) as support. Within the group, four species have so far been distinguished. None of them breeds in large rivers, even if suitable crabs are present, but in small watercourses in forested areas;
- *S. ochraceum*. This is the principal vector in southern Mexico and Guatemala, and is widely distributed in central and northern parts of South America. Larval habitats consist of trickles of flowing water and very small streams, often concealed by vegetation and fallen leaves (e.g. in coffee plantations).

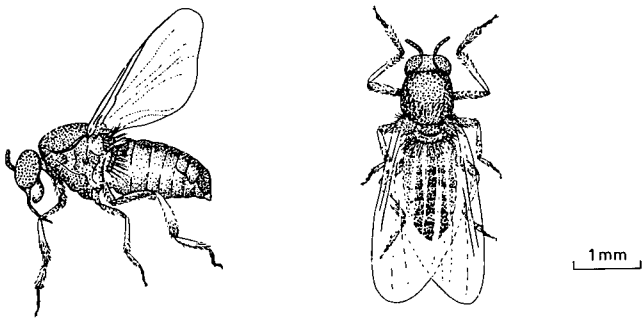


Figure 3.9 *Simulium damnosum*, a blackfly

3.4.2 Life Cycle and Bionomics

Adult flies of both sexes feed on plant juices. In addition, females take bloodmeals, biting man and a variety of animals and birds. Anthropophily of *Simulium* species involved in *O. volvulus* transmission is facultative, depending on the availability of animal and human hosts. Biting occurs outdoors at almost any time during daylight, but each species may have its preferred times of biting.

There is an important difference between the biting habits of African and American species. The African *Simulium* bite mainly on the legs and the lower part of the body, whereas American species prefer to bite on the head and the upper part of the body. This fact is important in understanding the clinical differences between *O. volvulus* infections in the two regions.

The biting of *S. damnosum* over the day may have a bimodal or unimodal distribution, being mainly governed by air temperature and humidity. Little is known about the sites where flies rest after feeding. The digestion of a bloodmeal under tropical conditions takes 2 to 3 days.

The productivity of blackfly breeding sites can be enormous, resulting in intolerable biting densities. The bites, although usually unnoticed until the fly has flown away, give rise to a painful and troublesome reaction in human and beasts.

It appears that, on the average, flies live about 2 to 3 weeks. For females of *S. damnosum*, it is accepted that their lifespan does not exceed 30 days. The life expectancy of forest flies was found to be substantially shorter (2 per cent alive after 7 days) than that of savanna flies (33 per cent alive after 7 days in the moist savanna, and 47 per cent in the dry savanna). Therefore, in dry savanna areas, about 15 to 20 times more female flies survive long enough to transmit *O. volvulus*.

Before the bloodmeal in each gonotrophic cycle, a dispersion flight takes place. Dispersal may follow linear or radial patterns, and is influenced essentially by vegetation, cloudiness, and humidity. In savanna areas, dispersal usually follows a linear pattern, whereas, in the forest, radial dispersal is more common and is possible throughout the year. Females have considerable intrinsic powers of flight. Flights of up to 80 km over a period of 24 hours have been reported. Aided by wind, the flights may be as far as 400 km.

Females mate only once in their lifetime and within a few hours of emergence. Each bloodmeal is followed by maturation of a batch of eggs to be laid 3 to 5 days later. Egg laying is followed within another day by a new bloodmeal. These cycles continue until the death of the female. Eggs (0.2 to 0.4 mm long) are always deposited in flowing and well-aerated water. The females of *S. damnosum* lay their eggs in batches of about 250. These are deposited on partially submerged supports such as rocks, tree branches, and trailing vegetation at water level, or down to 5 cm below the surface if algae is present. The eggs hatch within 2 to 3 days, and the young larvae move to the submerged part of the support. Larvae feed actively on organic material filtered from the water. They pass through 6 to 8 developmental stages, lasting a total of 8 to 12 days. After reaching their mature length of 5 to 13 mm, they moult into pupae. The pupal stage lasts about 3 days and the adult emerges from the pupa in an air bubble and takes flight upon reaching the water surface. The duration of the developmental stages is influenced by environmental temperature.

The breeding of *Simulium* is, naturally, closely associated with the flow of water in streams and rivers. In West Africa, three types of seasonal variations of *S. damnosum* populations have been observed:

- Synchronic variation, when the abundance of the vector is positively correlated with the flow of water;
- Inverse variation, with abundance occurring during the dry season;
- Bimodal variation, when the vector is only abundant during periods of maximum and minimum river flows.

Precise locations of the breeding places correspond to each water level and rate of flow of a river. Preliminary entomological surveys related to hydrological data therefore allow the accurate planning of operations to control *Simulium*.

Man-made changes in the environment may have pronounced effects on the breeding of *Simulium sp.*, and on the epidemiology of onchocerciasis. The construction of large dams is beneficial because they eliminate breeding sites over long distances upstream. In the vicinity of spillways, however, they may create new breeding sites, and will not affect the downstream breeding sites. Problems of highly intensified, rainy-season transmission through breeding on the spillways, gates, and channels have arisen from the construction of small earthen dams and in local, rice-growing irrigation schemes in savanna areas.

Deforestation can either increase or decrease transmission of onchocerciasis. In East Africa, the clearing of riverine forest can result in the complete disappearance of *S. naevi*. Ecological changes may also affect the distribution of hosts other than man. The absence of animal sources of bloodmeals may result in excess biting of man, as has been reported from Colombia where *S. exiguum* bites man for the lack of suitable alternative hosts.

For the geographical distribution of the main blackfly species, see Volume 2, Annex 1.

3.4.3 Control of the Vector

The extraordinary ability of certain species of *Simulium* to disperse over long distances poses a problem for their control. Control efforts therefore need to cover a sufficiently large area to reduce the risk of re-invasion from adjacent foci. Of special concern in this respect is whether the forest parasite-vector complexes are able to colonize the savanna.

Another factor is that *Simulium* control may require unusual physical effort. In the area of the Onchocerciasis Control Programme (OCP), for instance, multiple breeding sites of *S. damnosum* are spread over an entire river basin and must be reached and dosed every few days. Without facilities for spraying from the air, the problems would be insuperable.

The possible approaches to controlling the *Simulium* vector include:

- Environmental modification: The extremely beneficial effect of large dams in eliminating breeding habitats has already been mentioned. Such projects, however, are usually not undertaken for the sole purpose of *Simulium* control. On the other hand, the proliferation of small dams and small-scale irrigation has aggravated *Simulium*

breeding. A special type of spillway has been designed to avoid *Simulium* breeding (see Chapter 5). The periodic (weekly) drying of spillways has proved to be another effective measure;

- Chemical control: Larvae, because of their relative concentration and their mode of feeding by filtering particles suspended in water, are the only forms susceptible to insecticides that act when ingested. The use of DDT has ecological disadvantages, and tolerance and resistance have been reported. An ecologically more acceptable preparation, Temephos (Abate), which belongs to the organophosphorus group, was selected for use in the OCP area, but resistance has begun to develop. The larvicide must be released upstream of the breeding sites and is active over a variable range of the watercourse treated. Applications must be made periodically (7 days), at intervals shorter than the larval life span of the local species;
- Biological control: A preparation of *Bacillus thuringiensis* H-14 spores has become a valuable biological control agent. It is being used in those parts of the OCP area where resistance to Temephos has occurred, and is applied in a similar fashion.

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4 Data Collection for Disease Control

4.1 Epidemiological Studies

Epidemiological studies are conducted to collect information on infectious diseases in their various manifestations, and on the environmental factors involved in the transmission of these diseases. The studies are conducted among populations who are either exposed to infection or have acquired disease (Barker 1976).

In irrigation development, migration and resettlement are usually important determinants of the composition of the population. It is therefore useful to distinguish the following population components:

- Temporary residents: Temporary labourers, engaged for the construction of the engineering works, will reside in the area until these works have been completed. At a later stage, temporary (seasonal) labourers may be employed in agriculture;
- Relocatees or evacuees: Communities whose land and homesteads will be inundated by a future lake;
- Scheduled migrants: People being resettled by the authorities in the project area. Resettlement may take place among 'host communities' of permanent residents;
- Unscheduled migrants: People (e.g. fishermen, traders) who are attracted by the new development and hope to find opportunities to improve their livelihood.

When the creation of man-made lakes is motivated by multiple development objectives – and especially when irrigated agriculture is included – the resettlement population will comprise mainly the first three of the above categories. If, however, the lake is to serve a single purpose (the generation of hydro-electricity), an influx of unscheduled migrants, seeking to benefit from the 'unused' opportunities, must be expected.

The team assigned to conduct epidemiological research for health planning will need to have sufficient background in the related scientific disciplines (see Figure 4.1), and should be familiar with the normal procedures and options of environmental health

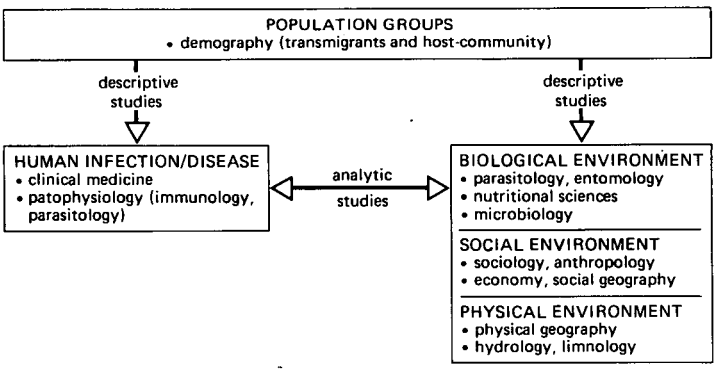

Figure 4.1 Types of epidemiological studies and the related scientific disciplines

engineering. The size and composition of the team will, of course, depend on the scope of the assignment. As a minimum, a competent parasitological epidemiologist will usually be required. If the assignment allows the employment of more team members, a behavioural scientist and an entomologist would perhaps be the most relevant. Very specific research may require specialists on a consultant basis, if such information is not available locally.

4.2 Timing of Data Collection

Irrigation projects are developed in a number of stages, which together form the project cycle. Appropriate health data should be collected in each stage.

4.2.1 Stage I: Identification

In Stage I, potential health problems need to be identified and a forecast made of the adverse health effects that could result from the project.

Once the geographical location of the proposed project is known, an assessment of health risks can be made by inference. Often, such risks can be inferred from the geographical location itself (see Volume 2, Annex 1) and from a comparison of the proposed project area with surrounding regions or with other projects in the same country or river basin. This will usually imply a detailed review of the biological and health literature and interviews with the health authorities. If diseases that form a potential health risk are identified, their seasonality of transmission should be determined in order to plan the timing of field surveys. The information on seasonality needs to include the months of greatest transmission, the influence of rain on the number of insects or snails, and the influence of the annual changes in climate on the human population and the aquatic ecology.

A field reconnaissance to identify the relevant disease agents and vectors in the project area is useful at this stage – if it can be made during the proper season. The reconnaissance should preferably be done by experienced investigators (epidemiologist, biologist). Logistics and transport must be well organized to ensure that a large area can be covered in a short time.

If this initial assessment and reconnaissance show that specific health risks can be expected from project development, a more detailed forecast of future events should be made. As will be explained in Section 4.7, there are various ways in which forecasts can be made. Much may be said about uncertainties in the mathematical precision of forecasts. Their main point, however, is that they can predict trends in the habitat and population dynamics of insects and snails, and in the dynamics of the transmission of disease agents in the human population. Such predictions can be quite accurate. Much will depend on the experience and understanding of the investigator.

4.2.2 Stage II: Preparation

In Stage II, a design and feasibility study of the project is made. This should include studies on disease transmission under alternative project designs.

The objective of the health component in the feasibility study is to determine strategies that will keep disease transmission at or below existing levels, at a cost commensurate with project benefits. A maximum estimate of the cost of disease control can be made from cost figures per capita or per hectare, which can be obtained from disease-control programs operating in similar irrigation schemes. This will provide some guidance for the maximum expenditures that can be tolerated in selecting design features that might reduce the costs of a control program.

The completion of this analysis may require full epidemiological surveys to confirm and clarify the initial information about disease transmission, and to forecast the effects of alternative control strategies. For large projects, the importance of pilot project development for the collection of epidemiological and ecological data is beyond question.

Although mathematical simulation models are not sufficiently reliable for their predictions to be trusted in absolute terms, they can provide valuable figures for comparing the relative impact of alternative designs. If such models are used, the comparisons should include the effect of design modifications aimed at disease prevention, as well as operational interventions by health programs and their costs. With the aid of these simulations, it will be possible to determine the costs of keeping disease transmission at or below the existing levels, which is usually an acceptable public-health goal. (See further in Section 4.7.2.)

4.2.3 Stage III: Final Design

During Stage III, the final design of the entire irrigation system will be made. This should include details of the features to be incorporated into the design to prevent disease and details of the operational procedures needed to control transmission.

It has been stipulated more than once that one single method will seldom be adequate to control vector-borne diseases in large populations of people. Instead, because of the complexity of disease transmission and the difficulty of maintaining any one single control method, it is advisable to use all available measures in a rational, integrated combination. It is important to recognize at the outset the difficulties of trying to maintain permanent control in the face of drastic changes in ecology, populations, governments, and economic conditions.

The operational control program must be within the capabilities and financial resources of the existing health agencies, or else it must be one of the responsibilities of the project authority. If the latter, the necessary personnel, organization, and resources must be specified. If the health problems warrant the expense, a periodic monitoring of disease prevalence and transmission should be included in the operational plans.

4.2.4 Stage IV: Implementation; Stage V: Operation; and Stage VI: Evaluation

In Stages IV, V, and VI, additional field data should be collected and the relevant transmission and operational variables monitored and evaluated. Disease transmis-

sion is a dynamic process and only data collected over a longer span of time will cover all variations.

The main purpose of evaluation in these stages (see further in Section 4.8) is to identify failures in the functioning of the proposed control measures. Evaluation may reveal that correction measures or complementary inputs are required.

4.3 Control Strategies

It is important to clarify the difference between strategies aimed at disease eradication and those aimed at disease control. Eradication strategies consist of brief, intense attacks on the disease, and of protection against re-invasions. In the tropics, eradication of endemic diseases has been successful only on islands and in isolated areas, or in regions where ecological conditions were not particularly suitable for the diseases. In other places, it is not yet possible to eradicate diseases – or only at costs that are prohibitively high – so strategies are aimed at control, or containment.

Control strategies usually start in high-priority areas, and, depending on the success of the measures and the severity of the problem, may expand into other areas and continue indefinitely. Control strategies do not usually try to eliminate importations of a disease or its vector into the area – a key feature of eradication strategies. For planners of irrigation schemes, the eradication of diseases, or of their snail or insect vectors, is seldom an option. Instead, they should plan permanent measures to lower the level of disease transmission.

There is also a fundamental difference between control strategies for endemic diseases and those for epidemic diseases. Epidemic diseases must be controlled quickly, usually by temporary, emergency programs lasting only a few months. The economics of such programs are not as important as their effectiveness and speed. Extra resources can be mobilized for epidemic control programs because the public is usually highly motivated to participate in them by the sudden and spectacular impact of epidemics of, say, malaria or cholera.

In contrast, endemic diseases are seldom high in the public consciousness because they are always present. As well, because of the difficulty of effecting changes in their extensive webs of transmission, endemic diseases must be controlled with long-term considerations in mind – covering spans of one or two generations, not one or two years. A primary consideration in these long-term strategies is the stability of control: a measure of the permanence of the control methods. Other major considerations are low costs – of necessity usually requiring that the measures be handled under the normal operating budgets of ministries of health or agriculture – and that they do not include continuous purchases of materials requiring hard currencies.

Given a final design that includes preventive measures, one must always expect some residual transmission. This must be dealt with by an organization established to suppress transmission and treat disease. The strategy to be followed by that organization – if it is to be realistic – should be developed in cooperation with local agricultural and health authorities. If the residual transmission is expected to be significant, a supervisory board, consisting of representatives of the executing agencies as well as

national and international experts, should be formed. The task of this board – after the initial construction phase of the irrigation project is over – would be to coordinate and modify the control strategy, if necessary, and to ensure cooperation between the agricultural, irrigation, and health agencies.

4.4 Climatic Determinants of Schistosomiasis

The geographical distributions of malaria and river-blindness are fairly well defined – unlike schistosomiasis, whose geographical distribution is considerably more complex. The three species of schistosome parasites differ in the dynamics of their distribution and transmission. Each species is transmitted by a separate genus of snail, so the distribution of snail genera is the first and most obvious limitation on the distribution of human schistosomiasis.

Climatologically, the habitat requirements of the three genera – *Biomphalaria, Bulinus*, and *Oncomelania* – can be deduced from the climatic characteristics of the major geographical regions in which they occur (see Volume 2, Annex 1).

Although water temperatures certainly determine the northern and southern latitudes that limit the tropical genera, some other features, probably climatic, must determine the eastern and western longitudinal limits of each genus. *Oncomelania* is only found in a narrow band in the Orient between longitudes of 100 and 140°E; *Bulinus* is only found in Africa and the Middle East between longitudes of 20°W and 60°E, while *Biomphalaria* has a slightly wider distribution covering the Americas and Africa between 75°W to 50°E. Neither *Bulinus* nor *Biomphalaria* is present in Asia. An interesting aspect of this distribution is that there are many tropical areas devoid of all three genera, and many large areas where at least one genus is completely absent.

Besides water temperature, other important determinants appear to be annual rainfall and the length of the dry season. It is tempting to try – on the basis of the latter two parameters – to explain snail distribution on a global scale. The simple criteria, however, help only partly; exceptions to the general rule are manifold and are difficult to explain.

It seems best to rely – as a first step – on the country-wise list of snail distributions given in Volume 2, Annex 1, and then – as a second step – to study each situation on its hydrological characteristics (e.g. river-bed configuration, type of flood wave passing), its local climatic anomalies, and the peculiarities of its wet and dry seasons.

4.5 The Nile Shift

Before 1940, the predominant species of bilharzia infecting people in the Nile Valley was *Schistosoma haematobium*, the urinary form of the disease. There were only rare occurrences of *S. mansoni*, the intestinal form. By the early 1950's, however, in the (then) partially developed Gezira Irrigation Scheme along the Blue Nile, the prevalence of the two species was found to be equal. Although, by the late 1970's, the urinary form was still dominant in some areas, in the heavily irrigated Nile Delta near Cairo and in the (now) intensely irrigated Gezira and Khashm El Girba Schemes of Sudan, the intestinal form had attained a striking excess over the urinary form. This shift in the type of bilharzia occurred after the construction of the Aswan High Dam in

Egypt and the Atbara and Roseires Dams in Sudan (Figure 4.2). All three dams had heavy impacts on aquatic ecology, permitting intensified irrigation downstream, and perhaps quickening the earlier, more gradual changes in bilharzia infections.

This change from the urinary form of bilharzia to the intestinal form has been called the Nile Shift. Despite its name, it applies to all of Africa and the Middle East, wherever the two forms of bilharzia could coexist because of the presence of the appropriate snail hosts. It is quite significant because it marks a shift from light, seemingly inconsequential, urinary infections to heavy, debilitating, and even lethal intestinal infections.

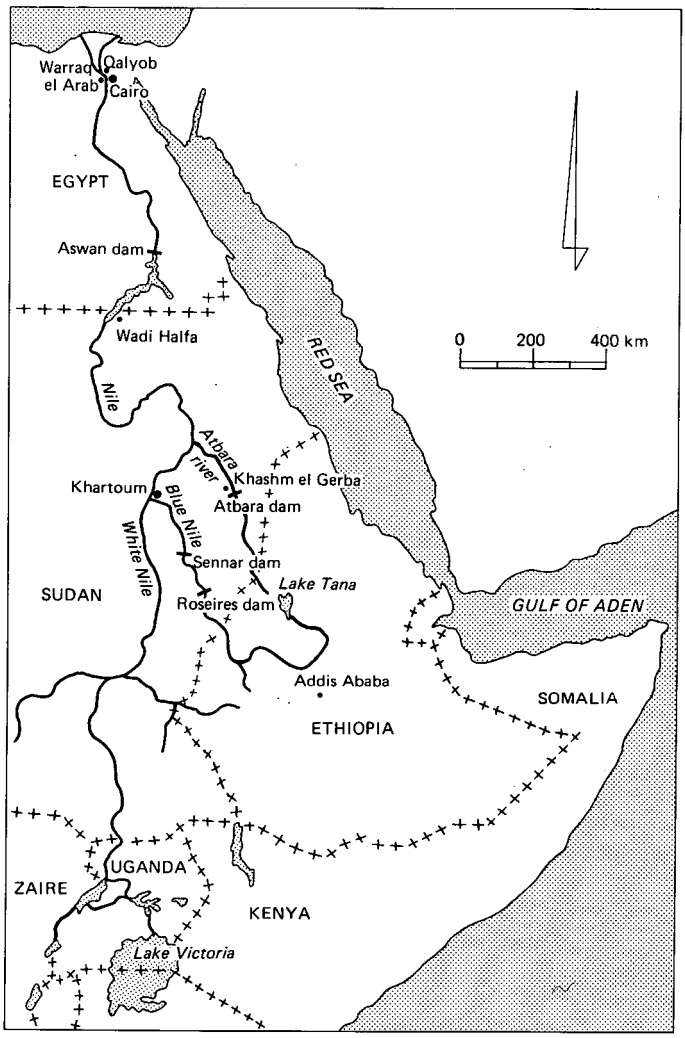

Figure 4.2 Location of major dams and irrigation schemes in the Nile Valley. Many of these projects, finished in the last 20 years, have caused severe outbreaks of intestinal bilharzia, replacing the previously light prevalences of urinary bilharzia, which did not constitute such critical public-health problems

The experience in the Gezira Scheme constituted a medical emergency, filling the hospitals with patients suffering from extremely debilitating infections.

Field observations from Puerto Rico on the number of snails in aquatic habitats and the number of those snails infected by *S. mansoni* gave a possible clue to the cause of the Nile Shift. The explanation is based on the difference between the transmission of intestinal and urinary bilharzia, in terms of the excretion of bilharzia eggs (faeces for *S. mansoni*, urine for *S. haematobium*). The conclusion has been postulated that in dry areas, or in simple irrigation systems with only short periods favourable for snail populations, the urinary form predominates. But when irrigation is intensified and the numbers of snails increase markedly, the intestinal form overcomes its disadvantage in the snail phase of the transmission cycle. Then, in the human hosts, the intestinal worms dominate over those of the urinary form, and have the extra advantage of a longer life span.

It is precisely this shift to intestinal bilharziasis that was observed in the Nile Valley. It is likely to occur elsewhere in Africa with further developments in irrigation. Irrigation and agricultural planners should be aware of the potential Nile Shift (Colette et al. 1982).

4.6 Crops and Related Diseases

There are typical associations between crops and diseases: a conspicuous example is rice and malaria. The linkage in almost every case is water. Sugarcane is nearly always irrigated, and is usually cultivated continuously, so it is not surprising to find a strong link between sugarcane and bilharzia (Jobin 1980).

4.7 Forecasting Vector-Borne Diseases

4.7.1 The EHIA Approach

The concept of Environmental Health Impact Assessment (EHIA) was developed to identify, predict, and appraise environmental factors that may affect human health. These factors are not disease agents in themselves, but may facilitate human contact with disease agents or may weaken human resistance to infections (WHO Regional Office for Europe 1983). The concept can also be applied to vector-borne diseases. It is particularly useful in Stages I (Identification) and II (Preparation) of the project cycle.

The EHIA procedure contains a number of steps, the most important of which is the 'forecast'. Its starting point is usually a checklist designed to identify all factors that may be relevant for appraisal. These could include geological, biotic, demographic, economic, and structural components of the specific environment, which together affect the health of the population in the area. The checklist could contain a multitude of factors. For example, water as a breeding site for insects and snails could be considered from the points of view of its availability, chemistry, physical properties, surface distribution, groundwater level, type of irrigation, drainage, and sullage.

To forecast future developments in vectors and diseases and their impact on health, a new checklist is needed for each phase of the project.

The major methodological problem in the EHIA is to organize the information so as to highlight crucial relationships between the factors. This can best be done with interaction matrices. These are charts in which one set of factors forms the columns, and another set forms the rows. The points of intersection then require clarification as to the importance of the interaction. For instance, different mosquito vectors require specific breeding habitats, and various aspects of the operation of an irrigation system may create such breeding habitats. With the aid of a matrix, it is then possible to predict when and where breeding sites will be created (see Volume 2, Annex 5.3).

Guidelines for forecasting the implications for vector-borne diseases in water-resources development have been prepared for PEEM (Birley 1987). This is a programmed text or workbook, adapted from the EHIA procedure. A minimum number of questions are posed in a format that permits reasonably accurate answers without the need for field surveys. It is assumed that informed answers to the questions can be obtained locally (e.g. from key personnel of the ministry of health). These guidelines are particularly useful for making a rapid assessment of the health risks in Stage I of the project cycle. Figure 4.3 outlines the forecasting procedure.

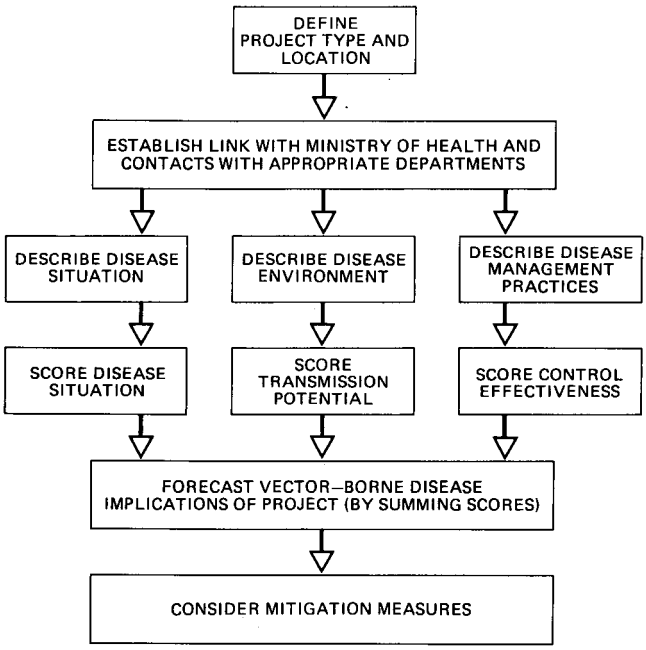

Figure 4.3 Logical steps required for forecasting the implications for vector-borne diseases in water-development projects (Source: Birley 1987)

4.7.2 Mathematical Epidemiological Models

Mathematical epidemiological models are simplifications of the highly complex natural processes by which vector-borne disease are transmitted. Predicting the disease-transmitting consequences of natural and man-made environmental changes is the all-important purpose of the models. It is therefore unfortunate that the state of the art is still in its infancy. Although computers can provide the computational requirements, the limitations are due to the selection of variables. As a consequence, predictions are less sound than one would wish. In general, the main benefit of using models lies in an improved understanding of disease transmission and of the effectiveness of intervention strategies.

Gradual progress in the quantification of biological and epidemiological processes has made it possible to develop the first generation of models that can simulate populations of mosquitoes, blackflies, and snails, or the transmission of malaria, river blindness, and bilharzia in human populations. While the models have undergone only limited testing, several have been compared with a variety of field conditions and were found to give reasonable predictions. They are all relatively new, however, and have not been used by persons other than their original authors. Any attempt to use a model in predictions to guide engineering design decisions should be made in cooperation with the model's author.

The models mentioned here have all been formulated and made operational on computers. They are relatively convenient for comparing alternative designs in order to select the least dangerous design. This is usually done with very simple models. The value of the models is that they formulate the mental concepts in a numerical fashion, which can be examined, evaluated, and replicated by other persons.

The transmission of malaria has received more mathematical analysis than that of any other tropical disease, culminating in a number of models (McDonald 1968; Dietz et al. 1974; Molineaux et al. 1978). The most comprehensive is the Garki Model, which has been tested under a wide range of conditions in the Sahel Zone of Africa, originally in Garki in northern Nigeria (Molineaux and Gramiccia 1980).

Bilharzia transmission has been simulated by many models that follow many diverse approaches (Barbour 1978; Anderson and May 1982; Anderson 1983). The simplest and most widely tested is a model by Rosenfield, which was originally developed in Iran and further improved by the analysis of bilharzia data from St Lucia (Rosenfield et al. 1977). It is fairly simple to operate, requiring a minimum amount of data, especially the observed relation of incidence of disease to prevalence of disease – the other main variable being the length of canals suitable for the habitat of the snail involved in transmission.

River blindness has been much less quantified than the other two diseases, but two recent models have been developed as a first attempt to assist in strategic decisions about the prevention and control of this disease (Dietz and Remme 1985).

Models have been developed for the simulation of populations of mosquitoes and other insects under various environmental conditions. Many models are available for mosquitoes (Haile and Weidhaas 1977). A population model for blackflies (Birley et al. 1983) has recently been developed and calibrated for specific use in control programs in West Africa. The model was developed to determine the optimum interval

between insecticidal spraying of the breeding sites. Snail populations have also been simulated with a model by Jobin (Jobin and Michelson 1967). It has been calibrated and verified with data from two species of bilharzia snails in Zimbabwe and Puerto Rico.

4.7.3 Making Predictions

Predicting Snail and Insect Habitats

After an irrigation scheme has been designed, a complete list of types of water bodies should be made to assess their potential for supporting insects or snails. The reservoir, canals, and drains should be grouped by geometry, by mean water velocities, and by length of periods of complete dryness, based on design parameters. For each of these groups, estimates should be made of expected water temperature and clarity, and of expected amounts of aquatic vegetation. These parameters can be inferred from similar irrigation schemes or from pilot farms nearby. This information – in tabular form for the entire irrigation system, and in calendar form for the important water bodies – provides the basic matrix for estimating where insects or snails are likely to be found.

Predicting Populations of Snails and Insects

Population dynamics of mosquitoes, blackflies, and bilharzia snails have been studied under laboratory and field conditions. This has provided a reasonable understanding of their birth and death processes, and of the influences of terrestrial and aquatic climate, available food, and habitat space. It has also provided some comprehension of the influence of crowding, competition from other species, and predation.

Predicting Human Populations and Disease Transmission

After the likely numbers and locations of the relevant insects and snails have been established, the next step is to estimate the numbers and locations of people to be expected as the irrigation scheme develops. The estimates of human populations should recognize the importance of migrant and seasonal labour in agricultural schemes, the difficulties of controlling the locations of temporary housing, and also the tendency of temporary or informal communities to grow rapidly and become permanent, even though they were not included in project plans or authorized by planning agencies.

Human population estimates should include a classification by ethnic and occupational groups, and estimates of age and sex distributions. These factors directly influence contact with surface waters and their contamination, housing arrangements, sanitation, and sleeping habits – important matters in the transmission of water-associated diseases.

After the locations and numbers of people, snails, and insects have been estimated

and plotted on a map of the project area, their estimated travel ranges should also be drawn and the overlapping areas indicated. These will be the locations for disease transmission. They may range from limited transmission foci if the human population is sparse and the canals far away, to intensive zones of transmission in heavily populated areas where the canals and drains are numerous and close to human habitations. (More details on this will be given in Chapter 9).

In addition to assessing the numbers of people in the transmission zones, an estimate should be made of the duration of transmission, whether it be restricted to one or two months a year by low temperatures or dry canals, or whether it continues year round. This duration, when coupled with the frequency of contact between people and disease vectors, will largely determine the intensity of transmission and eventually the severity of disease to be expected.

An example of forecasting is presented in Volume 2, Annex 2. It is an account of a health-assessment process in a pre-construction study for a proposed rice irrigation project in southern Mauritania.

4.8 Monitoring and Evaluation

4.8.1 Types of Evaluation

Monitoring refers to the measurement, collection, and recording of pre-selected types of data that allow evaluation within the planning process. In health programs, monitoring is often referred to as surveillance. Health monitoring requires an integrated system of making observations on health and environmental factors, and of scrutinizing, storing, and retrieving those data for specified purposes of protecting and improving human health. Monitoring should be an action-oriented activity.

When an irrigation project is being rehabilitated, it is important to have a clear picture of the current state of disease transmission: what diseases are present, how they are caused, and in how far they are attributable to irrigation. A thorough inventory is needed and is easily made. In this respect, a rehabilitation project is in a far more favourable position than a future new irrigation project, where everything depends on 'forecasting'.

The ultimate objectives of allocating resources for infectious-disease control are to reduce the transmission of infection and the incidence and prevalence of the diseases. These objectives cannot be achieved unless the control measures instituted are, firstly, functioning in the correct way and, secondly, are receiving the necessary support from the community (WHO 1983). Thus, three distinct forms of evaluation need to be supported by information from the monitoring system:

- Type I Evaluation, which concerns the various vector-control measures and how they function or operate. Corrective actions can be changes in design and operation, or additional institutional inputs;
- Type II Evaluation, which concerns the participatory behaviour of the community towards environmental-management measures, and whether the population utilizes these and other control measures. Corrective actions can be the promotion of community participation, hygiene education, the provision of incentives, and regulatory measures;

- Type III Evaluation, which concerns the effectiveness and efficiency of the control strategy, and the health, social, and economic benefits obtained from it. Type III Evaluation is only appropriate for a project known to be functioning correctly and receiving the necessary community support. Corrective actions can be a change in the control strategy, or the provision of complementary inputs.

Evaluations should be conducted in this order, because deficiencies found in the evaluation of later stages call for improvements in the output of the previous stage, or in the inputs of the stage under review. Figure 4.4. illustrates the relationship of the monitoring system to the three evaluations.

4.8.2 Selecting the Variables for Monitoring

For each type of evaluation, the monitoring system should be able to provide information on independent and dependent variables. Independent variables concern the technical, organizational, administrative, and resource features of project implementation; these will be dealt with in later chapters. Dependent variables concern the epidemiological variables; these have been discussed in Chapters 2 and 3 and are summarized in Table 4.1.

A practical approach to monitoring and evaluation is presented in Volume 2, Annex 5.3. It makes use of three matrices in which the breeding of specific mosquito vectors is related to potential man-made breeding habitats and to the technical and operational activities responsible for their creation.

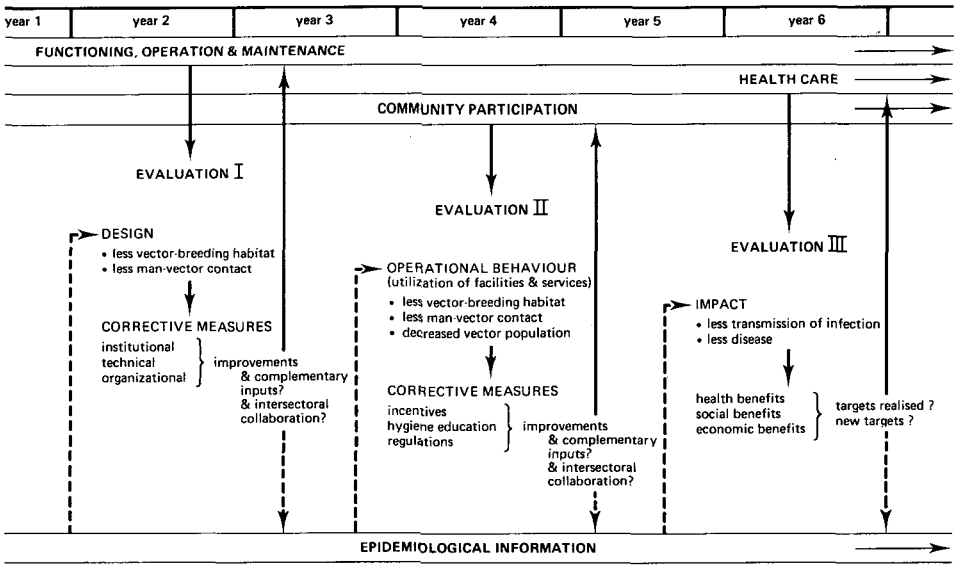

Figure 4.4 A schematic representation of monitoring and evaluation in the integrated control of vector-borne diseases

Table 4.1 Epidemiological variables for monitoring and evaluating the integrated control of vector-borne diseases

CONTROL METHODS	EPIDEMIOLOGICAL VARIABLES									
	Breeding habitat	Larvae/ pupae	Adult vectors density	Vector survival	Man-biting rate	Water contact	Popu-lation coverage	% infected	% diseased	Mortality
Environmental modification	x	x	x					x	x	x
Environmental manipulation	x	x	x		(x)			x	x	x
Residual insecticides control			x	x	x		x	x	x	x
Non-residual biochemical control		x	x		x			x	x	x
Biological control		x	x	x				x	x	x
Reduction man-vector contact					x	x	x	x	x	x
Prophylaxis/immunization							x	x	x	x
Treatment							x	x	x	x
Corresponding type of EVALUATION					I (and II)				III	

4.9 Field Studies

4.9.1 Preparation and Orientation

The first steps in preparing field studies are to establish contact with all agencies that will be interested in the findings (including the ministry of health, if not already involved) and to inform the civil authorities and populations of the villages or area where the field work will be conducted (Bennett 1979; Cairncross et al. 1980).

A protocol and plan of operations has to be prepared. Ideally, the population will be aware that an irigation project is being planned, and that the studies to be conducted are for their benefit. If sufficient attention is given to informing the people about the purpose of the health-related research, this may provide a significant stimulus to awaken or improve community participation in the project, especially if the findings and consequences for disease control are fed back to them.

Any government or medical personnel directly concerned with the community must be approached, and the objectives should be explained to them. Community leaders may be the last to be approached because they are in the lower echelons of the hierarchy of officials. Nevertheless, they are extremely important to the success of the study and to any actions requiring the cooperation of the community afterwards. It is also good practice to sound out the reaction of members of the community by informal interviews in homes and market places.

Attention should be given to data on type of crops, cropping pattern, and cropping intensity; type of irrigation and scheduling of irrigation water supply; canal maintenance schedules; features of water storage. Topographical maps and metereological and climatological data are needed. Information on vegetation and other ecological features is of great relevance.

4.9.2 Demographic Information

The study area is the geographically defined region in which the irrigation scheme is to be implemented. A prerequisite for epidemiological studies is that information be obtained on population size and various demographic variables, if this is not already available. If possible, such information should be obtained for each of the four migrant categories mentioned earlier (Section 4.1). In most countries, census data are available. These might not be very recent, in which case estimates of the current population can be made by extrapolation. If demographic information is not available, or is considered to be unreliable because of migratory movements, demographic surveys must be incorporated into the study.

4.9.3 Epidemiological Information

For studies on the occurrence and transmission of vector-borne diseases, information is required on the prevalence and behaviour of the parasite in the human population, and the species and population dynamics and bionomics of the vector or vectors involved.

To find out the number of patients treated for these diseases in hospitals and other health facilities, one can consult health-service statistics, which are a readily accessible source of information. It must be realised, however, that, for estimates of the prevalence and incidence of infectious diseases, such statistics are usually extremely unreliable and incomplete. The reasons for this are the unequal distribution of health-care facilities (especially in rural areas), the variation in diagnostic skills of health personnel and those working in medical laboratories (if such laboratories exist at all!), and the many factors that influence the use of health-care facilities by the population. It must be concluded that, in most tropical countries, health-service statistics may provide qualitative information on 'which diseases' occur, but are wholly inadequate for estimates of the incidence and prevalence of these diseases.

Health-service statistics can fulfil the function of surveillance. If an increase of a certain infection is evident from the records, this should provide a signal that something is wrong and that additional investigations and surveys are urgently required.

Ministries of health in many tropical countries have special departments for the investigation and control of vector-borne diseases. Parasitologists and entomologists working in these departments often have an intimate knowledge of the type and behaviour of local species of parasites and vectors. Such people form perhaps the most important source of advice and information for planning the integrated control of vector-borne diseases in projects. The routine data that are collected, however, are usually intended for the purpose of monitoring the national or regional control programs operated by the department. They do not particularly suit the objectives of forecasting and evaluating in an irrigation project. Also here, it can be said that such departments are an important source of mainly qualitative information, but usually do not fulfil the need for quantitative information on transmission dynamics in the irrigation project.

The conclusion is that existing information in health departments may be important for preparing a qualitative account of the diseases and vectors prevalent in the area. This information is needed in Stage I of the project. The more detailed quantitative information, however, required for selecting and preparing a plan for the integrated control of vector-borne diseases, requires active research, which can only be done through surveys (Abramson 1984; WHO, in press).

4.9.4 Surveys

Surveys are usually conducted among a representative sample of the reference population (i.e. the population of the defined geographical area in which the project is to be implemented). Two types of surveys can be distinguished (Abramson 1984):

- Cross-sectional surveys: Data are collected at one time and are used to describe the health situation. Cross-sectional surveys can be repeated periodically and thus provide a series of pictures of the situation at different points in time;
- Longitudinal surveys: Data are collected from the same sample (cohort) at different points in time. This method enables an assessment of changes that may have taken place over the period. Longitudinal surveys result in a continuous series of observations (film) of the sample cohort in time.

The cross-sectional design is simpler and is more frequently used. Longitudinal studies

are more expensive and time-consuming, require a more complex and rigorous methodology, and are difficult to manage.

An intermediate solution is the 'time-series study', which combines elements of the cross-sectional and longitudinal surveys. A time-series study begins with a simple cross-sectional survey. It requires that households included in the sample are carefully registered. During follow-up surveys, the original sample households are included in the new samples. With this approach, the end result will be a combination of cross-sectional data at different points in time and longitudinal data on a restricted group of households. If migratory movements are not intensive, the end results may compare favourably with those of a longitudinal study, but can be obtained at less cost and with less effort.

Another aspect of health surveys concerns the inclusion of a control group in the time-series of observations. In projects which incorporate a pilot study in the planning process, the setting for a control group is readily available. If there is no pilot study, however, a control group will have to be selected from outside the project. If, for the purpose of planning and evaluation, it is desirable to obtain more accurate and precise estimates of the health effects of proposed interventions, it is absolutely necessary that a control group be included.

Generally, project implementation is accompanied by many social and economic changes in the community – many of them influencing health and acting as confounders of specific interventions for the integrated control of vector-borne diseases.

Of the various possible survey designs, the strongest evidence of health effects (Type III Evaluation) will be obtained from the time-series study (with control group) or from long-term studies (with control group). Recently, the case-control study design, a technique originating in cancer epidemiology, was identified as a realistic, rapid, low-cost, and valid method for assessing health impacts (WHO 1985; Briscoe et al. 1986 and 1988).

Unfortunately, all too often, one has to rely upon cross-sectional analyses, or even case studies, which can make it very difficult to attribute any observed changes to the interventions that have been made.

4.9.5 Sampling

It is hardly ever necessary to make observations on the entire population. Drawing the correct type and size of sample, therefore, constitutes a key decision in field surveys. The two major types of sampling are probability and non-probability sampling. The underlying principle of probability sampling is that all elements (mostly individuals or households, but sometimes entire villages) have an equal chance of being selected in the sample. Various devices such as stratified sampling, multi-stage sampling, or cluster sampling can be used to improve the random selection procedure. Correctly drawn probability samples produce results that are representative of the whole community. For certain purposes, representativeness is less essential, in which case it might be easier to rely on non-probability samples (e.g. sections of the population, market visitors, typical examples of breeding places).

Resources for epidemiological research are usually scarce. Given the limited

resources, the dilemma arises whether to collect precise data from a large sample on a few subjects, or to collect less precise data from a small sample but on a broader range of subjects. Particularly in evaluation work, assessing the merits of such trade-offs means decisions for the researchers. The issue is illustrated in Figure 4.5. If a research design is chosen which stresses minimizing sampling error (Zone A), this will imply fewer resources to use, more sophisticated measurement methods, and some restriction on the breadth of coverage. To the extent that it is reasonable to generalize, statisticians tend to demand a strategy in the direction of Zone A, economists and medical personnel Zone B, and behavioural scientists Zone C.

4.9.6 Research Methods

Research for the purpose of planning and evaluating the integrated control of vector-borne diseases requires a truly multidisciplinary approach, covering variables in the fields of epidemiology, parasitology and entomology, irrigation and agriculture, economy and sociology. Four basic methods of data collection can be used to obtain the required information (Simpson-Herbert 1983; Abramson 1984):

- Participant observation;
- Key-informant interviewing;
- Open-ended interviewing;
- Questionnaire and biomedical and technical surveys.

The first three methods are primarily qualitative. Surveys normally provide semi-quantitative or truly quantitative data.

4.9.7 The Collection of Urine, Faeces, and Blood

Examination of urine, faeces, and blood (or skin snips) is essential for the epidemiological diagnosis of most vector-borne infections. The difficulties encountered in collecting specimens for examination are often dependent on the attitude of the people. Collections in schools, factories, and the like will be easier than collections from populations in the field. Inadequate and incorrect labelling (numbering) of specimens is often a source of error, loss of data, and waste of effort.

People from whom specimens will be collected (or in the case of children, their par-

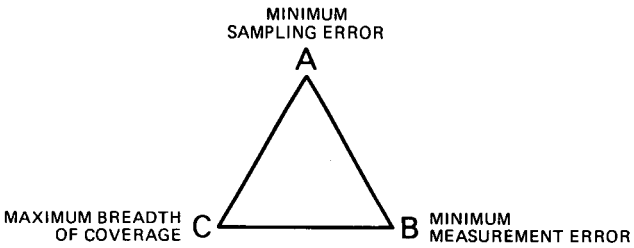

Figure 4.5 Multiple goals in survey design and sampling (Source: Cairncross et al. 1980)

ents) must know exactly why the specimens are being collected. Moreover, people expect to be rewarded for their cooperation. If pathogenic parasites are diagnosed or other diseases are observed during the procedure, the best reward would be to treat at least one of those.

Urine is the easiest specimen to collect. One can be reasonably sure which urine belongs to whom, and there are generally few cultural objections to giving urine.

Stool collection is more difficult. The main problem here is to make sure that the faeces belongs to the person who says it does.

The collection of blood may be very difficult because supernatural qualities may be attributed to it, even in quite sophisticated societies. Although people may permit capillary blood to be taken from a finger, they often refuse to give venous blood.

4.9.8 Logistics

Surveys usually have to be conducted in rural areas and under relatively primitive conditions. The field team often have to live and work for prolonged periods in rough circumstances, without piped water and electricity, and have to stay in simple hotels or tents. Such constraints need not be serious as long as the expedition has been planned realistically and with due attention to the comfort (and remuneration) of the field workers.

It is a good idea to try to involve local university departments or research institutions in the execution of the surveys. Lecturers may welcome the opportunity to be involved in research, and students may gain valuable experience by being exposed to the real development problems of their country. Moreover, students often make good and intelligent field workers. Alternatively, secondary-school-leavers can be trained to do the less technical parts of the survey. For the more demanding observations – parasitological, entomological, and engineering – properly trained personnel should be employed.

It is of great importance that the field workers who interview and communicate with the community at least speak the local language. Preferably, they should come from the same area, be familiar with the local customs, and speak the vernacular.

Transport facilities are among the most essential logistical requirements for surveys in rural areas.

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5 Engineering Control Measures in Large Reservoirs

5.1 Introduction

In the tropics, reservoirs constructed for irrigation and hydro-electric power require careful planning because of their vast potential for causing health problems. The planning should cover not only the design of the reservoir, but also its operation.

Since the Second World War, much useful information has become available about such reservoirs. Studies have been made of the large reservoirs in Africa, of many smaller man-made lakes in Puerto Rico, of recently constructed reservoirs in Asia, and also of reservoirs in the temperate zone, particularly those in the Tennessee Valley in the U.S.A., where the Tennessee Valley Authority developed reservoir operation as part of its integrated malaria-control program (Mills 1984; TVA 1974).

Reservoirs play three roles related to health:
- A biological role, because they may serve as breeding habitats for insects and snails;
- A social role, because human populations are displaced by dam construction and the subsequent flooding of their former communities;
- An economic role, because the reservoir attracts people to it for its economic productivity in terms of fishing, agriculture, and perhaps recreation.

The easiest consequences to predict are those of the biological role. From the conditions that can be expected in the reservoir, estimates can be made of the influences of reservoir ecology on the population dynamics of aquatic organisms. Predictions of the social and economic consequences are much harder to make. The problems of resettling displaced communities can be severe if preparations have not been adequate. Economic developments due to fisheries or agriculture can take unexpected turns or may happen in complex ethnic patterns. The sociological and economic consequences of large reservoirs should receive careful attention from the relevant governmental agencies – from the initial planning stages onwards – and those agencies should utilize local expertise to understand the customs, interests, and attitudes of the populations affected.

There are some fundamental differences between the large, recently constructed reservoirs in Africa and the smaller man-made lakes in Puerto Rico or the Tennessee Valley – differences that affect the kinds of measures that can be taken to control snails, mosquitoes, or blackflies.

The large reservoirs in Africa (e.g. Lake Volta or Lake Kariba) are enormous, solitary lakes, completely dominating their rivers. They are primarily storage reservoirs for water that will be used in irrigation or the generation of electric power. Flows out of those reservoirs cannot be manipulated beyond the direct requirements for irrigation and power. Nor can the flows into the reservoirs be controlled, being determined by upstream rainfall and runoff. Coupled with their extremely long shorelines, these reservoirs have basic characteristics which make it unlikely that environmental-management methods (e.g. water-level fluctuations, or the application of chemical pesticides) will be feasible for the control of insects or snails.

In contrast, the smaller reservoirs, being part of a network of similar reservoirs in the same river system, are extremely well suited to environmental management. If water-level management for insect or snail control is being applied in an upstream reservoir, a downstream reservoir can utilize any water lost from upstream. Although care is required in planning such measures, they are inherently more tractable in the smaller, run-of-the-river systems than in large reservoirs. Even if only two small reservoirs form the system, they offer considerably more operational flexibility than one large reservoir.

There are also fundamental differences between large, natural lakes and large man-made reservoirs. The natural lakes are older, of course, and have reached a more stable ecological level; the residence time of their water is significantly longer than that of the reservoirs, and their annual fluctuations are much less. This gives them an ecological stability far beyond that in even the largest of the man-made lakes (see Table 5.1). This has important repercussions for the location of human communities around the lakes, and for the shoreline characteristics that provide habitats for insects, snails, and vegetation. Around the widely fluctuating reservoir of Lake Volta, for instance, permanent human communities are located above the high water levels. Their distance from the water's edge thus varies seasonally, as does the shoreline vegetation, and hence the aquatic snail populations, producing highly seasonal patterns in the transmission of urinary bilharzia.

Table 5.1 Residence time and annual fluctuations in natural lakes and man-made reservoirs in the tropics

Water body	Residence time in years	Depth in metres		Annual mean fluctuation in metres	
		max.	mean	max.	mean
Natural lake					
– Victoria	100	79	40	1	0.2
Man-made reservoirs					
– Volta	4.2	78	19	4.3	2.5
– High Dam	1.8	85	25		
– Kainji	0.4	60		10	

5.2 Basic Concepts

When a dam is to be built, engineers will collect information about the dam site. Much of this information can be used directly in predicting the suitability of the future reservoir as snail or insect habitats. To make these biological predictions, one must obtain the engineering data and assemble it in a useful form. It is then possible to locate the areas of suitable habitat in the reservoir and to determine the seasonal changes in those areas. Particular attention should be given to the expected shoreline configuration and to the normal fluctuation pattern to be expected in the water level. From this information, expected insect and snail populations can be estimated, making it possible to prescribe control methods based on the operation of the reservoir.

5.2.1 Extent of Habitats

The expected reservoir outline can be obtained from a topographical map, and the proposed maximum water level for an average year can be traced on this map. To refine the precision for further analysis, one can divide large reservoirs into geographical basins of uniform depth, width, shore slope, and orientation to prevailing winds.

Data on wind speed and direction are needed to predict shoreline erosion and the suitability for snail and insect habitats. The seasonal changes in wind patterns should be examined to determine the prevailing winds during the seasons when the reservoir is full.

By combining the wind data with data on soil types along the shoreline, one can estimate which shorelines will erode and which will be stable. Along the exposed or eroding shorelines, vegetation, bilharzia snails, and malaria mosquitoes will not be able to establish their habitats, but will instead be found in protected areas (e.g. coves or bays) where wind and waves do not penetrate.

Unfortunately, it is not easy to compute the expected maximum wave height. Nevertheless, as a preliminary approximation, one can assume that a shoreline where the wave height will exceed 0.30 m will not be a suitable habitat for bilharzia snails. Areas where the waves exceed 0.10 m will not be suitable for malaria mosquitoes. It is thus possible to exclude obviously unsuitable portions of the reservoir, although this does not mean that the remaining portions will be populated. Many other conditions have to be met: shore slope, substrate, water clarity, temperature, and the extent of water-level fluctuations.

For bilharzia snails, a significant measure of reservoir suitability is the extent of 'illuminated shoreline' (i.e. that portion of the shoreline at a depth less than the penetration of light; see Figure 5.1). If the illuminated shoreline is flooded for significant periods during the season when water temperatures are suitable for snail reproduction, suitable habitats will be created. The illuminated shoreline falls within the 'photic zone' (i.e. the layer of water in which vegetation receives sufficient light to provide food and protection to bilharzia snails). To calculate the illuminated shoreline, one must estimate or infer the photic depth in the reservoir for appropriate seasons of the year, based on Secchi disc measurements from the inflowing streams, by inference from data on similar reservoirs, or by more detailed considerations related to sedimentation

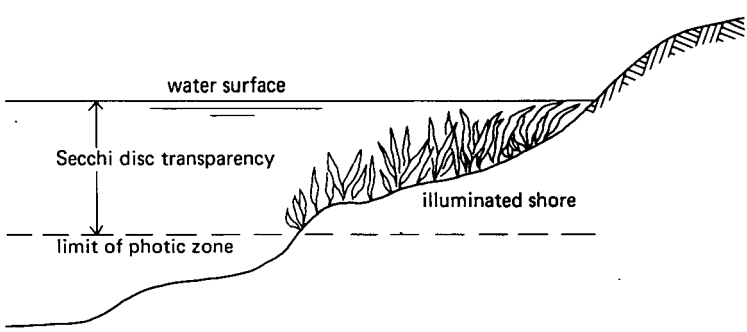

Figure 5.1 Definition of 'illuminated shoreline' in reservoirs

and plankton growth in the surface layers. The extent of illuminated shoreline in km^2 is roughly proportional to the carrying capacity of the reservoir for bilharzia snails.

For malaria mosquitoes, a similar parameter is the 'intersection line' (see Chapter 3, Section 3.1.4, Breeding and Vegetation).

The tropical blackflies which transmit river blindness will not be found in the reservoir itself, but may breed on the spillway of the dam or in any related structures where high water velocities occur (Adekolu-John 1982).

5.2.2 Seasonal Changes

In a reservoir, the most noticeable effects of seasonal changes relate to the water level, water temperature, water transparency, and the growth of vegetation. These factors control the basic population dynamics of insects and snails, and the human activities that influence the transmission of diseases.

The gross seasonal effects of an annual fluctuation cycle were observed in Lake Kainji in Nigeria, where the year was divided into four stages of water level:

- High Lake level: During this stage, the shore biomass was very high, with emergent vegetation at its maximum density. In contrast, the biomass on the bottom of the Lake, including the organisms attached to submerged trees, was at its minimum. In Lake Kainji, this period is roughly from November to March, when the clear waters at the end of the annual flood are entering. The surface water transparency in the reservoir improves during this stage from 0.1 m to 2.0 m;
- Falling Lake level: As the inflow decreases in April, the Lake level drops because of outflow, and the emergent vegetation slowly declines because of being stranded and dried. Those organisms attached to the floating vegetation survive, whereas the other shoreline organisms are quickly reduced to very low numbers. The Lake water is clear at this time, so the population of bottom organisms is increasing;
- Minimum Lake level: When this stage occurs in July and August, the emergent vegetation has been left stranded and disappears, while the bottom organisms reach their maximum value. At this time, large numbers of snails, stranded by the receding water, can be found decaying on the shoreline;
- Rising Lake level: This stage begins in August when the first highly turbid flood waters enter, flooding the previously stranded shoreline, and touching off population explosions among shoreline organisms, partly due to the decomposition of the terrestrial vegetation. There is also a re-growth of the emergent aquatic vegetation, and a rapid die-off among deep-water organisms due to the high turbidity.

For snails, this typical annual cycle in Lake Kainji is experienced as if it were the cycle in the Sahel Region, including the annual drought. Even though the Lake may contain considerable quantities of water during the stages of low Lake level, the snails stranded on the shore near the maximum water level perceive this period as a drought that will last 5 to 7 months (Bidwell 1976). If the water level recedes slowly, the snails can accommodate to being stranded and some will revive as the water level rises, beginning population growth again. Because of this perceived annual drought, *Biomphalaria* species, which transmit intestinal bilharzia, are not usually found in reservoirs with

great contrasts in their annual cycles (although they *are* found in stable, natural lakes). Instead, the Bulinus species predominate, touching off highly seasonal transmission of urinary bilharzia.

The water temperature in most African reservoirs is suitable for the breeding of snails and insects throughout the year. In other areas, especially at high elevations, cold weather may lower the water temperature below that suitable for reproduction. This factor should be investigated to determine whether the seasonal transmission cycle of bilharzia might be affected.

5.2.3 Human Activities

Human contact with lake water can vary markedly as a function of fishing or agriculture, and in relation to the distance from the village to the water's edge. In Lake Volta, these factors – in conjunction with changes in shoreline vegetation – lead to a highly seasonal pattern of bilharzia snail infection, with infected snails found only in January, February, and March, during the high water level.

The changes in water level in Lake Volta greatly affect the snail infection rates. Each year, the infections are highest in the season of early Lake drawdown and lowest at low water. At high water level, the places where people enter the water are smaller because of the wide zone of marginal emergent vegetation. The majority of these sites are shaped like small pockets. The vegetation along the sides of the pockets, and along the shore itself, creates barriers that concentrate the bilharzia larvae inside the pocket and also keep the water calm. Such well-defined sites make it easy to pinpoint the centres of human water contact – the processes of both snail infection and human infection being highly focalized.

Channel-shaped sites of water contact are also common at high water levels, but it is difficult to determine the transmission patterns at those sites.

At low water level, almost all sites of human contact with the Lake are open beaches. With no emergent vegetation in the water to confine human activity on those beaches, water contact is diffuse and larval density is considerably reduced. Snail infection rates in these sites are always low, except when heavy growths of the submerged weed *Ceratophyllum* are present.

While it may be difficult to pinpoint sites of human contact with water in swamps and rivers, the sites in Lake Volta are easily recognizable and are highly consistent. The intensity of water contact is high, not only because the villagers are mainly fisherfolk, but also because the water is of good quality and is therefore attractive as a water source.

Despite this clear epidemiological picture at lakeside, controlling bilharzia in those areas with drugs or pesticides is difficult, partly because of a high level of migration among the population in their search for more productive fishing and farming ground, and also because of the large number of people living in isolated villages somewhat removed from the Lake. The activities of these people can be monitored sometimes, but almost never controlled. In certain situations, if the seasonal nature of human activities reduces the times of contact and transmission, bilharzia transmission can be interrupted with less expensive means than drugs and pecticides (e.g. by removing emergent vegetation).

Malaria transmission around such reservoirs is also related to the distance of human settlements from the lakeside and the activities of the local population. Malaria transmission sites cannot be defined as easily as those for bilharzia, but it is obvious that communities who live or farm or fish near the lakeside will be at greater risk than communities 5 or 10 km away.

5.2.4 Water-Level Fluctuations to Strand Debris, Snails, and Larvae

The rapid recession of the water level in a reservoir will strand floating debris and aquatic vegetation; it will strand and kill aquatic snails, and will strand mosquito larvae and also expose them to predation by fish. The recognition of these facts led the Tennessee Valley Authority/TVA to apply the technique of lowering water levels for malaria control. (The TVA program cannot be applied directly to tropical reservoirs because of the importance of the winter-summer cycle in malaria transmission in the temperate climate of Tennessee).

Water-level fluctuations in reservoirs are also used for malaria control in the streambed below. The periodic high rates of discharge in the streambed when water levels are being lowered in the reservoir flush the mosquito larvae out of their protected sites (Boschi 1979).

For TVA reservoirs with constant or slowly-receding water levels, the fluctuation applied is 0.3 m within a period of 7 to 10 days. This aims at eliminating the shoreline plants and stranding floating debris – important factors for malaria mosquitoes because their larvae are not found on clean water surfaces.

The numerical measure of a shoreline's suitability for mosquito breeding is the length of its 'intersection line'. So, in managing the water levels in a reservoir, the main objective is to manipulate the water level so as to minimize the intersection line at critical times of the year when temperatures are favourable for breeding. The effect of water-level manipulations on mosquito larvae is both direct and indirect. The direct effect is that water is withdrawn from the marginal vegetation, thus exposing the larvae to an open and clean water surface where they cannot survive. The indirect effect is that marginal plants and drifting or floating material are stranded, thus depriving the larvae of food and protection.

As developed by the TVA for the temperate climate of Tennessee, the water-level management for malaria control consists of the following phases:
- Initial filling;
- Surcharge;
- Constant level;
- Fluctuation;
- Seasonal recession.

The phases can be applied singly or in combination, depending on the seasonal conditions in the reservoir. For details, the reader is referred to the original literature: *Malaria Control in Impounded Waters* (Bishop, Hollis, and Mansur 1947), to the *Manual on Environmental Management for Mosquito Control* (Rafatjah 1982) and to Volume 2, Annex 3, of the present book.

The use of rapid reservoir drawdown to strand bilharzia snails has been investigated for small reservoirs, or for large reservoirs where the normal slow recession rates could be changed to periodic rapid drops, followed by short periods of stable levels. The method was studied on small ponds in Puerto Rico, where siphon spillways were constructed to cause periodic, rapid drops in pond levels. (See further in Section 5.3.1 and Annexes 2, 3, and 4 of Volume 2).

5.2.5 Flushing

For flushing out stream sections, the water source need not necessarily be a reservoir. A sudden release of water from an upstream section of a stream (or canal) can flush out a downstream section. Two forms of flushing can be distinguished:

- The stagnant pools in a predominantly dry streambed are flushed out by intermittent release from an impoundment;
- A continuous flow, sufficiently slow to allow mosquito breeding, is supplied with an extra discharge, which destroys the larvae.

When an amount of water is quickly released into a stream, the vertical flow is converted into a turbulent flood and soon forms part of the crest of a wave travelling parallel to the streambed. The turbulence at the outset of the wave results mainly from the rebound of the water from the streambed. The length and height of the wave and the velocity with which it travels depend on the volume released, the discharge, and the stream dimensions.

Of waves applied for mosquito control, Williamson and Scharff (1936) describe waves with lengths of several hundred metres, heights of 10 to 20 cm, and durations of 3 to 5 minutes from the start until practically complete subsidence and return to normal stream flow.

The effect of flushing on mosquito larvae is four-fold (Rafatjah 1982):

- Larvae are dislodged and stranded;
- The increased velocity dislodges and exposes larvae and eggs;
- Stirred-up bottom sediments bury mosquito larvae;
- The invasion of marginal vegetation is checked.

In general, the flush wave and the turbulence accompanying it seem to be the operative factors, rather than the velocity of the current, although, no doubt, some larvae will be washed out of populous streams during the subsidence of the flush wave. Which effect will prevail depends on the topography – flat terrain being favourable to stranding, and steep terrain being favourable to dislodging. Other determining factors are the amount and kind of vegetation, and the suspendability of the soil.

Whatever the effect of flushing is, it is the overall effectiveness that counts. One way of expressing effectiveness is the percentage of mosquito larvae that are eliminated. This percentage will be 100 just downstream of the flushing device, and will be zero at some distance from it. Such a percentage says little, therefore, when it is not accompanied by an indication of the distance over which it holds true.

In an experiment in which coloured confetti was used as a substitute for larvae, an effectiveness of 90 per cent was found over a distance of 1500 m (Worth and Subrahmanyam 1940). It was concluded that the flush was effective for stretches of between 800 and 1200 m.

Table 5.2 presents some figures on flushing, including figures about the observed effective distance.

Kruse and Lesaca (1955), using existing information on effective distances as determined from actual larvae dippings in the Philippines, correlated the effective distance with the volume of water used, the discharge rate, and the width and slope of the stream. They plotted the existing data of 13 streams, apparently with a maximum water rise of 0.15 m, against effective distance. The line corresponding to the most favourable agreement is determined by the equation

$$D = 210\left(\frac{Q \cdot V}{w^2 \cdot s^{0.5}}\right)^{1/3}$$

with

D = effective downstream distance of larvicidal flush (in m)
Q = maximum discharge (in m^3 per sec)
V = storage volume per flush (in m^3)
w = average width of flushed stream (in m)
s = average slope of flushed stream (in %)

For example: $Q = 0.30\ m^3/s$, $V = 30\ m^3$, $w = 0.50$ m, and $s = 1\%$

$$D = 210 \cdot \left(\frac{0.30 \cdot 30}{0.50^2 \cdot 1^{0.5}}\right)^{1/3} = 693\ m$$

It is acknowledged that the results given by the equation are often on the low side compared with the effective larvicidal action actually found.

The equation provides no more than a rough estimate, mainly indicating what can happen in natural streams. For the more uniform conditions of irrigation and drainage canals, other criteria will have to be derived.

Concerning the frequency of flushing, information from literature points to the fact that larvae reappear within a week after flushing (Russell 1932; Williamson and Scharff 1936). This corresponds with the period of mosquito development from egg to adult, which is 1 to 2 weeks. Thus, if the effectiveness of the flush is sufficient, a frequency of once a week should be sufficient to control mosquito breeding. This is true for the direct effect on larvae. For the indirect effect of reducing the intersection line by curbing the growth of vegetation, more frequent flushings may be required.

WHO (Rafatjah 1982) has stated that flushing should start at the beginning of the breeding season, with a cycle as short as one flush per hour, and should end, when the stream is drying up, with one flush per week or longer, and that it is mandatory that at least two flushes a day be provided at the time of peak mosquito production.

The frequency of flushing will vary, of course, with the nature of the channel, the volume released, and the type of vector. The permissible flushing interval should be determined by judgement and checked by observation. One should also keep in mind that the frequency of flush and the amount of water discharged per flush are interchangeable, to a certain extent, and that, within certain limits, a prolonged flush controls a greater length of channel than more frequent flushes (Ramsay and Anderson 1940). Summarizing, we can say that a frequency of once a week is the minimum and that

Table 5.2 Effects of flushing in channels, as found in literature

References	Country	Vector species	Volume released (m^3)	Maximum discharge rate (m^3/s)	Normal dischgarge rate (m^3/s)	Release period (min)	Frequency	Height of flush wave (cm)	Width of channel (cm)	Gradient (m/m)	Observed effective distance (m)
Russell 1932	Philippines	*A.minimus*				25-30	Twice, one day a week		1-2		> 200
Williamson and Scharff 1936	Malaysia – Cameron Highlands	*A.maculatus*					Once or twice a week				> 110
	– Penang	*A.maculatus*	50.0			2		7-15		1/8	> 250
MacDonald 1939	Sri Lanka	*A.minimus?/ A.fluviatilus?/*	13.6	0.036		5-10?			0.6	Slight	800-1200
		A.varuna?/ A.culicifacies?	28.2	0.110		5-10?					1100
Worth and Subrahmanyam 1940	Sri Lanka	*A.culicifacies*	1330	0.340	0.043	80[1)]			7	1/380	1400
			835	0.380	0.031	50[1)]			4	1/183	130
			2490	0.435	0.108	130[1)]		2-25	12	1/108	150
			538	0.560	0.026	20[1)]			4	1/422	40
			1870	0.665	0.623	50[1)]				1/252	110
Ramsay and Anderson 1940	India (N.Bengal)	*A.minimus*		0.036					0.6		[2)]
				0.072							[3)]
				0.110					1.2		25
			181	0.290		10	Hourly		2.4		110
			455	0.290		30	Every 3 hrs		2.4		240
Cochrane and Newbold 1943	Grenada	*A.argyritarsis*		0.036?	'small'	8-9	Every 30-45 min	20	1.8	Steep	400-800[4)]

[1)] Calculated with mean discharge rate
[2)] Flushing was said to have 'little or no effect'
[3)] Flushing was said to be 'partially successful'
[4)] Breeding was said to be 'markedly less, but not entirely disappeared'

a higher frequency is advisable as long as a sufficient amount of water can be released per flush.

In literature, all cases of flushing deal with natural streams. For irrigation canals, the incorporation of flushing will engender problems (possible overbank flow; interference with the normal water conveyance schedule; loss of water). Nevertheless, calculations of irrigation requirements usually include a leaching requirement, which is generally accepted to prevent salinization. Why, then, should the calculations not include a 'flushing requirement'?

A flushing requirement would probably not be necessary for canals that carry water intermittently with a frequency of, say, once a week. But in canals that are unlined and where effective weed control is not feasible, flushing can be highly effective for mosquito control. In such canals, check structures can be built at intervals corresponding to the effective distance of the flush, with provision made for an upstream reservoir. The structure should include a gate, which can be closed to give the normal design flow in the canal, and opened to produce the flush discharge.

For drains, the situation is simpler. If there is a reasonably constant drainage flow, automatic flushing can easily be incorporated.

Flushing Devices

In the period 1930-1950, especially in the Philippines and in the former Ceylon, many flushing devices (sluice gates, siphons) were constructed for the control of the stream-breeding malaria vector. The basis for their design was experience and common sense. Later, Kruse and Lesaca (1955) presented a theoretical analysis that was intended to lead to the intelligent and practical design of such structures. Those authors studied the then existing successful and unsuccessful installations, and combined theory and field and model observations into empirical formulations. Unfortunately, after 1955, no more original research has been conducted on flushing devices, probably due to the onset of the insecticide era.

At the beginning of this century, when flushing was first applied as a larvicidal measure, simple hand-operated sluice gates were used. Other devices (e.g. automatic tippers and an automatic siphon designed by J.S. de Villiers) are described by Williamson and Scharff (1936). An automatic siphon as used in malaria control consists of some form of tube with two limbs or chambers of unequal length. Water is conveyed by atmospheric pressure over a dam or retaining wall from the upper reservoir to a lower level in such a way that the action is self-initiating and self-arresting.

The 'de Villiers' siphon was used as a basis for the design of the 'MacDonald' siphon (MacDonald 1939). Since then, flushing has been associated with automatic siphons and no more mention is made of the use of sluice gates, except recently (Boschi 1979). Since 'MacDonald', hundreds of anti-mosquito siphons have been installed, most of them in Sri Lanka, India, and the Philippines.

The advantages of the automatic siphon lie mainly in its self-initiating and self-arresting features, which give the intermittent flow that disturbs the larval habitat downstream. An automatic siphon helps to eliminate failures due to the human factor (Dy, Bernardo, and Bernardino 1950), and reduces labour input (Williamson and

Scharff 1936). With hand-operated devices, it will be difficult to give more than two flushes a day every day throughout the breeding season, especially if many sites are involved and manpower is limited, and if the sites are not easily accessible. Automatic siphons, however, are expensive and not easy to design, construct, or maintain. They require regular visits by field staff to ensure their proper operation during the critical breeding season. Leaks in the siphon must be repaired and blockage by floatage removed. Where inflow, and thereby flushing frequency, becomes low and where sites are easily accessible, hand-operated gates are a better alternative.

An automatic siphon works in the following way. One or more of them are incorporated in a dam constructed across a stream or canal. The action of this combination of dam and siphon is to collect a reservoir of water above the dam; in the reservoir, the water level gradually rises according to the rate at which water flows into it; then, each time a certain level is reached, the siphon comes into action and automatically discharges the water at a fixed rate, depending on its design. The importance of the reservoir makes the difference between anti-mosquito siphons and siphon spillways. The aim of a siphon spillway is to prevent the water upstream from rising above a certain level, but if this can be combined with adequate water-level fluctuations for vector control along the reservoir shores, so much the better.

Normally, large fluctuations of the water level are prohibited, and thus the difference between the level at which siphoning starts and the level at which siphoning stops is minimized, thereby minimizing the flushable volume.

Figure 5.2 shows a siphon and the accompanying terminology of Naylor (Blacklock 1939).

For an automatic siphon to begin functioning, it must be 'primed' (i.e. the air must be evacuated from the upper bend of its curved throat and 'vacuum' conditions created in it). This is not as difficult as it might seem. No mechanical means (e.g. pumps or the like) are required. Provided that the downstream limb of the siphon is properly sealed to prevent new air from entering the throat, the air particles are automatically carried away by the fast-moving current of water in the throat – a downstream sealing trough serving as a water-seal.

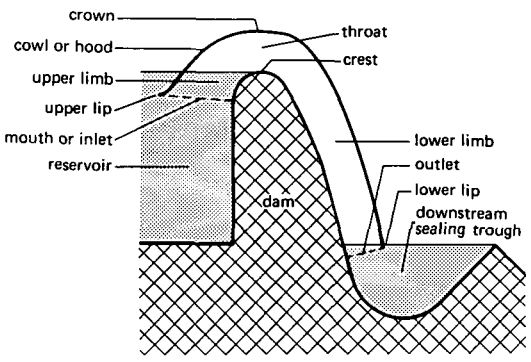

Figure 5.2 A siphon

A method of sealing, often applied together with a water-seal, is the creation of a sheet of falling water or 'nappe', which acts as a water diaphragm; the nappe prevents air from entering through the outlet, but does not hinder the escape of air. Figure 5.3 shows an emergency siphon, which employs both a water-seal and a nappe (Neyertec 1986). As the upstream level rises above the nominal value, the flow through the siphon passes through the three stages shown in Figure 5.3. Between Stages 1 and 3, the right proportion of entrained air is maintained by the combined effect of the 'priming step' and the 'partializing vent'.

The nappe, deflected by the step, draws air out of the siphon, whilst air entry is increasingly throttled by the rising upstream level. During priming, water is wasted, so priming should be abrupt and the evacuation of air rapid. The same holds true for breaking off the siphon action. If this is not abrupt, water will be wasted. This means that, at this point, ready air entrance must be secured.

Historically, since 1940 – apart from the more recent Neyertec siphon – three basic types of siphons have been applied. These are the MacDonald type (MacDonald 1939), the Legwen-Howard type (Kruse and Lesaca 1955; WHO 1982), and the Smith type (Dy, Bernardo, and Bernardino 1950). Other types could be classified as variations on one of the basic types, according to the principle of operation (i.e. how priming

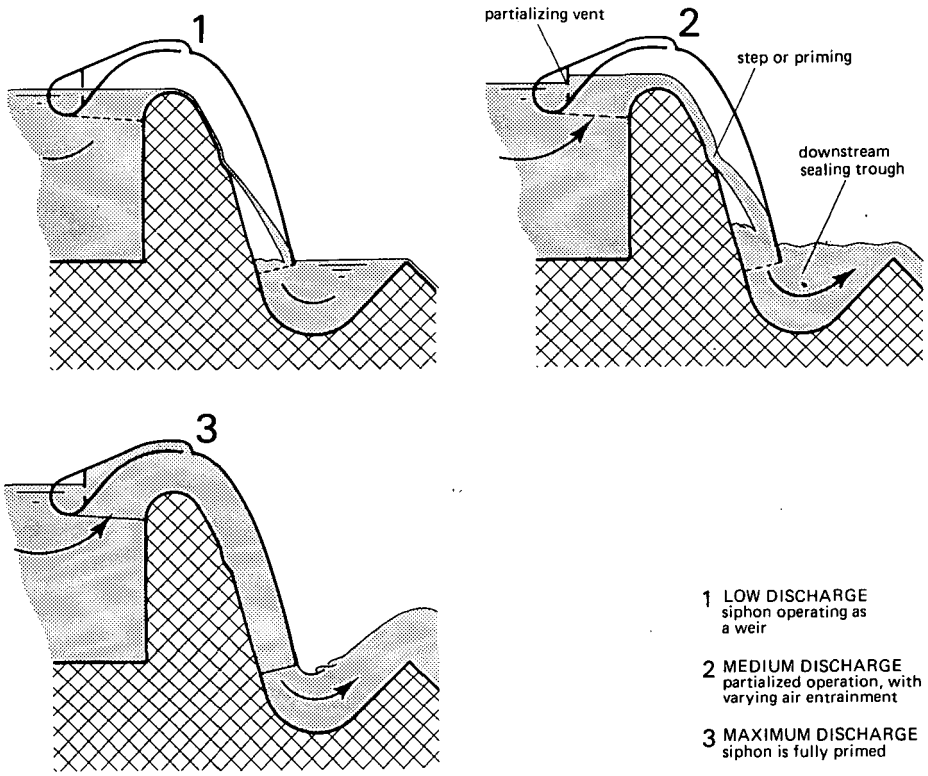

Figure 5.3 Emergency siphon with water-seal and nappe (after Neyertec 1986)

and breaking occurs). Of these other types, mention is made of the Dooars design (Ramsay and Anderson 1940), the Grenada design (Cochrane and Newbold 1943; Newbold and Cochrane 1947), the block type and funnel type (Worth and Subrahmanyam 1940), and the Ejercito type (Ejercito 1940; 1941).

The purpose of an anti-mosquito siphon is 1) to provide a certain discharge 2) of sufficient duration 3) without too much wastage of water. The values of these design criteria follow from the specific situation. Which design is most suited is further determined by the demands on transportability and ease of construction and maintenance, which in their turn are governed by topography and the availability of funds, materials, labour, and skills. Once the design discharge has been determined, one can look for the type of siphon which, singly or as a battery, produces this discharge. Two important criteria are:

- The flushing velocity, which is set rather arbitrarily at 0.40 to 0.50 m/s;
- The effective distance, or length of effective larval control, which determines the required spacing of the flushing siphons.

5.2.6 Shoreline Modification

The technique of shoreline modification (whether or not in combination with a rapid recession of the water level) is applicable for both bilharzia and malaria control. It consists of straightening irregular edges by grading, and improving drainage by ditching and filling. For further information, see Volume 2, Annex 2.

5.2.7 Biological Control

Especially in large reservoirs, the use of chemical pesticides to control snails or mosquitoes seems a futile waste of money, given the continuous re-invasion of these vectors. In Lake Volta, short-term methods to control bilharzia were successful, but had to be abandoned because they were too expensive for the Government of Ghana to continue them. The program was terminated, leaving the lakeside villages exposed to bilharzia re-infections.

The need for a logical strategy of long-term control has long been recognized. Studies in Puerto Rico and elsewhere have indicated that such a strategy might be based on the biological control of the bilharzia snail by the snail *Marisa cornuarietis*. (There will be more about this in Chapter 8).

5.2.8 Vegetation

Aquatic vegetation in a tropical reservoir evolves as a result of the initial riverbed vegetation, nutrient conditions in the reservoir, soil and erosion conditions on its shoreline, and the pattern of seasonal fluctuations in its water levels. The floating and emergent vegetation can often interfere with the normal uses of the reservoirs, so methods have been developed for its control. As well, vegetation provides both food and shelter for snails and mosquitoes, which constitutes another reason for controlling it.

The geographical distribution of weeds occurs as winds and currents erode exposed shorelines and prevent vegetation from rooting. Colour and plankton in the surface waters determine the depth to which sunlight penetrates, and consequently determine the pattern of submerged vegetation and the depth of algae populations.

The distribution of favourable soils also influences the types and patterns of vegetation. So, if one has sufficient information on soils, wind, and the nutrients in the waters entering a proposed reservoir, one can make some general predictions about the distribution of vegetation to be expected in it.

Mosquitoes and Vegetation

Early malaria-control personnel in Asia noted the detrimental effect of shade trees on certain species of malaria mosquitoes, leading to several ideas about controlling mosquitoes by controlling vegetation.

In reservoirs sufficiently far from the equator, a well-developed technique is now employed for mosquito control: winter drawdown is used to kill certain types of rooted aquatic vegetation growing on the reservoir shoreline, thus depriving mosquito larvae of protection and food (i.e. the length of the intersection line is reduced). In small interconnected reservoir systems on the same river, the reservoir levels are manipulated to strand floating vegetation and debris, also depriving mosquitoes of shelter.

Snails and Vegetation

Aquatic snails are even more dependent on vegetation than mosquitoes are, so bilharzia-control programs have long utilized weed control to supplement drugs and pesticides. In Lake Volta, the bilharzia snails were found to be closely associated with the presence of *Ceratophylum*, a submerged weed that blanketed the western shoreline before the catastrophic drought of the early 1980's. Snail control on the Lake included the manual removal of vegetation prior to an application of bayluscide, the chemical used to kill the snails.

Other kinds of vegetation on the same Lake influenced human access to its waters, thus restricting the water-contact points and focussing the geographical patterns of bilharzia transmission to those portions of shoreline not blocked by heavy rushes and woody vegetation.

Questions related to the Control of Vegetation

In contemplating the control of aquatic vegetation in tropical reservoirs, one should recognize that the greatest danger of disease lies in those areas closest to human settlements. Conversely, the areas far from such settlements need not be freed of vegetation, insects, or snails, at least not for the purpose of protecting health.

A major question in preparing reservoir sites prior to flooding is whether to cut and clear trees and other vegetation below the reservoir's expected high-water line. This can be an extremely costly undertaking in forested areas, but the advantages

for health lie in a reduction of the intersection line and thus in a reduction of mosquito production, and in a better accessibility of shoreline for boats involved in operations for malaria and bilharzia control. Partly flooded treetops will increase the intersection line, and may even double it by their tendency to trap debris.

5.3 Suggested Design Guidelines and Costs of Disease-Control Measures in Reservoirs

The planning and design of irrigation reservoirs to avoid health problems involves, first, an assessment of the potential danger of the reservoir in transmitting diseases, and secondly, a selection of the most cost-effective approach to controlling diseases, comparing preventive measures included in the design and operation of the reservoir with remedial control measures instituted after the reservoir has been completed.

Prescribing control measures for large reservoirs such as Lake Volta or Lake Kariba is particularly difficult because of their size and their uniqueness. New reservoirs of such magnitude will not be common in the future, but, if built, will deserve extensive analysis and perhaps pilot studies on potential control methods before their plans are finalized.

More common in the future will be medium and small reservoirs. Selecting control measures for such reservoirs should be made from among the various methods now available. It is primarily for these reservoirs that the following methods are discussed.

5.3.1 Alternative Bilharzia Control Measures in Two Lakes in Puerto Rico

The range of control measures available for small reservoirs can be illustrated with a comparison between two reservoirs in Puerto Rico: a small lake in a steep mountain valley (Lake P), and a larger lake with a flat shoreline (Lake G) (Jobin 1973). Information about these reservoirs is given in Table 5.3.

The measures available for snail control in these reservoirs are:

- Chemical control with bayluscide;
- Biological control with the large snail *Marisa*;
- Rapid drawdowns on a monthly schedule during the breeding season of the bilharzia snails.

The three measures will be examined to indicate how one would make an estimate of their cost and effectiveness.

Both Lake P and G supply flow for hydro-electric power and irrigation to a scheme on the south coast of Puerto Rico. Before the flow is passed through turbines, it is stored in another lake.

In addition to the flow from River P, Lake P receives overflow from a diversion on another river. The combined annual inflow is 30 million m^3 or 82,000 m^3/day. The storage volume at spillway level is 700,000 m^3, thus the mean residence time is very short, just 9 days.

The potential habitat area is limited in Lake P by the steep slopes and the poor penetration of light. The calculated illuminated habitat is only 1,200 m^2, compared

with 134,000 m^2 for Lake G, where the shore is much flatter and the water clarity is 3.4 m. Snail reproduction in Lake P, also limited by cool weather, occurs only from April to December, whereas it occurs all year round in Lake G.

Table 5.3. Characteristics of Lakes P and G

Characteristics	Lake P	Lake G
Drainage area in km^2	25	25
Volume in million m^3	0.7	18.6
Surface area in hectares	10	200
Annual inflow in million m^3	30	17
Flow-through time in days	9	390
Mean depth in m	7	10
Total shore length in km	1.0	7.5
Mean shore slope (horiz.:vert.)	3:1	5:1
Illuminated shore zone in m^2	1,200	134,000
Minimum shore slope	5:1	30:1
Maximum shore slope	1:1	1:1
Fluctuation range in m	1	14.5
Mean rate of fall in m/month	0	1.4
Mean rate of rise in m/month	0	4.8
Month of maximum elevation	–	November
Month of minimum elevation	–	July
Mean monthly temperature in °C	22.9	24.2
Minimum monthly temperature in °C	(Feb) 18.3	(Feb) 20
Maximum monthly temperature in °C	(Jun) 24.0	(Jul) 27
Snail-breeding season	April-December	all year
Mean Secchi-disc depth in m	0.4	3.5
Prevailing wind direction	NE	NE
Fetch on exposed shores in km	negligible	0.4
Calculated max. wave height in m	0	0.3
Elevation in m	453	448

With the prevailing northeasterly trade-winds in Puerto Rico, the waves striking the southwest shoreline would be insignificant in Lake P and about 0.3 m high in Lake G. However, over half of the shoreline in Lake G is protected from the wind, thus the suitable illuminated habitat in Lake G is about 80,000 m^2, if the proportion of exposed shoreline is deleted from the total illuminated habitat.

On the basis of field data from Puerto Rico and other places, it can be assumed that infected snails are not found during the months of low or rising water level, but only when the reservoir levels are high or slowly receding. Thus, infected snails would be found year round in Lake P and from October to May in Lake G.

Chemical Control

The toxic chemical bayluscide would have to be applied monthly to all the suitable illuminated habitat during the period when infected snails are present. The cost of the chemical, applied at 0.5 mg/litre, would be U.S. $24 per kg of active ingredient. Treatments are relative to a depth of one-half the Secchi-disc depth (Lake P: 0.5·0.4

m, and Lake G: 0.5·3.50 m). For Lake G, treatment is required only 8 months of the year because of the large annual fluctuation cycle. Details of costs are given in Table 5.4.

Biological control

Both Lakes are suitable for the biological control agent, *Marisa*, which would establish itself in a fairly large population within two years of being introduced. Because of various natural catastrophes (e.g. extreme drought), the *Marisa* might have to be replanted in the reservoirs about every 10 years. A single planting of about 1,000 *Marisa* would be sufficient for Lake P, and about 2,000 for Lake G. The harvesting, transport, and planting cost for this snail is about U.S. $0.03 per snail, and the success rate is about 90 per cent. Thus the pro-rated annual cost for the biological control of snails in Lake P would be U.S. $4, and in the larger Lake G about U.S. $8 (Table 5.5).

Table 5.4 Cost of chemical control of snails in two small reservoirs in Puerto Rico, in 1984 U.S. Dollars

Item	Lake P	Lake G
Suitable habitat area in m^2	1,200	80,000
Mean depth of habitat area in m	0.20	1.75
Number of monthly chemical treatments/year	12	8
Annual volume treated in m^3	2,880	1,120,000
Applied concentration of bayluscide in g/m^3	0.5	0.5
Cost of bayluscide per m^3 treated	$ 0.012	$ 0.012
Subtotal – Annual chemical cost	$ 35	$ 13,440
Labour in man-days	24	16
Wages per man-day	$ 35	$ 35
Subtotal – Annual labour cost	$ 840	$ 560
Travel in vehicle – kms	240	160
Cost per vehicle/km	0.50	0.50
Subtotal – Annual transport cost	$ 120	$ 80
Total – Annual cost of chemical control	$ 995	$ 14,080

Table 5.5 Cost of biological control of snails in two small reservoirs in Puerto Rico in 1984 U.S. Dollars

Item	Lake P	Lake G
Lake shoreline in km	0.1	7.5
Number of *Marisa* needed	1000	2000
Cost per *Marisa*	$ 0.03	$ 0.03
Total cost per planting	$ 30	$ 60
Number of years to dominate lake	2	2
Period of re-seeding in years	10	10
Probability of success in domination	0.9	0.9
Years of successful control per 10 year planting	7.2	7.2
Total – Annual cost of biological control	$ 4	$ 8

Both reservoirs are used primarily for storage, with a third equalizing reservoir downstream in the system. This means that daily or weekly changes in discharge from the upper two reservoirs would not seriously affect the power-generating capacity of the lower reservoir, or the irrigated area, as long as the required monthly mean flows are maintained. Thus, periodic rapid drops in water level could be employed as a snail-control method, provided that adequate discharge devices and control structures are installed in the reservoirs.

The cost of this method would be the amortized construction costs, plus the annual operating costs to produce the required water-level fluctuations. The final calculation of these costs will not be possible, but the first step in the calculations will be made: the definition of the size and timing of the discharges from the reservoirs.

Such fluctuations are effective during the season when snails are laying eggs, so for 9 months from April to December in Lake P and all year round in Lake G. In Lake G, however, the water level recedes only from November to July, also 9 months. Thus the rapid recessions could be induced weekly for 9 months of the year. The recommended drop is 0.5 m.

In Lake P, where the mean level is constant and the mean discharge is 82,000 m^3/day, the level could be raised 0.25 m above normal, then dropped 0.5 m in 7 days, then allowed to rise again 0.5 m in the following 7 days. This saw-tooth pattern of fluctuation would kill all snail eggs and many adults during the breeding season, holding the snail population near zero even when snails were washed in from the tributary streams.

The discharge from Lake P during the receding stage would have to equal the sum of the normal inflow from tributary streams, plus the volume of the drawdown over one week. The volume of the drawdown would be equal to the surface area of 100,000 m^2 times 0.5 m drawdown or 50,000 m^3. This would require an extra discharge rate of 7,000 m^3/day, thus the outlet structure would have to handle 89,000 m^3/day during the drawdown stage.

It is likely that the existing discharge capacity would be adequate to handle this slight increase in flow. To allow the water to rise again, the outlet gate would have to be closed slightly until the flow was reduced to 75,000 m^3/day.

This fluctuation pattern could be produced by a weekly adjustment of the discharge valve at a minor labour cost if an operator was already present or nearby. It could also be handled by remote or automatic control, if the proper equipment were installed.

If the outlet capacity were adequate, it would be more effective to decrease the time of the drawdown stage to as short as 1 day if possible, requiring a total discharge capacity of 132,000 m^3/day. This kind of fluctuation could be induced automatically by the provision of an additional siphon on the spillway, set high enough to prime when the reservoir level reached 0.25 m above normal. When the siphon was not discharging, the outlet flow would have to be set low enough to cause the reservoir to fill again in one week, at 75,000 m^3/day discharge. This type of siphon spillway would involve very little maintenance or operation cost and might be cheaper than a mechanically-operated valve, depending on local labour costs.

In the larger Lake G, the increased discharge requirement is significant. Normal annu-

al inflow is only 17,000,000 m^3, so mean outflow is 47,000 m^3/day. During the season from November to July, however, the discharge during recession is over twice that, or about 100,000 m^3/day. This discharge produces a vertical drop in reservoir level of 1.4 m/month or 0.3 m/week.

To achieve the desired drawdown of 0.5 m in 1 week in this reservoir would require an additional mean outflow of about 80,000 m^3/day. Thus the required outlet discharge would have to be 180,000 m^3/day, almost twice the normal rate. In addition to weekly costs for setting the discharge value, this additional flow requirement might have a significant construction cost, which cannot be estimated here.

Summarizing the analysis for these two small reservoirs, we can state that biological control is clearly the cheapest method (Table 5.6); in second place is either chemical control or water-level management, depending on design details of the additional outlet structures required, and additional operating costs.

Table 5.6 Comparison of annual costs (1984 U.S. $) for alternative snail-control measures in two reservoirs in Puerto Rico

Control method	Lake P	Lake G
Chemical control	$ 1000	$ 14,000
Biological control	$ 4	$ 8
Water-level management	small	significant

5.3.2 Estimated Costs of Snail Control in Lake Volta and the High Dam Lake

A completely different situation is encountered in snail control in the large man-made lakes in Africa. In these lakes, water-level management is unlikely as a control method because of the large surface area of the lakes when full (Entz 1970). In Lake Volta, where inflow often seems to be seriously deficient, it would be extremely unwise to waste water that is in such short supply. Thus the remaining possibilities for snail control are chemical and biological.

The cost of chemical control of infected snails in Lake Volta has been estimated at about $1 million annually (1984 $), based on the pilot program completed in 1980 (see Volume 2, Annex 3). No reliable estimate is available for the High Dam Lake, but if bilharzia is transmitted along its shores, the cost would probably be similar, based on the relative size of the Lakes (Table 5.7).

The cost of $1 million per year for chemical control is beyond the resources of Ghana or Egypt, or almost any African country. Thus the logical solution is to develop a biological-control method, applicable to these and other large lakes in the tropics. Estimating the cost of a successful biological method is not easy because trials with *Marisa* or other biological-control snails have not yet been conducted on any of these large lakes. Even though it seems that *Marisa* would be effective, there is a need for lengthy preliminary testing.

Table 5.7 Characteristics of Lake Volta and the High Dam Lake

Characteristic	High Dam Lake	Lake Volta
Year of completion of dam	1964	1964
Gross storage capacity in million m^3	153,000	165,000
Length of shore at maximum level in km	8,000	5,300
Surface area in km^2	5,500	8,700
Mean depth in m	25	19
Maximum depth in m	85	78
Transparency by Secchi disc – in m	0.2–0.3	0.2–0.4

In addition to the ecological problems, there are – for these large lakes – the difficulties of importing, establishing, and distributing the biological-control snails. (For details, see Chapter 8.) Anyhow, if everything works out well, the annual costs of biological control are definitely much lower than for chemical control (ratio 1:20).

5.3.3 Blackfly Control by Spillway Design

Almost all reservoirs have regulating or emergency spillways or outlet structures where shallow flows at high velocities (0.90 to 1.20 m/s) are favourable for egg deposition by blackflies (Burton and MacRae 1965). When these structures are being designed, provision can be made to minimize their suitability for blackfly breeding.

A pilot study in West Africa on the configurations of several types of spillway resulted in the following findings and recommendations (Quelennec et al. 1967):

- Stepped spillways are particularly favourable for the breeding of blackflies, and should not be used;
- For seasonal rivers, spillways of the Creager type or in the form of steeply inclined planes would reduce the time during which breeding can take place;
- Vertical-walled spillways are probably the best type for avoiding blackfly breeding;
- The use of sluice gates and siphons, by which the spillway surfaces would be periodically dried and breeding eliminated, should also be considered an effective design, especially in areas where the spillway would be a major source of blackflies. The automatic siphon will prevent Simulium breeding over small dam spillways.

Certain alterations in the design of concrete overflow crests of dams can help to destroy the habitat suitable for Simulium breeding (Diamant 1966):

- The spillway crest could be calculated to have a length that will keep the velocity of the flowing water under 1 foot/sec during normal flows. This is a costly suggestion because the required length of the spillway would be considerably increased;
- A straight pipe made of concrete or cast iron could be placed in the spillway, near normal water level. The pipe should slope in the downstream direction, and its diameter should be reasonably small so that under normal flows its inlet would be submerged, but would also prevent the water from reaching the crest most of the time. Simulium larvae are destroyed if, for a period of four to six hours, they are left exposed to the atmosphere and sun without water flowing over them. If the submerged pipe is calculated on the basis of reliable water-flow data, it can provide these dry intervals.

This discussion on blackfly control in reservoirs would not be complete without mentioning the potential for reservoir construction in West Africa in the area where the international Onchocerciasis Control Programme/OCP has effectively, although temporarily, controlled the blackfly. As people return to the banks of the West African rivers which had previously been uninhabitable because of the blackflies, they will develop the rivers for domestic water supplies, and eventually for hydro-electric power, while the riverine areas will be used again for agriculture. This development is a consequence, and even an objective, of the OCP. It is therefore important that the resultant small dams, sills, irrigation canals, and other structures be designed and operated in a manner that will prevent the blackfly from breeding in the surrounding area, and also prevent the invasion of bilharzia, malaria, and other water-associated diseases.

Such new water-resource development in West Africa could also reduce the need for the constant chemical applications applied in the present OCP, and could actually be justified as an addition to the present OCP strategy, which is inherently defective in long-range terms. The creation of reservoirs that flood out extensive rapids would permanently eliminate blackfly breeding sites, which must otherwise be repeatedly sprayed with chemicals. A careful selection of the reservoir sites and the spillway designs – combined with the proper location of agricultural communities, the provision of safe water supplies, and the careful design of irrigation canals – could result in disease-free zones of development.

The permanent elimination of breeding sites for blackflies by the submergence of rapids would be an excellent addition to the present OCP strategy and would be an additional economic benefit to be considered in a cost/benefit analysis. The OCP protects 18,000 km of river length at an annual cost of over $20 million (1984 U.S. $). Discounting part of the cost for evaluation, the annual cost of the chemical control operation is about $1,000/km of river protected. Thus a small dam might flood 10 or 20 km of river front and thus save $10,000 to $20,000 annually.

If such reservoirs were properly sited with regard to major breeding points and human populations, their real value could be multiplied several times this figure. Proposed water projects in West Africa should give special consideration to this aspect of health protection. It is an unusual situation in which the millions of dollars previously invested in the chemical control of the blackfly can and must be protected by some permanent changes in the aquatic habitats.

5.4 Practical Examples

Experience with health problems in reservoirs – and with subsequent remedial measures – has shown that a variety of measures used in a carefully planned and integrated program seems to be the most rational way of avoiding serious health problems. Three examples, presented in Volume 2, Annex 3, illustrate the variety of control measures that have been successfully used. They were applied in the malaria-control scheme of the Tennessee Valley Authority, to the bilharzia problems in Lake Volta, and to bilharzia problems in small irrigation reservoirs in Brazil.

Small reservoirs in Puerto Rico offer good examples of bilharzia control. These are described in Volume 2, Annex 4, Section 4.2. The anopheline mosquitoes transmitting malaria in Puerto Rico are not found breeding in any of the man-made reservoirs,

apparently because of the steep slopes and frequent and rapid recessions in the water level. This is true for the night-storage ponds along the coast, where water levels fluctuate daily, and also for the large reservoirs in the mountains, where fluctuations follow an annual cycle and the shores are steep.

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6 Engineering Control Measures in Irrigation Systems

Many tropical irrigation systems – with their networks of canals, regulating structures, intermediate storage points, and complementary drainage networks – have become enormous aquatic habitats for disease-bearing insects and snails. The systems thus form foci of disease transmission, apparently because of their basic characteristics (Figure 6.1). And yet, irrigation systems that do not harbour these diseases are occasionally found, even in normally endemic regions, thereby indicating that it is possible to design and operate the canals, structures, and drains in ways that reduce or eliminate health problems.

Experience in irrigation schemes has shown that diseases can be prevented primarily through canal design, crop selection, water management, location of housing, and canal maintenance. To help designers make decisions on these factors, we present basic concepts of the disease organisms and relevant design criteria to counter those organisms. Practical examples from existing irrigation schemes are presented in Volume 2, Annex 4.

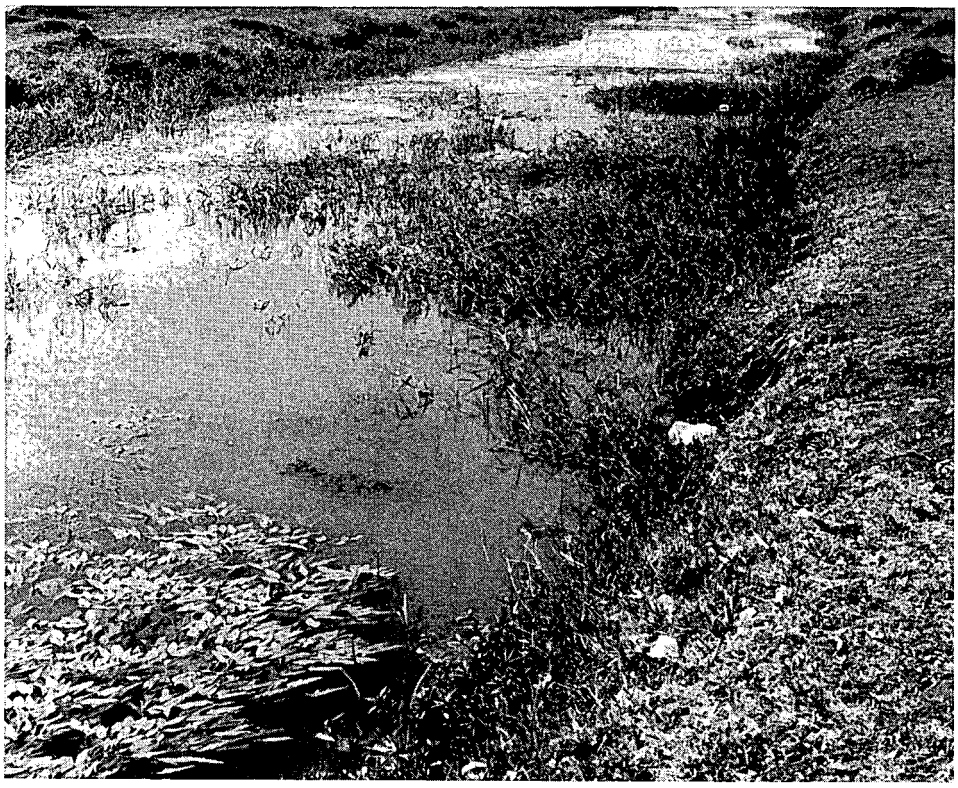

Figure 6.1 Irrigation canals that contain slow-flowing water for most of the year become blocked with aquatic vegetation and form ideal habitats for disease-transmitting snails and mosquitoes

6.1 Snails – Basic Concepts

6.1.1 Flow Velocities

For most insects and snails, the local velocity of flow is an important determinant of habitat suitability. Malaria and bilharzia are favoured by slow velocities, whereas river blindness is favoured by high velocities. Water velocity is especially important in bilharzia transmission for it affects the snail and also the miracidia and cercariae as they swim about in search of snails or people to infect. Snails exhibit a clear response to steady flow, depending on the velocity. A velocity high enough to prevent them from inhabiting canals can be determined for each species of snail.

Flow Velocities for Dislodging and Immobilizing Biomphalaria glabrata

To dislodge a snail from a canal bottom or other surface, a drag force must be produced on its shell to pull the snail from its position. A laboratory study, in three parts, was made on the subject:

- The drag forces were measured on dry shells for the pertinent range of flow conditions and snail sizes;
- The resistive ability of live specimens was defined on various surfaces;
- Live snails were studied in a controlled flow to verify the behaviour predicted from the first two parts of the study.

The study was made on *Biomphalaria glabrata* because of its importance in the western hemisphere.

The velocity required to produce a dislodging force on a snail of 0.013 m diameter was found to be 0.94 m/s at a distance of 0.013 m from the boundary, a smooth solid surface. This velocity distribution would also dislodge snails of all other diameters. For loose granular surfaces, a dislodging velocity of 0.36 m/s at a distance of 0.013 m from the boundary would dislodge all snails.

When snail behaviour in flowing water was studied, the snails' reaction was remarkably similar in all tests. At very low velocities, the snails pointed in random directions, moving about freely. As the flow increased, they showed a definite tendency to move against the current. Eventually, they faced directly into the flow and pulled their shells tightly over their bodies, with only the tentacles visible. At a velocity in the range of 0.20 to 0.30 m/s, the snails were completely immobile, and this immobilizing velocity was recorded for each snail.

The retraction position, facing upstream, offered the least resistance to the flow and was therefore the safest. The few snails that persisted in moving at this point soon lost their footing and were swept rapidly downstream. With further increases in flow, the snails attempted to remain in a retracted position. Eventually, their shells were pulled back by the drag, either because the snails tired or because they moved inadvertently. In this position, the drag on the shell became still greater, stretching the columellar muscle to the extreme. The snails frequently attempted to pull their shells back to a retracted position but were unable to do so.

Finally, the shell was stretched back in a horizontal position, oscillating rapidly. This action eventually pulled the snail's foot into a position perpendicular to the stream

flow. A short time later, the snail was pulled loose and was unable to regain its footing. The velocities at this stage were generally of the order of 0.60 m/s and were recorded as the 'dislodging velocities.'

A comparison of these results with those from the static-force tests showed that, for a diameter of 0.013 m, a velocity of 0.33 m/s will cause immobilization and 0.65 m/s will cause dislodgement.

Knowing the required velocity conditions, one can calculate the mean velocity that will produce the desired effect in a given channel section. Such mean velocities have been evaluated for the wide range of channel geometrics encountered in practice. They are summarized in Table 6.1. Velocities that would cause immobilization rather than dislodgement were chosen for the table. These are still significantly higher than values recommended by previous investigators and should prove conservative in design.

Table 6.1 Mean velocities in trapezoidal channels for controlling bilharzia snails in the western hemisphere

Canal discharge in m^3/s	Immobilizing mean velocity in the canal in m/s
1	0.58
5	0.67
10	0.71
20	0.75
30	0.78
50	0.81

A field study on the same species of snail (*Biomphalaria glabrata*) was conducted in natural streams in Venezuela, but the method used to estimate local velocities may have been unreliable. That study indicated that the snails could not populate in areas with velocities above 0.30 m/s, probably an underestimate. A likely explanation for the lower suggested velocity is that natural streams are significantly different from irrigation canals in terms of the dynamic nature of their flow. The flow in irrigation canals is generally kept constant, with only minor, gradually-made adjustments. In contrast, natural streams experience gradually declining flow, interrupted by sharp increases due to rainfall.

To evaluate the accuracy of the laboratory observations and predictions, a one-year field study was conducted in Puerto Rico to check the limiting velocities for *Biomphalaria glabrata* in the trapezoidal and unlined Patillas Irrigation Canal with relatively steady flow. The number of snails was found to be inversely related to the mean velocity at each station, thus indicating that there would be no snails if the canal velocity exceeded 0.55 m/s (Figure 6.2). This critical velocity correlated well with the prediction of 0.58 m/s from the laboratory study for canals of 1 m^3/sec discharge, roughly the discharge in the Patillas Canal during the snail study.

The field study confirmed the validity of the predicted design velocities for well-maintained trapezoidal canals, and indicated that the data are equally valid for lined

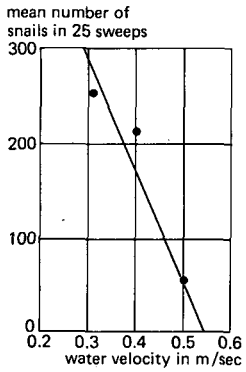

Figure 6.2 Number of bilharzia snails and water velocity in Patillas Irrigation Canal in Puerto Rico during 1959. At stations with higher velocities, fewer snails were found, indicating a maximum tolerable velocity of slightly less than 0.60 m/s

and unlined canals (Jobin and Ippen 1984; Jobin et al. 1984). It also appeared that the local velocity which reduced the snail motion to zero was the correct velocity to use in estimating the long-term suitability of a particular micro-habitat for the snail.

Other Snails

Most information available on snails concerns the bilharzia snail from the Caribbean Basin and Brazil, *Biomphalaria glabrata*. Only rudimentary field observations have been published for bilharzia snails from Africa, the Middle East, and Asia (Moore 1964). Those snails are generally smaller than *Biomphalaria glabrata*, but their general reactions to flowing water are similar. Exceptions to this are species of the amphibian snail *Oncomelania* in Asia, which is extremely small and has a thin streamlined shell that is probably affected very slightly by stream velocities.

6.1.2 Migration of Snails

Migration against Low Velocities

Observations in small irrigation schemes in Brazil indicated that low stream velocities are a strong stimulus to the upstream migration of bilharzia snails, and that the snails may travel upstream more than 1 m/day against stream velocities of around 0.10 m/s (Paulini 1963). Subsequent studies in a uniform concrete channel in Puerto Rico showed that the upstream migration could proceed as fast as 2 m/day at low stream velocities, but stream velocities up to 0.20 m/s reduced the migration to a standstill. At higher stream velocities, the snail population reacted with a downstream migration, travelling as far as 7 m/day when pushed by a current as high as 0.30 m/s.

Thus, under ideal conditions, one might find these small snails migrating as far upstream as 30 m/month, or between 300 and 400 m/year, and also migrating as far

downstream as 200 m/month or over 2 km/year. Flotation or dislodgement by the snail itself could carry them much further downstream, as much as 20 or 30 km/day. So, in an irrigation canal of uniform cross-section with steady flow, one might expect considerable population movement.

The studies in Brazil and Puerto Rico indicated that the upstream migration can be accelerated by the provision of food upstream, or it can be reduced by the presence of sub-lethal doses of toxic chemicals, which result in rapid dislodgement of the snails and their carriage downstream, even if the chemical dose is quite low.

Velocity Gradient and Snail Distribution

A 12-month field study conducted in two main irrigation canals in Puerto Rico (Guajataca Canal and Patillas Canal) illustrated the impact of migration against steady current on the stable distribution patterns of snail populations. It also showed the importance of the velocity gradient in influencing snail distributions in canals where the velocity gradually changes along the length of the canal. The study concerned two snail species: *Biomphalaria* and *Marisa*.

Snail populations and water velocities were monitored monthly. Fourteen stations were established in the Guajataca Canal and six in the Patillas Canal. At each sampling station, 100 m of canal was surveyed for snails by a person taking 100 sweeps with a wire-screen dipper while walking upstream in the canal (Figure 6.3). The snails were counted and measured but not returned to the canal. From the collection at each station, the largest snail and a random sample of 10 snails were measured to the nearest

Figure 6.3 Searching for snails during 1978 surveys of Patillas Irrigation Canal in Puerto Rico

millimetre to obtain a gross indication of snail sizes. At the two ends of the sampling station, the water velocity was measured with a small current meter.

Stable populations of the large ampullarid snail *Marisa cornuarietis* were found in both canals at almost every station during every survey. No bilharzia snails were found during the year of velocity measurements, but they had been present during previous surveys prior to the introduction of the ampullarid snail.

In the initial portion of the Guajataca Canal, Stations 1 to 6, the ampullarid snails were clearly influenced by the velocities, which were higher than those in other portions of this Canal or in the Patillas Canal. In the first part of the Guajataca Canal, the lowest velocities were 0.36 m/s at Station 1, gradually increasing to 0.94 m/s at Station 5, and then decreasing again in the downstream direction (Table 6.2). One would expect few snails at the station with the highest water velocities, and in fact only two ampullarid snails were found at Station 5 during the entire year of surveys (Table 6.3). Unexpected, however, were the 2500 snails found at Station 3, where the velocities were 0.66 m/s, a fairly rapid flow for snail habitats. At upstream and downstream stations with lower velocities (Stations 1, 2, and 6), there were fewer snails, despite the general preference of this ampullarid snail for quiet waters (Figure 6.4). In contrast, the size-distribution of the snails was fairly logical, with the largest snails found at the stations with the lowest velocities.

Table 6.2 Long-term average velocities in m/s in the Guajataca Irrigation Canal in Puerto Rico, 1979-1980

Station	Mean velocity (m/s)
1	0.36
2	0.56
3	0.66
4	0.77
5	0.94
6	0.49
7	0.36
8	0.28
9	0.40
10	0.42
11	0.34
12	0.40
13	0.36
14	0.35

Table 6.3 Numbers of *Marisa cornuarietis* in initial portion of the Guajataca Irrigation Canal in Puerto Rico (result of 13 dippings spread over period February 1979 to February 1980)

	Station					
	1	2	3	4	5	6
Totals	35	194	2502	451	2	103

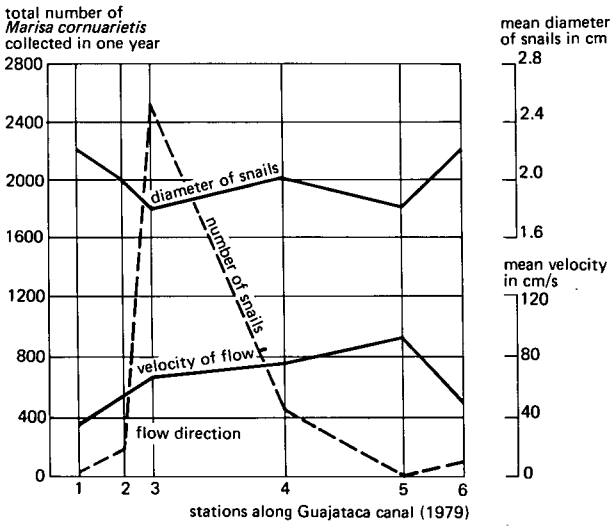

Figure 6.4 Relation between numbers of ampullarid snail *Marisa cornuarietis* and velocity gradients in Guajataca Irrigation Canal in Puerto Rico, 1979.

The clumping of the snails at Station 3 illustrates a common characteristic of aquatic snails noted in previous laboratory and field studies: their tendency to 'march' against the current. This peculiar reaction makes it appear that the snails are moving in formation, because they all move at the same speed. In the fast flow of the Guajataca Canal, the *Marisa* were almost all pointed upstream, slowly marching in formation against the current. The bilharzia snail *Biomphalaria glabrata* does the same. Marching as fast as 25 m/day was recorded for one snail in a short laboratory study.

The downstream variation in stream velocity observed in the first six stations of the Guajataca Canal caused the *Marisa* to march rapidly at the stations with fast flow, moving out of Stations 4 and 5 towards Station 3. Above Station 3, however, the velocity dropped abruptly, so low that apparently it no longer stimulated the snails to march. This caused the faster-moving snails coming from the rear to pile up on those slowing down at Station 3.

The velocity at Station 3 was 0.66 m/s, indicating a fairly high threshold for the stimulation of marching in this snail. Laboratory studies on the bilharzia snail showed initiation of marching at water velocities of 0.05 or 0.10 m/s, and a maximum tolerable velocity of less than 60 cm/sec for canals of this size. Thus the Guajataca Canal was largely unsuitable for the bilharzia snail because of the fast flow.

The Patillas Canal, which also had the highest velocities in its downstream portion, had lower and more tolerable annual mean velocities than did the Guajataca Canal. In the Patillas Canal, the resulting upstream aggregation one would expect due to marching was in fact observed in previous snail surveys. In a 1957 study, 85 per cent of the bilharzia snails were found at the first two stations.

From these examples, it can be seen that the velocity gradient in an irrigation canal is an important determinant in the location of snail habitats, and should be taken into consideration when a system is being designed, especially if housing is being located near the canals.

Inter-System Migration and Introduction from Outside

The migration of snails within a canal system must also be seen in the light of inter-system migration, or of their introduction from outside habitats. The First Law of Snail Control is: 'The snails will always move in', because most new irrigation schemes in endemic areas are invaded by bilharzia snails within a year or two.

The new Rahad Irrigation Scheme inaugurated in central Sudan in 1978 was populated by *Bulinus truncatus* in January 1980 and soon after by *Biomphalaria pfeifferi*. Such introductions are commonplace in new schemes, and isolating the schemes with physical or mechanical barriers seems unable to overcome the weight of the First Law.

And like unto it is the Second Law of Snail Control: 'The snails always come back.' Attempts to eradicate snails by applying toxic chemicals seldom remain effective in irrigation schemes for more than a year, even when enormous overdoses of chemicals are used in relatively confined systems. Chemical applications in Fayoum Province of Egypt have been going on for over 20 years at a cost of over $100,000 a year, and the snails always come back.

The mechanisms by which the snails invade such systems are not clearly documented, but must include flotation or passive transport on objects floating down from an upstream reservoir, passive transport in mud attached to wandering birds or cattle, and, in areas like the Sahel, continuous dispersion along nomad trails where drinking water, carried in goatskin bags, is replenished at many water sources along the route. The snails are small and, under favourable conditions of high humidity, can survive desiccation for long periods. Many means of passage can thus be imagined, and one should not contemplate the exclusion or eradication of snails from irrigation schemes.

6.2 Mosquitoes – Basic Concepts

6.2.1 Flow Velocities and Water-Level Fluctuations

The aquatic stages of stream-breeding mosquitoes – the eggs, larvae, and pupae – can be destroyed or dislodged by the water flow. The design figure used for devices that flush the mosquitoes in natural streams in Asia and the Caribbean islands is 0.40 to 0.50 m/s when a short flushing wave is periodically pulsed down a stream habitat by intermittent discharges. For the design of steady flow in irrigation canals, this figure is much higher than necessary because flow above 0.10 m/s is adequate to dislodge larvae. These figures are quite approximate, however, because the precise role of water velocities in dislodging mosquito larvae has not been carefully studied.

Although the use of flushing siphons has generally been intended to wash away the mosquito larvae immediately downstream, it is quite possible that the rise and fall of the flood wave is as important as its downstream velocity. The delicate eggs

of the mosquito are damaged as they are thrown up and stranded on the stream banks, rocks, or the stems of grasses and reeds in the stream. An interval of only a few hours between flushes is enough to ensure complete drying of the eggs and their consequent death. For this reason, daily flushing during the mosquito-breeding season is quite effective in controlling larvae production.

The impact of water velocity on mosquitoes deserves further research because there is some indication that increased levels of turbidity also have a detrimental effect on some malaria mosquito species.

6.3 Blackflies – Basic Concepts

6.3.1 Flow Velocities

Eggs, larvae, and pupae of the blackfly *Simulium damnosum* are typically found attached to submerged trailing grasses, but may also occur on rocks, concrete, wood, or metal structures in irrigation canals over which fast-flowing water is passing. The eggs are laid slightly above or below the waterline, usually in 'white-water' reaches where velocities exceed 0.80 m/s but are less than 3.00 m/s, and where high rates of flow and oxygenation are occurring.

In irrigation schemes of central Sudan, the blackflies are occasionally found along the main canals at control structures. Here, however, the seasonal breeding is governed by climate, not velocities, and can occur at velocities as low as 0.50 m/s. The flies are more commonly found at the cataracts on the main Nile or in the forested zones of southern Sudan.

In West Africa, breeding seems to be most common at 1.00 to 1.50 m/s, and this is also generally true for the Congo River Basin. In Central America, blackflies have not been studied intensively and such data are not available for the American species.

6.4 Siltation and Aquatic Vegetation in Canals

The problems of sedimentation and aquatic weeds are familiar to engineers operating irrigation schemes in the tropics, but deserve careful attention by the design engineer. Experience with weed-control programs is leading to a more complete understanding of the problem, which should be examined in detail when designs are being made.

Older irrigation schemes often develop problems with siltation and aquatic vegetation in their canals, causing them to become favourable habitats for insects and snails. Even if a system was properly designed and initially operated with little or no siltation or vegetation, any expansion or intensification of irrigation beyond the original plan often leads to heavier irrigation flows during seasons when quantities of suspended sediments are higher, and to longer seasons of irrigation, thus giving vegetation time to develop larger standing crops.

In canals originally operated 6 or 7 months of the year, the 5 or 6 dry months often provided ample opportunity for the natural control of aquatic weeds through desiccation, and also made the removal of weeds and silt quite easy. If this schedule is eventually supplanted by 11 or 12 months of irrigation, the weed growth becomes extremely

dense, and can, in itself, accelerate siltation. The siltation increases because of larger flows for longer periods, especially when water requirements grow so large that it is not possible to reduce flows during the season of highly turbid water. Increased siltation can also stimulate weed growth by high nutrient levels in the sediment, leading to a further acceleration in sedimentation.

These consequences of longer irrigation seasons should be carefully evaluated when existing schemes are being considered for expansion or intensification.

6.4.1 Snails

The growth of aquatic weeds causes an increase in the numbers of certain species of bilharzia snails. *Biomphalaria*, the snail genus that transmits intestinal bilharzia, produces eggs in direct proportion to the amount of vegetation in the habitat. *Bulinus*, the snail that transmits urinary bilharzia, is not so clearly linked to the density of vegetation, but is strongly associated geographically with the presence of certain types of weeds. Thus the portions of canals infested by weeds will also be infested by bilharzia snails and, for *Biomphalaria*, the months when the weed infestations are the most dense will also be the months when large numbers of snails are found.

6.4.2 Mosquitoes

Many malaria mosquitoes such as *Anopheles arabiensis*, the vector of malaria in central Sudan, breed in stagnant or slow-moving water of irrigation and drainage ditches in the absence of emergent vegetation, but do not breed very well when there is flow or tall emergent vegetation. Thus the mosquito populations do not breed in the minor canals as the snails do, but are found in small field ditches and drains that contain stagnant water for long periods. Control in these ditches is accomplished more effectively by drying than by weed control.

6.4.3 Blackflies

Tropical blackflies often deposit their eggs on vegetation that overhangs canals, laying the eggs above the waterline if spray maintains high humidity, and also slightly below the waterline. Although vegetation is not the only site they use for egg-laying, its removal can have a significant impact on blackfly reproduction.

6.5 Travel Ranges

Estimating or predicting the patterns and intensities of disease transmission in a proposed irrigation scheme can be improved if one knows the travel ranges of the aquatic organism involved. If malaria mosquitoes have a normal flight range of 4 km and a large village is planned 500 m away from a major drainage canal, special precautions will be required that would not be necessary if the village were to be placed 5 km from the canal.

Travel ranges have been estimated for the active movement of aquatic organisms in the absence of water currents or wind. Thus the passive movement expected from the planned water velocities or prevailing wind speeds must be added vectorially to the active movement of the organisms in the irrigation system under consideration.

6.5.1 Schistosomes

The miracidia of the parasitic schistosome hatch from the eggs when they reach fresh water, and can swim for about half a day while they are searching for a suitable snail to penetrate (Chu et al. 1966). The loss of a miracidium's penetrating ability occurs sometime before it loses visible signs of life. Field estimates show that the organism's horizontal limit for penetrating snails is about 10 to 20 m from its point of hatching.

The cercaria of the schistosome are very active and seek a human or mammal as host as soon as they leave the snail, usually around midday. They have a short life-span of less than a day, and lose their ability to penetrate human skin even quicker. Their searching motion does not seem to have the horizontal component found in that of the miracidia, but instead seems to be largely vertical, consisting of periodic rises to the surface, followed by a slow return to the bottom. Thus their horizontal travel range is smaller than that of the miracidia and seems to be a maximum of about 2 to 3 m.

6.5.2 Snails

The speed at which snails migrate with or against the current depends on the size of the snails, the shape of their shell, and the velocity of the current, as was described in Section 6.1.2. For the small bilharzia snails, the daily migration rate against the current is about 1 m/day at water velocities of 0.10 m/s, while downstream migration occurs at higher velocities near 0.30 m/s, or about 7 m/day. Estimating the active life period at 100 days, this could mean a maximum travel range of 100 m upstream or 700 m downstream.

6.5.3 Mosquitoes

The normal flight range of mosquitoes is small (1 to 5 km). They avoid being dispersed by strong winds, perhaps by staying in protected regions near the ground. But, under the influence of wind, their maximum travel range during life (5 to 10 days) can reach 10 to 30 km (Garett-Jones 1957; Gillies 1961).

6.5.4 Blackflies

For *Simulium damnosum* in savannas, the range can be 80 km, but distances of up to 400 km have been recorded.

6.6 Other Habitat Characteristics

In addition to flow velocity and vegetation, the main environmental factors affecting the distribution and dynamics of snails and insects are water temperature and water clarity. Water chemistry is not usually a factor in the distribution of snails or insects in irrigation schemes because water suitable for irrigation is also generally suitable for aquatic life. Water temperature is undoubtedly the main determinant of biological activity and has an important bearing on seasonal changes in survival and reproduction rates.

6.6.1 High and Low Limits of Temperature

The molluscan stages of schistosomes, aquatic snails, and the aquatic stages of mosquitoes and blackflies are directly affected by water temperatures. For schistosomes, the normal development time is retarded in cold water, slowing propagation until it ceases entirely at temperatures near freezing.

Data from Iran about the effect of seasonal changes in water temperatures on the incubation period of bilharzia infection in *Bulinus truncatus* snails shows that the cercarial development of *Schistosoma haematobium* lies at around 25 days for a water temperature of around 25 °C, while 100 days are needed at a temperature of about 10 °C. Snail reproduction accelerates to a maximum at around 25 °C, with upper and lower limits near 20 °C and 30 °C.

The larval stages of mosquito development are also retarded by colder water temperatures, with very rapid development occurring at the normal temperatures of tropical surface waters.

The larval stages of blackflies show a similar response to water temperature.

6.6.2 Water Clarity

Probably because of its influence on the development of microscopic algae as a food source, the clarity of water exerts a controlling effect on the suitability of canals and drains for snails and insect larvae. In irrigation systems along the Blue Nile in the Sudan, the rainy season of June to September is a period of high water turbidity due to silt erosion with runoff from the rains, and a near disappearance of bilharzia snails. This effect is probably magnified by the high water temperatures occurring at this time, which are also partly due to the heating of the water from solar radiation absorbed by the turbid particles.

The habitat requirements of mosquitoes also include the effect of sunlight and shade, perhaps also partly an indication of the basic amount of microscopic vegetation available for food.

6.6.3 Salinity

Although some information is available on the effect of sea water on snail and mos-

quito breeding, it is unlikely that salt concentrations in irrigation systems will reach high enough levels to have any appreciable effect on either snails or mosquitoes.

Bilharzia snails can live in 25 per cent sea water, and malaria mosquitoes can breed in nearly 100 per cent sea water.

The salinity of irrigation water in schemes may influence which species of mosquito is the malaria vector, but it would not suppress mosquito breeding to any significant extent because most mosquitoes can tolerate more salinity than agricultural crops can.

6.7 Human Activities related to Water-Associated Diseases

In tropical irrigation schemes, there are three human activities that strongly affect the transmission of water-associated diseases:

- Human contact with irrigation and drainage water containing bilharzia snails (Hustings 1983);
- Human contamination of those same waters with faeces and urine;
- Sleeping in areas unprotected from mosquitoes during the seasons of malaria transmission.

6.7.1 Water Contact

Water contact is often related to the occupations of adults, and to the recreation of young boys. Non-occupational water contact, water contamination, and sleeping are often ingrained patterns of behaviour of entire populations – habits that would require generations to change. Furthermore, they are habits that have developed in response to environmental and social conditions. Before such habits could be changed, alternative sanitary facilities and sleeping quarters would have to be provided. (For more information on these subjects, see Chapter 9).

The frequency, duration, and range of human contact with snail-infested waters have been studied in various tropical irrigation schemes. They are related to the age, sex, and occupation of the persons, as well as to the time of day and season of the year (Tables 6.4 and 6.5). Bilharzia prevalence in the Nile Delta is usually higher in males than in females, and is closely associated with irrigated farming, fishing, and boating.

Prevalence usually increases rapidly with age, up to the end of adolescence when it reaches a peak, followed by a rapid decrease with age in urinary bilharzia and a slower decrease in the intestinal form.

Studies along the Nile River in Egypt have shown the relationship between variations in water-contact habits and variations in disease. The travel ranges of people in relation to the canals and other water bodies near their communities play a role (Kloos et al. 1983).

From these and other data, it can be estimated that the range of travel varies with age, sex, and occupation, at least in communities where the only form of transport is by animals (Table 6.6).

Table 6.4 Prevalence of bilharzia by occupation and sex in the Nile Delta, 1960

Occupation	Prevalence
Farmers and farm labourers	
Male	53%
Female	43%
All other occupations	
Male	25%
Female	25%
Total	25%

Table 6.5 Prevalence of bilharzia by occupation in Nile Delta, 1960

Occupation	Prevalence
Farmer	51%
Farm labourer	42%
Landowner	36%
Fisherman	60%
Boatman	52%
Water carrier and washerwoman	48%
Domestic servant	32%
Skilled labourer	31%
Other manual	19%
Clerical	21%
Professional	35%
None or other	32%
Total	36%

Such tables can be prepared for typical communities through the simple questioning of knowledgeable persons. More precise observations linking the travel ranges and water-contact patterns are time-consuming and expensive, but can be done when decisions are being made about large irrigation schemes. Whatever information is available, it will be useful in understanding and even estimating the prevalence of infection to be expected in an agricultural community, including variations by location, age, sex, occupation, and season.

Mapping human communities and travel ranges for the various population groups can broadly indicate the potential transmission of bilharzia in irrigation schemes under design. These maps can be coupled with maps of the expected snail distributions and potential travel ranges of schistosome miracidia and cercariae, thus giving the expected location and intensity of parasite transmission.

Table 6.6 Estimated range of travel away from household by sub-groups within agricultural communities

Age group	Sex	Occupation	Normal daily travel range in kilometres	Maximum monthly travel range in kilometres
Infants and pre-schoolers			0.1	0.1
School-aged			1	2
Adolescents	M		4	8
	F		2	4
Young adults	M		5	10
	F		1	5
Married adults	M	Farmers	5	10
	M	Others	8	10
	F		1	5
Elderly			2	4

6.7.2 Human Contamination of Water

Human contamination of snail-infested waters through urine or faeces is necessary for the continued transmission of the schistosome parasite. Because of the private nature of such contamination, however, far fewer data from observations are available, in comparison with data on water contact. Generally, it is assumed that the daily patterns of defecation are fairly regular – near the person's household and in secluded places. Schistosome eggs probably enter the water when people use the water to wash themselves after defecation, although perhaps direct defecation into the water occurs occasionally. Eggs may also hatch from faeces deposited near the water if the water level rises and submerges the faeces.

Contamination of water with eggs of the urinary form of bilharzia is probably much more common and geographically diffuse, being caused primarily by small boys urinating into the water from canal banks or entering the water to swim.

The only ways to break the continued transmission are to improve the people's hygienic behaviour and to provide them with certain basic needs: drinking water, washing and bathing facilities, sanitation. (For further details, see Chapter 9.)

6.7.3 Sleeping Habits

Malaria transmission is facilitated when large numbers of people sleep outdoors during hot weather, or sleep in houses that have no protection against invading mosquitoes. Malaria mosquitoes usually bite at night and although they may have preferences for indoor or outdoor biting, a basic factor to be evaluated in analyzing transmission is whether the people sleep in protected areas.

Sleeping habits have been studied in malarious areas. They are usually related to night-time temperatures, climatic conditions, and types of housing. A numerical definition of these habits can assist in locating housing within irrigation schemes so as to minimize health risks. The necessary information can be obtained by simple house-to-house questionnaires or by observations.

6.8 Drainage Systems

Malaria mosquitoes, tropical blackflies, and bilharzia snails can all be controlled with efficient drainage because they all depend on water to complete their life cycles. The insects must pass through a short aquatic phase, starting with the deposition of the eggs. In Asia, the bilharzia snails are amphibious, spending a short time out of water during their immature stage; in the rest of the tropics, the snails spend their entire life in the water. Adult snails, however, can resist drying for extreme periods, especially those species living near semi-desert areas. So, control of these insects and snails requires data on the time that the various species can withstand dryness (Chu et al. 1967). For blackflies and mosquitoes, such times are relatively short because the immature stages must be completed within a few weeks or less, but some of the snails can survive for several months. The survival period is also affected by air temperatures and humidity in the micro-climate, and, for the snails, by predation from ants, rodents, birds, and animals.

Drainage is most effective against malaria mosquitoes because their favourite habitats are swamps or flooded areas amenable to being drained. Blackflies do not usually breed in such areas and snails are usually too resistant to drying. For snails, drainage can suppress population increases and can limit the geographical extent of snail populations and the sites of human contact with water. In swampy areas subject to annual flooding, however, it is extremely difficult to eradicate snail populations by drainage.

6.8.1 Drainage System Design Time (to control mosquito breeding)

The design time for drainage systems aimed at controlling the breeding of mosquitoes is the time between the deposition of eggs on the water surface and the emergence of the flying adult form. This covers the developmental times for the eggs, larvae, and pupae. The maturation time is a direct function of water temperature and is generally about 1 week for temperatures of 30 °C to 32 °C, and 2 weeks for 20 °C to 25 °C. Recommended times for the design of malaria-control drainage have been given as 2 weeks, with 1 week recommended for *Culex* and other mosquitoes that transmit filariasis.

The recommended times have not been precisely established because such an analysis would also require the inclusion of the unfavourable effect of high temperatures on survival rates. Very low survival occurs at the higher temperatures when maturation occurs so rapidly. As a safer rule, to cover all mosquitoes in the tropics, it might be wise to use 1 week as the time required for water removal.

6.8.2 Half-Life of Survival Time (for snail control)

If bilharzia snails are to be controlled by drainage, the approach is quite different from that for mosquitoes. Rapid drying is helpful but, in irrigation schemes, the critical feature in the design is the time before re-flooding or re-submergence occurs. Long dry periods will kill a large fraction of the adult snails and all of the eggs and juveniles. If drying occurs periodically during the normal egg-laying season – which is governed by water temperatures, water turbidity, and the availability of vegetation as food – the overall decrease in egg-laying and the increased death rates of adults may be enough to depress or even eliminate the snail population, at least in areas where breeding is restricted to only a short portion of the year.

The death of snails due to drying should be thought of in terms of 'half-life' of survival for each snail species and for given climatic conditions. The half-life is the time of dryness in days for half of the population to survive. It depends primarily on the speed of drying and on the micro-climate during the dry period. Thus, in Puerto Rico, the half-life of *Biomphalaria glabrata* was only 15 days if stranded because of a sudden drop in water level, but increased to 160 days if the drop in water level was slow because of natural evaporation and filtration (Table 6.7).

Table 6.7 Survival of bilharzia snails when dried, in terms of half-life in weeks, for rapid drying and for slow drying by evaporation

Snail species	Country	Half-life in weeks for survival of 50% of original population	
		Rapid drying	Slow drying
Biomphalaria glabrata	Puerto Rico	2	23
	Brazil		
	– Paulista		12
	– Olinda		3 to 5
Biomphalaria alexandrina	Egypt		5 to 10
Bulinus globosus	Zimbabwe	2	4
Bulinus truncatus	Iran	2	20 to 40
Bulinus truncatus rohlfsi	Ghana	1	

Unless the drained areas receive water only once a year through normal rains, the snail populations will usually revive in sufficient numbers to replenish the habitat. Estimating the success of such populations in surviving requires considerable data

on the snails' population dynamics. These data can be analyzed by computer simulations.

6.9 Guidelines for the Design of Irrigation Systems

Although health and other specialists tend to notice only their own professional specialty, and perhaps one disease may seem to stand out against others in a given irrigation project, nonetheless, in such tropical situations, there are usually two or three other water-associated diseases being transmitted at the same time. All of these diseases should be dealt with in one program if the measures are to be economically justifiable and operationally practical.

When such measures as drainage, water management, canal maintenance, and crop rotation are introduced to control snails, they may have concomittant impacts on mosquitoes or other disease vectors. More than likely, the careful planning of such environmental modifications, if coupled with other public-health measures aimed at the diseases, can result in multiple benefits.

6.9.1 Design Procedure (The 10-Steps Approach)

For planners and engineers in the process of designing irrigation and drainage systems for areas where the risk of disease is severe, a careful and special approach is needed. Designing such systems for disease prevention can involve the systems' most costly measures, i.e. those related to the design velocities. Increases in canal velocity may lead to a loss in irrigated acreage, and to significant changes in the costs and benefits of the system. Nevertheless, where health is an issue, the approach can be applied to the planning of any water-resources development.

The approach we recommend involves ten steps, which should lead to a rational combination of preventive design measures and post-construction control programs. The essence of this approach is the recognition, early in the planning stages, of both the health and the agricultural costs of canal and drain design.

The procedure requires the planner's acceptance of the health goal of 'No additional disease due to the irrigation system'. It also requires an ability to estimate the increased disease transmission under a specified system design and an ability to estimate the cost of post-construction operational programs to control that transmission. These are specialized requirements that can perhaps be fulfilled in qualitative terms for small irrigation schemes, but merit detailed quantitative analyses for large schemes.

The ten steps of the recommended planning procedure are:

1) Make a First Design of the canal and drain system, based strictly on agricultural considerations, but giving special attention to good drainage and to the control of silt and aquatic weeds.
2) With the normal procedures, estimate the annual costs and benefits of the First-Design system, including the costs of operation and maintenance for silt and weed removal.
3) Accept the health goal of 'No additional disease due to the system'. This means

that the prevalence of disease prior to construction should not increase after the irrigation scheme is in operation. In some cases, a more ambitious goal might be set, that of lowering the final prevalence to an even more healthy level, lower than the initial prevalence.

4) Estimate the increase in prevalence to be expected after the First Design is in full operation.
5) Plan an operational control program and estimate the annual cost of bringing the disease prevalence down to the accepted level.
6) Using the annual cost of the control program as an upper limit, redesign the canals and drains to decrease disease transmission by one or more Alternative Designs that may include various combinations of:
   - Higher flow velocities;
   - Improved longitudinal velocity gradients, perhaps by the elimination of night storage in canals;
   - Intermittent drying of canals and drains;
   - Changes in crops or in irrigation practices to allow periodic drying of canals, ditches, and fields;
   - Increased capacity of drainage system;
   - Increased silt and weed removal;
   - Flushing;
   - Fluctuations of pond levels.
7) Estimate disease prevalences that may result from each of the Alternative Designs.
8) For each of the Alternative Designs, estimate the costs of disease-control programs to bring disease prevalence back down to the original level.
9) Again, for each of the Alternative Designs, estimate the additional costs of construction, operation, and maintenance, as well as losses in agricultural productivity due to smaller crop areas and lower production.
10) Compare the annual costs for each of the Alternative Designs with the costs for the First Design, and select the optimum design, reflecting both health and agricultural concerns (Table 6.8).

The design options listed in Step 6 will be further discussed in subsequent sections of this chapter and in following chapters.

6.9.2 Recommended Velocities for Canals

Of all the organisms that play a role in transmitting tropical diseases in irrigation systems, the ones most affected by the design velocity selected for the canals will be the bilharzia snails.

The precise velocities needed to flush away mosquito larvae have not been established, although early investigators recommended 0.40 m/s. Theoretically, the larvae cannot resist any velocity at all, but in fact they remain in the protected, weedy edge of slowly flowing channels, protected from hydraulic dislodgement by the weeds. It is clear that the mosquito larvae cannot resist velocities anywhere near as high as those tolerated by the bilharzia snails.

Data on dislodging velocities for snails have been established for a few species, and,

Table 6.8. Fictitious example of matrix for comparing annual costs of Alternative Designs with First Design of canal and drain network in proposed irrigation system, giving consideration to health as well as to agricultural costs and benefits.
Goal: No additional disease – prevalence remains at original level (e.g. a low prevalence of 12%).
Fictitious annual costs are given in millions of U.S. dollars

Design alternatives	First Design	Alt. 1	Alt. 2
Project cost for First Design	10		
New prevalence of disease without program for disease control	75%	50%	25%
Cost of post-construction program for disease control	6	2	1
Additional irrigation system costs beyond the costs for First Design	0	1	2
Cost of lost agricultural productivity compared with First Design	0	1	3
Total cost for health and agricultural components	16	14*	16

* Alternative 1 at $14 million is thus cheaper than the First Design, which costs only $10 million for the irrigation system, but which requires a subsequent health expenditure of $6 million

for *Biomphalaria glabrata*, the projections made for trapezoidal, well-maintained canals have been confirmed in the field as was discussed in Section 6.1.1. The maximum velocities that the snails can withstand are roughly 79 to 80 cm/sec for large canals and 60 cm/sec for small canals (Table 6.1).

The dislodging velocities required for snail control are within the velocities tolerated by blackflies, and are much lower than the maximum velocities tolerated by the flies.

The suitability of extensive canal systems as snail habitats should be analyzed not only in terms of mean velocities but also in terms of longitudinal velocity profiles, especially for those canals in which the velocities are significantly less than 60 or 70 cm/sec and can thus easily be populated by snails. Some canal systems, especially those with night-storage provisions in their secondary or tertiary canals, have a rapidly dropping velocity gradient in the downstream direction, making the ends of these storage canals ideal places for weeds and snails. Health problems are often compounded by camps or small villages located on canal banks.

As was discussed in Section 6.1.2, snails in canals with low but noticeable flow tend to point into the flow, the entire colony moving upstream in a parallel, concerted migration, which gives the impression that they are 'marching' in formation. This marching tendency can be utilized to control the snails, even when the water velocities cannot be raised high enough to dislodge them. A velocity gradient increasing in the downstream direction would cause the snails to congregate at the upstream end, where it would be easy to kill them with single applications of chemicals. This might be occurring in such 'flow-through' systems as the Fayoum Canal in central Egypt, where applications of chemicals from upstream have been unusually effective. In 'dead-end'

canal systems such as the Gezira Canals in the Sudan, however, the velocity gradient is in the wrong direction, decreasing downstream. Thus the snails accumulate in the lower reaches and ends of the minor canals, and are extremely difficult to reach with chemicals applied at the upstream end.

The snails' marching tendency could be put to other uses, such as the creation of velocity barriers in the canals at places near human settlements or subject to frequent water contact and contamination by people. The snails might be induced to migrate above these points and perhaps avoid being contaminated and infected with the schistosomes. It would be well for irrigation engineers to be aware that snails are marching in their canals.

It is particularly important to examine the canal velocities in those reaches that are less than 2 km from human settlements. If the large majority of bilharzia transmission is taking place in villages near such reaches, one could consider taking special measures in those reaches, especially if the bilharzia is the intestinal form.

6.9.3 Canal Maintenance

Infrequent cleaning of canals leads to flatter hydraulic gradients. As the canals fill with sediment, their hydraulic radius decreases, and the resistance to flow from large aquatic vegetation increases, all causing the velocities to drop below the original design values. The silt encourages vegetation, which also provides food, shelter, and habitat sites for insects and snails (Chu et al. 1967; van Schayck 1983). Thus a program for silt removal and vegetation clearing is often a necessity for health as well as for agriculture. Such programs are expensive, but if the irrigation water contains large amounts of suspended solids, they should be contemplated from the planning stage onwards.

All groups of aquatic plants (emergent, submerged, floating, algae) can produce enormously, often occupying far larger surfaces than terrestrial plants (van Zon 1986).

Aquatic plants also have points in their favour. They are, in fact, indispensable, but it is always the quantity that causes trouble. For fish, plant material is vital; it provides a hiding-place from predator birds, acts as substrate for food organisms, and serves as a spawning place. Emergent plants can prevent erosion, especially on sandy banks and slopes.

But, as remarked, it is the quantity that causes trouble. Quantities are increased by light and nutrition, or by introducing a species in a new place where natural mechanisms to control its growth are absent. A deep canal will decrease the amount of submerged weeds because light does not penetrate far in most waters. The effect of more nutrients, called eutrophication, has to be controlled by eliminating the nutrient sources (e.g. uncontrolled drainage from heavily fertilized farm land). High phoshate and nitrate levels are particularly troublesome.

The Management of Aquatic Vegetation

Aquatic weed management has to be flexible and must involve many different methods that can be used when other methods fail or when other water functions are added to the existing ones (van Zon 1986).

There are three methods of combatting aquatic weeds: chemical, mechanical, and biological. These methods can have a direct impact on vector control, because certain herbicides are snail killers at the same time, and, more importantly, have an indirect impact, because there is a definite relationship between aquatic vegetation and vector habitat.

Chemical Control

Many countries forbid the use of herbicides in water because of their harmful side effects, such as:

- Toxicity for water organisms other than plants;
- Accumulation and persistence. Some compounds stay active for a prolonged period in the water or in aquatic organisms. In food chains, these compounds can accumulate and reach high concentrations;
- Influence on the biotope of aquatic organisms;
- Selectivity of herbicides. In floating plants (e.g. water-hyacinth), control leads to more light in the water and more growth of submerged species.

No particular herbicides will be mentioned, except for those that have molluscicidal or insecticidal properties as well.

One of these is acrolein (aqualin). The compound is primarily a herbicide, so its application as a molluscicide is economical in irrigation schemes where there is a need to kill submerged aquatic weeds. It is molluscicidal and ovicidal at herbicidal concentrations. Its effectiveness has been demonstrated in the laboratory, and in field operations in Puerto Rico, Egypt, Sudan, and Tanzania. It is very poisonous, but it is relatively cheap and decomposes within a few days.

Further, there are Paraquat (Gramoxone) and Diquat (Reglone). Both these herbicides are effective against adults and eggs of planorbid snails, at 4 to 6 ppm for 24 hours of exposure.

There are also the Carbamates. These compounds are primarily insecticides. At least three of them – Rhodiacid, Sevin, and Zeetran (Ziram) – have been tested as molluscicides in a limited way. The compounds, especially Ziram (Zinc dimethyldithiocarbamate), have been recommended for use in those countries where it is desirable – in the same water body – to kill mosquito larvae (in malaria and filariasis control), Simulium larvae (in onchocerciasis control), and Cyclops (against Guinea worm infection). They are not toxic to fish but are relatively toxic to mammals.

Mechanical Control

In general, there are two types of mechanical control: the harvesting type and the non-harvesting type. Non-harvesting mechanical control is still commonly practised in the bigger canals of Western Europe. The method consists of bringing a mowing-boat into a canal so frequently that the mown material is small enough to float. This method is, in fact, a very objectionable one, for some of the same reasons as for persistent herbicides: the water is dead for a prolonged period, all the nutrients stay in the water, and the method is expensive, both in manpower and in energy.

Where it is possible to control aquatic weeds by a mechanical method (see Figure 6.5), it is one of the best methods, provided that the plant material is removed well

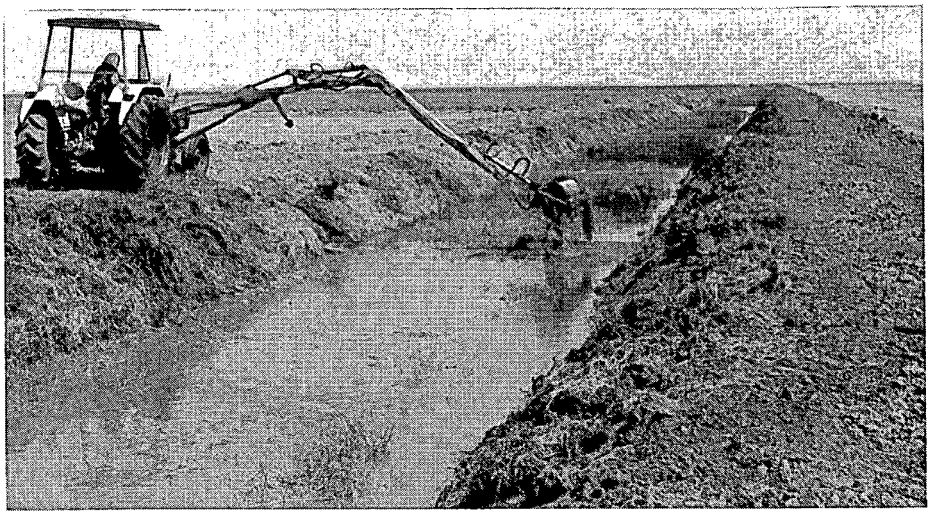

Figure 6.5 Light infestations of weeds can be removed by a rake attached to a small farm tractor. For efficient operation, the bank of the canal must first be dressed by grader or bulldozer

away from the water. If it is deposited along the bank, the decayed material will sooner or later flow back into the water, but if it is removed farther away, all the nutrients in the vegetation are taken away as well, which means that the following weed problem will, in principle, at least be no worse.

Of course, one cannot control weeds mechanically without thinking about the functions of the waterway concerned. It would not be wise to remove all plants during the breeding periods of important fish species, for instance, but in general this risk is not as great as with herbicides because mechanical control is normally done rather slowly and usually not with 100 per cent effectiveness.

(For the characteristics of power-driven tools for controlling canal weeds, see Sagardoy et al. 1982.)

An important disadvantage of mechanical control is its cost. Machines are expensive because they have to be designed and built for many different situations (there being no standardized ditches), and because they operate rather slowly. In countries where manpower is relatively cheap, mechanical weed control without self-propelling machines can sometimes be applied, but even this is expensive because of the great amount of manpower required and the high frequency with which the operations must be repeated.

(For the characteristics of hand tools for controlling canal vegetation, see Sagardoy et al. 1982.)

Manual cleaning (Figure 6.6) is easy to manage, but exposes the canal cleaners to heavy bilharzia infections if they are not protected. In the Americas and in Africa and the Middle East, the canal cleaners and other people obliged to work in the water are best protected by limiting the hours in which they are in the water to the early morning, before 10 a.m. Except in Asia, the schistosome parasites do not appear in the water in large numbers until about noon, and in the field they lose their ability

Figure 6.6 The manual removal of aquatic weeds in irrigation canals is usually the only economically feasible method in tropical countries

to infect people within 12 to 18 hours, so are no longer infective by the following morning. Men working in the water from sunrise until 10 a.m. are relatively safe from infection. If they are to continue working after 10 a.m., they should work from the banks, using long-handled tools and minimizing water contact. Such men with continuous occupational exposure should be examined yearly and, if found to be infected, should be treated with the appropriate drugs (Tameim et al. 1985).
The disadvantage of high costs can be eliminated if the weed material is sold or utilized as a soil additive in the form of organic fertilizer, or as animal feed, or as the basis for pulp, paper, fibre, or biogas.

A final remark on mechanical control concerns the control of excessive sedimentation (silting). Most of the machines used for removing silt (Sagardoy et al. 1982; Table – Machinery for canal cleaning) can do a certain amount of weed clearance.

Biological control

There are two main methods of biological control. The first is the use of selective agents (i.e. agents that attack one, or only a few, weed species). In general, the effect of this is often the same as that of a very selective herbicide: one weed species disappears and others take its place. This type of control is often applied where chemical control was not sufficiently successful or where continuous mechanical or chemical control was too expensive. This is especially so in the case of the water hyacinth, for which various methods of biological control are being studied to lower the costs of overall aquatic weed control, and also in the case of blue-green algae, which can hardly be controlled in any other way.

The other method of biological control uses polyphagous organisms. These can reduce the growth of all (or nearly all) the species present to an acceptable level, which is often the objective in aquatic weed control. They include the mammal *Trichechus* (sea-cow or manatee). Various experiments, especially in canals and lakes in Guyana, showed that these animals are not selective in their food choice and are very efficient: one adult consumes more than 200 pounds of wet vegetation a day. However, some important conditions for their use (e.g. high temperature and deep water) are not always fulfilled. Moreover, there is a lack of knowledge on sea-cow husbandry and breeding. A threat of their extinction already exists in their natural habitats. To collect more knowledge on the subject, the International Manatee Research Centre has been founded in Guyana, with tropical countries in Latin America, Africa, and Asia participating in it.

There are also birds and reptiles, but herbivorous fish are at present the most promising. Many species have been investigated, but most of them have one or more properties that make them of low practical value or of only local interest. This can be their selectivity, as in the American silver-dollar fish, which consumes tender shoots only, or in the Asian *Trichogaster pectoralis*, which almost exclusively feeds on duck weed. Some polyphagia have their disadvantages: the *Tilapia melanopleura*, for example, is an excellent weed controller, but is also an excellent predator of other fish (and of snails, for that matter).

The best practical possibilities now being offered are:

- The grass carp or white amur (*Ctenopharyngodon idella*) (van Schayck 1983). This is a non-selective herbivore from China, well adapted to both low and high temperatures. Natural breeding of this species is impossible in most parts of the world and, where breeding might be possible (which increases the risk of the fish becoming a pest), there are prospects in the use of sterile hybrids between the grass carp and the Israeli carp (*Cyprinus carpio*), and in the use of the monosex grass carp;
- *Hypophthalmichthys molitrix*, the silver carp. This is a plankton feeder, which also comes from the East Asian river systems. It has a practical value in lakes against blooms of green monocellular algae in East and Middle Europe, where it is being used at the moment on quite a large scale;
- The bighead (*Aristichthys nobilis*) is also a plankton feeder from East Asia. It is less selective in its feeding than the silver carp, consuming large quantities of zooplankton, but also blue-green algae, a big problem in eutrophic lakes all over the world;
- *Tilapia* species are found in all tropical waters. Some of them are useful for weed control in warmer countries, especially *T. mossambica* against green plankton blooms and *T. nilotica* against filamentous algae. *Tilapia* species are very fecund and are therefore only suitable where predators (or human consumers) can keep their numbers down.

A great deal of research has been done on insects, mites, and snails (e.g. on *Marisa cornuarietis* and *Pomacea australis*, which are not exclusively herbivorous). Work on fungi, bacteria, and viruses has only just started.

6.9.4 Lining

Step 6 of the 10-Steps Approach covers such issues as flow velocity and weed control – issues in which canal lining can play an important role. Canal lining, in general, can constitute an extremely valuable part of an irrigation system, and can, directly and indirectly, be a highly beneficial environmental-management measure for vector control.
The advantages of lining the entire cross-section of an irrigation canal are:

- It increases water velocities, thus preventing the flow from being sluggish, which favours snail and mosquito breeding;
- If properly maintained, it eliminates rooted growth and facilitates the removal of floating weeds, thus depriving mosquito eggs and larvae of protection and shelter and snails of their main source of food;
- As seepage is less, it reduces the need for drainage. Drains, which always represent an active or potential danger of mosquito and snail production, can be smaller and will be drier most of the time;
- It facilitates the control of residual vectors by water management and/or by the application of chemicals;
- Especially hard-surface linings have a direct effect on disease prevalence because they prohibit the snail vectors from sheltering in the soil against burning when the canal dries out. This only counts when the slope of the canal bottom is sufficient to empty the canal entirely.
- The lining of a canal is an incentive to use planks as bridges over the canals. The better the construction of the lining, the stronger this psychological effect will be;
- Lining the irrigation system is also an incentive for planning and constructing special bathing places for children and drinking places for cattle. These will have a favourable effect on the control of disease transmission. In residential areas, canal stretches should be lined and places selected for the construction of side slopes in the form of steps, which provide easy access for bathing and laundering. (In unlined canals, such concrete steps should also be considered, or else plank bridges close to the waterline.);
- Finally, lining can be regarded as a basic sanitary measure because it will increase the effectiveness of other vector-control measures (e.g. maintenance, molluscicidings) or will reduce their costs.

Other advantages of lining – of a more general kind, but certainly no less important – are:

- Reduced cross-section (smaller value of the roughness coefficient and larger flow velocity), with, as a consequence, lower costs for land acquisition, less loss of land, less earthwork, less evaporation, smaller dimensions of structures and bridges, and fewer structures;
- In flat areas, the opportunity to get a larger land area under command, while maintaining a certain minimum flow velocity;
- Less sedimentation and less growth of aquatic vegetation, which means reduced maintenance costs.

(For References on canal lining, see Kays 1977; Komya 1965; Kraatz 1977; Reuss 1980; Rosenfield and Bower 1979; South 1957; Unrau 1975; Xu 1983; Yokogawa 1972.)

6.9.5 Special Structures

People (and cattle) should be prevented from wading through water to cross a canal. Small, simple bridges (1.50 m wide or less, and thus too narrow for cars) should be installed at an appropriate density. For cattle crossings, such bridges should be provided with a sort of trap to guide the cattle to the bridge and with a closed parapet so that the cattle cannot see the water.

If canals are maintained by mowing boats or small dredgers, ramps will have to be constructed in the canal embankment for the easy release of equipment into the canals.

Provision should also be made for drinking places for cattle. Ramps can be used. A better solution is to select a site in an irrigation canal close to a drain, and to transport the water by siphon across the embankment and into a fenced pond. Excess water from the pond can be evacuated into the drain.

6.9.6 Intermittent Flow

Interrupting the flow in an irrigation canal has a severe impact on aquatic insects and snails. The continuous presence of water is one of the factors that make a canal a suitable habitat for these organisms. If the seasonal population dynamics of the insects and snails are understood, it may be possible to achieve control by the judicious drying of the canals for relatively short periods.

Aquatic snails require a month or two to grow – from hatching to maturity – before they are large enough to shed cercariae and transmit schistosomes to man. So, interrupting the flow every month or less would cause severe disruptions in bilharzia transmission. In canals that flow for two months, the length of dry period needed to control the snails depends on the season of the year and the rapidity and completeness of the drying.

If the canals do not drain well, or if the water is eliminated by evaporation instead of drainage, the 'dry' period will have little or no effect except to interrupt reproduction while the snails are out of the water. However, complete drainage of the water within a few days will cause high death rates, depending on the length of time that the canal is kept dry. Although these figures vary with snail species and location, rapid drying will, in general, cause 50 per cent mortality if maintained for 2 weeks and 75 per cent mortality if maintained for 1 month (see Table 6.7). If 1-month-long periods of no flow are scheduled quarterly in a theoretical canal where breeding occurs year-round, the net impact on the snail population would be to eliminate it very quickly.

The requirements for the control of malaria mosquitoes are quite different from those for snails. The mosquito larvae can develop in 1 or 2 weeks after the eggs are deposited in the water, so the flow would have to be interrupted after only one week, depending on the mosquito species and the water temperature. Mortality during the larval stages is very high, even with incomplete drying, so a dry period of a few days is sufficient to kill all of the larvae.

Blackfly larvae deposited on sills, weirs, or other solid objects in the canal are also susceptible to flow interruption or even a lowering of the water level in the canal. Their eggs require about 3 days for maturation, and can be killed with 1 day of drying. Blackfly lay their eggs on fixed objects at the surface of the water, so a lowering of 0.40 or 0.50 m is sufficient to expose and kill most eggs.

In temperate climates, a 4-day interruption in flow every 6 weeks has been found sufficient to control blackfly breeding, but in West Africa or Central America, the interruption would probably have to be repeated every 2 weeks (McMahon 1967).

6.9.7 Design and Operation of Drains

One of the earliest and most effective measures developed against mosquitoes was the rapid drainage of rain or flood waters – the free surface water being removed before the mosquito larvae had time to mature. Such drainage systems must operate repeatedly during the rainy season, whenever water impounds.

Control of bilharzia snails by drainage is much simpler and less costly. The surface waters should be removed in about 1 or 2 months, requiring a much smaller drainage system than that needed for mosquitoes.

Blackfly control is seldom accomplished by drainage because the flies do not breed in flooded areas but only in fast-flowing water.

Unfortunately, providing drains to empty flooded areas is not the end of the problem with mosquitoes and snails. They will quite often populate the drains themselves and such drainage systems, natural or engineered, can often become major transmission sites. So, clearing and maintaining the drains is an important part of the health effort. In general, the same guidelines can be used as those for the operation of canals for mosquito and snail control, but there is an additional option in cases where frequent dredging, weed removal, or drying is not possible: the use of periodic flushes through the drains to dislodge mosquito larvae. The method has been evaluated for snail control also, but it does not appear to be practical in drainage systems because of the high velocities that would be required.

6.9.8 Flushing

Section 6.2.1 described the use of flushing siphons to wash away mosquito larvae and explained how the rise and fall of the flood wave in downstream sections can throw mosquito eggs and larvae up onto stream banks, leaving them stranded.

In drains, too, periodic flushing can be used for mosquito control. Experience in natural streams has shown that flushing due to heavy rains is effective and that this can be simulated by periodically opening flashboards on small impoundments or by installing automatic siphons.

6.9.9 Fluctuation of Pond Levels

Pond-level fluctuations for the control of snails were discussed in Chapter 5.

6.10 Costs of Control Measures

In the process of combining preventive design measures with post-construction operational programs for disease control, an important step is estimating the costs of those programs. Engineers and planners usually have access to costs for components of proposed irrigation systems, but costs for disease-control programs are not so easily obtained. Since the latter costs are related to chemical control, to chemotherapy, and to the provision of safe water, it seems appropriate to deal with these costs in a Technical Note ('Costs of Control Measures: An Overview') after the other relevant chapters have been considered.

6.11 Practical Examples of Environmental Control of Diseases in Irrigation Systems

Annex 4 (Volume 2) presents four practical examples of the environmental control of malaria, bilharzia, and diarrhoeal diseases associated with water in irrigation schemes. The examples cover a broad range of geographical, agricultural, and social conditions. They include the large Gezira-Managil Irrigation Scheme in Central Sudan, a sugarcane scheme in Puerto Rico, the new Dez Pilot Irrigation Project in Iran, and sanitation works on the island of Java.

These examples demonstrate that considerable experience has been accumulated in recent years in clarifying the importance of environmental factors in the transmission of water-associated diseases. The need to include them in our book bears witness to the fact that designing irrigation schemes to prevent disease transmission is still in a primitive stage, despite the accumulated experience. It is still an art at present, not yet a science.

The examples also provide insights into how environmental factors can be put to use in the development of long-term and stable strategies for disease prevention and control. At another level, they re-assert the value of ecological approaches to disease control – approaches that were initially developed before World War Two. Ecological approaches were discarded with the discovery of the miracle pesticides and drugs, symbolized by DDT and penicillin. They are now being re-introduced and are of particular importance for design engineers, who can provide for them in new irrigation schemes at relatively low cost.

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7 Control Measures in Farm Water Management

7.1 Crops and Related Diseases

History gives clear examples of the relationship between crops and diseases: sugar cane and bilharzia; cotton and rice and malaria; Asian tea cultivation and endemic malaria and hookworm. In certain islands in the Caribbean, coffee cultivation has been associated with hookworm, and bananas with bilharzia. In the period before a vaccine for yellow fever became available, the disease was strongly connected with sugar cane, but in this case the mosquito vector was breeding in the clay evaporation pots used in the primitive processing of sugar.

Sugar cane is almost always irrigated (Figure 7.1) and is usually cultivated continuously. It is not surprising to find strong links between its production and bilharzia in such diverse places as Zimbabwe, Malagasy, and Puerto Rico. Volume 2, Annex 4, traces the slow increase in the prevalence of bilharzia in Puerto Rico, which clearly coincided with the introduction of irrigated sugar cane.

In East Africa, a combination of rice irrigation and pest-control measures to combat rice-stem borers produced a double peak in malaria mosquito populations. Rice irrigation had the effect of extending the natural malaria season, which had previously been confined to March-May, and adding an additional peak in November-December after the rice had been transplanted into shallow muddy pools, which became the breeding

Figure 7.1 Flowering sugar cane in Puerto Rico, a crop that requires about 2 m of irrigation water a year

sites for the local malaria vector, *A. gambiae*. A surge of mosquitoes was also touched off each time 'Dimecron' was sprayed to control the rice pests – the spray apparently killing off the natural predators and competitors of mosquito larvae.

A particularly severe mosquito problem has occurred in rice cultivation on flatlands in Portugal and China – in China especially in the floodplains along the Yangtze and the Yellow Rivers. Conventional control methods with pesticides were impractical, and eventually a method of intermittent irrigation was applied to help deal with the mosquito problem.

In almost all of these associations between crops and disease, water is the common factor. The seasonal water requirements for rice, sugar, and cotton are high, and irrigation systems able to provide large amounts of water for several months of the year are needed. Labour requirements are similarly high during one or more phases of the cultivation cycle. The large work forces required often live in the area temporarily, under conditions of minimal sanitation. As such, they provide a reservoir of infection from which transmission can start. Even if water requirements are modest, as they are for tea, coffee, and bananas, conditions favourable to the spread of disease can develop. A similar, if less obvious, disease hazard can occur when several crops are grown in rotation, giving rise to additional water requirements and extra labour inputs.

Sometimes, the physical requirements of a crop can coincide with the micro-climatic and soil conditions favoured by certain snail and insect species. Design criteria intended for certain crops may, in fact, have the adverse effect of providing excellent conditions for the transmission of diseases.

The well-documented associations between agricultural crops and diseases should serve as a warning to planning engineers that, if they are to avoid the creation of large-scale health problems, they need to give the matter careful attention.

7.2 Farm Water Management: Some Major Issues

7.2.1 The Tertiary Unit

Farm water management takes place inside the tertiary unit, which, in fact, forms the heart of an irrigation scheme (see Figure 1.5). Although the scheme authorities are generally responsible for the flow of water from its source to the tertiary offtake, when it passes through the tertiary offtake into the tertiary unit, it enters the domain of the farmers. The group of farmers within the tertiary unit are responsible for distributing the water through the tertiary and quaternary ditches to quaternary and sub-quaternary units, at which point each individual farmer assumes responsibility for applying the water to his fields.

A tertiary unit may contain many fields. Ensuring that each field receives an equitable share of irrigation water demands a collective effort on the part of the farmers. Farm water management, then, involves the distribution of irrigation water inside the tertiary unit, the application of water to the individual fields, and the drainage of any excess water.

7.2.2 Irrigation Efficiency

The question of irrigation efficiency should be taken very seriously. This emerged from the results of a world-wide inquiry into irrigation schemes (Bos and Nugteren 1974).

The inquiry defined the field application efficiency as the ratio between the quantity of water supplied at the field inlet and the quantity of water needed to maintain the soil moisture at the level required by the crop. Figure 7.2 provides some striking data on field application efficiencies.

The water distribution efficiency is defined as the efficiency of the canals or conduits in distributing the water from the conveyance network to the individual fields. The inquiry found these to range between 0.60 and 0.90.

Many factors play a role in the efficiency of irrigation. Figure 7.2 indicates some of these factors, but others (e.g. the depth of application, flow rate, farm size, scheme size) exert their influence.

Taking average figures for surface irrigation, which are an application efficiency of 0.60 and a distribution efficiency of 0.70, we find the tertiary unit efficiency to be $0.60 \cdot 0.70 = 0.42$. This means that, on the average, 58 per cent of the water delivered to the tertiary unit is not used by the crop. Such excess water has adverse effects, not only on productivity, but also on the environment, which becomes increasingly suitable for vector breeding.

Perhaps, in summarizing, we can say that anything that helps to promote a high irrigation efficiency also promotes vector control. This could be an apt slogan for planners, designers, operators, and farmers.

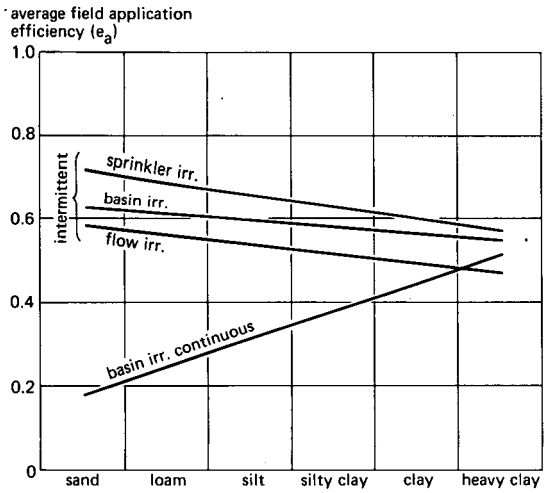

Figure 7.2 Average field application efficiencies for various irrigation methods as related to soil type (Bos and Nugteren 1974)

7.3 Crops and Husbandry Practices

7.3.1 'Wet' Crops (rice, in particular)

In the humid tropics, the food crop produced in the largest quantities is rice, and rice is the crop that occupies the largest planted area as well. While rice growing does not necessarily create a vector problem – and other crops and cultivation practices may also introduce health risks – the usual method of growing rice in bunded fields under water layers of 0.10 to 0.15 m provides an ideal environment for many vector species, with the consequent prevalence of vector-borne diseases. As rice production expands, often into areas where these diseases are endemic (particularly in Africa), attention needs to be drawn to the dangers that might arise and to the potential for systematic action to avoid these dangers.

Relationship between Crop Characteristics and Mosquito Production

The pattern of production of many, although not all, mosquito species is closely related to the growth pattern of the rice plants (WHO 1982; Trinh Ton That 1984). Traditional transplanting methods often favour the intensive breeding of *Anopheles* mosquitoes. The relationship between water depth, rice height, other environmental conditions, and mosquito breeding will vary somewhat from area to area because of differences in soil conditions, husbandry practices, and mosquito species. In general, however, it seems that after the rice is transplanted, larval populations are low. A few weeks later, as the rice plants grow, mosquito productivity is at its maximum. When the plants attain a height of between 60 and 100 cm, mosquito populations decline. Mosquito production either terminates when fields are drained prior to harvest, or continues at a low level in the scattered pools of residual water.

In rice fields, the number of malaria mosquito larvae and adults coincide precisely with irrigation activities, showing a single peak of mosquitoes in single-cropped fields, and two peaks in areas of double cropping.

There is usually a strip, 20 to 30 cm wide, between rice plants and the edges of a rice field. This habitat can support *Anopheles* breeding throughout the rice growth cycle. There may be a succession of species. In Kenya, for example, as rice grows taller and *A. gambiae* and *A. arabiensis* larvae decline, there is sometimes an increase in *A. funestus*, a vector that likes shade.

Where rice is broadcast, as opposed to being transplanted, mosquito production begins only when the month-old seedlings are flooded. At that time, rice height is optimal for mosquito production, and the post-flooding of the next four weeks can result in very large mosquito populations. As the rice lengthens, conditions become less favourable, and breeding decreases and tends to shift to more open and exposed places such as turnouts, scour holes, and levee gates. Broadcasting requires an almost completely dry field before it is sown. If a field has been poorly levelled, small pools can remain, forming habitats for mosquito larvae.

With *Cx. tritaeniorhynchus*, larval populations are often largest in the fallow fields after harvest and a few weeks after the new rice is planted.

The main rice cultivation season in the tropics begins with the onset of the rains. At that time, all the farmers tend to start preparing their rice land. The resulting high demands for water, energy, manpower, animal power, fertilizer, and seed paddy may mean that cultivation is delayed in some places. With water everywhere and a rice crop in various stages of growth, there are risks of crop diseases and opportunities for mosquitoes to proliferate. These problems can be overcome by dividing the area into blocks and observing, say, four cropping calendars, staggered at intervals of 2 weeks, instead of one cropping calendar for the whole area. This will lower the overall peak water demand and allow a better control of vectors. If a rice-based cropping system has 'dry' crops in the off-season, however, such staggered crop calendars will be difficult to organize.

Intermittent Submergence of Rice Fields

In irrigated rice fields in Portugal, an effective method was developed to control the local malaria mosquito, *Anopheles sinensis*. Rice fields that would normally be flooded continuously were intermittently dried (WHO 1982). The water was on the fields for 10 days, then off for 7 days. Over a period of 4 years, this practice reduced mosquito larvae by more than 80 per cent. In addition, there was a slight increase in rice yield and quality, and less water and weeding were required.

Rice cultivation on the flatlands of China is also a major cause of mosquitoes and diseases, particularly in the plain between the Yellow and the Huai Rivers, in the basin of the Nanyang River, and in the plain between the Yangtze and Hansui Rivers. The malaria mosquito in these regions is *Anopheles sinensis*, which is also responsible for the transmission of Malayan filariasis. The mosquito *Culex tritaeniorhynchus*, the major vector of Japanese B. encephalitis in East Asia, is also common in these areas.

In China in 1980, the mosquitoes transmitted over 2 million cases of malaria, calling for unusual efforts in disease control. A method of intermittent submergence was successfully tested on 10,000 hectares in Henang Province. It consisted of a 3-to-5-day interval between irrigations, when only a shallow layer of water was applied; this disappeared within 1 or 2 days (Pao-Ling Luh 1984). During the 2-week transplanting period, the fields were filled to a depth of 4 to 6 cm. For the entire remaining 100 days of the growing period, the fields were irrigated between 21 and 26 times.

This system of intermittent submergence reduced the mosquito larvae to 10 per cent of the numbers usually encountered (Figure 7.3), with a subsequent reduction of 60 per cent in the number of adult mosquitoes. The yield of rice was 13 per cent higher and the amount of water saved was one-half to one-third of the amount normally applied (Figure 7.4). This method is practical in sandy areas like the alluvial plain of the Yellow River, but requires efficient scheme management and operation.

7.3.2 'Dry' Crops

The difference between a wet crop and a dry crop is that a wet crop can withstand a permanent water layer, whereas a dry crop requires that the field surface become dry soon after irrigation water has been applied. This means that a dry-crop field

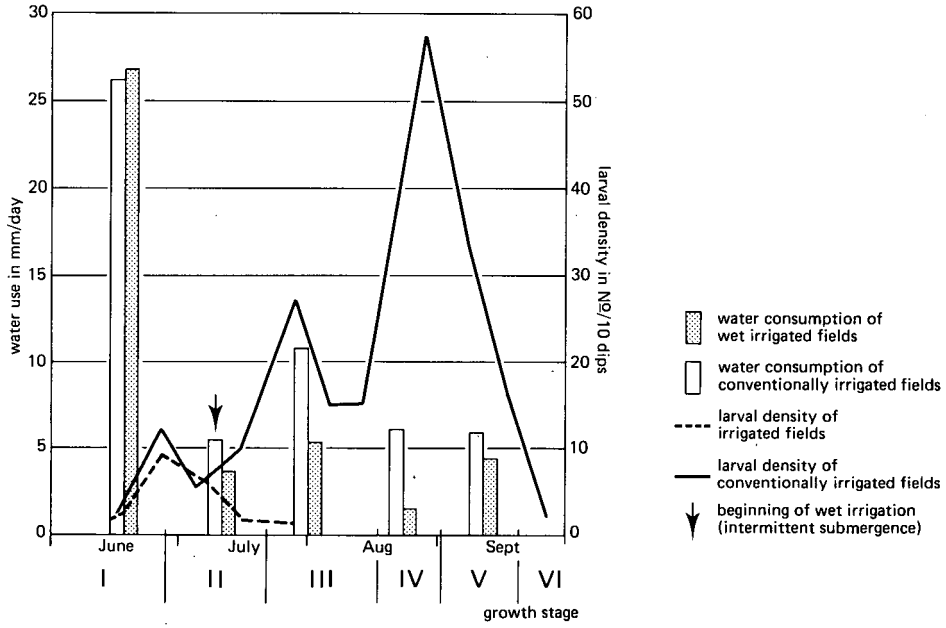

Figure 7.3 Comparison of the larval densities of *Anopheles sinensis* and *Culex tritaeniorhynchus* between fields of wet[1]) and conventional[2]) irrigation (after Ge Fengxiang et al. 1981)

[1]) 'Wet' irrigation: intermittent submergence with a thin water layer; when that layer has evaporated or evapotranspirated, a new layer is applied.

[2]) 'Conventional' irrigation: a permanent water layer of 5 to 15 cm is maintained.

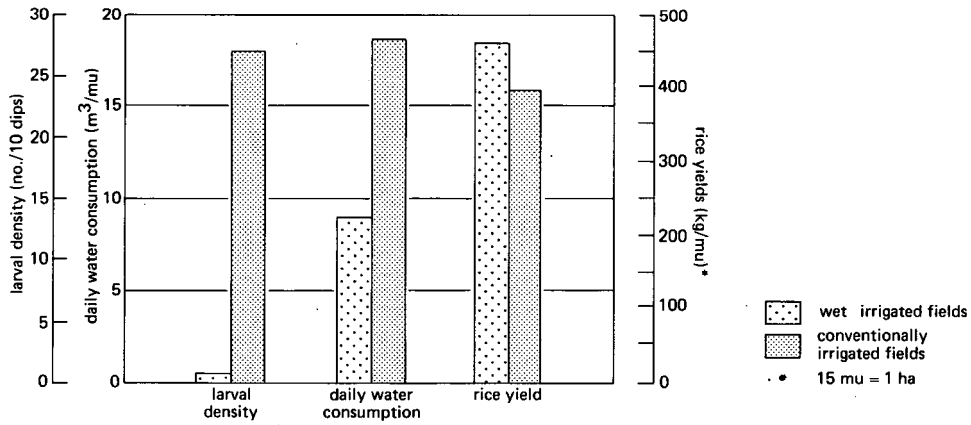

Figure 7.4 Comparison of larval densities, yields, and water consumption in the fields of wet and conventional irrigation (after Ge Fengxiang et al. 1981)

should always be supplied with water on an intermittent basis.

Many dry crops are grown in rows on ridges – the irrigation water being supplied via the furrows between the ridges. Sometimes, the ridges and furrows are located within a basin, and the irrigation water is then applied to the basin as a whole.

7.4 Elements of Farm Water Management

In this section, the following elements of farm water management will be discussed: land forming, field irrigation methods, water distribution and delivery, drainage, night irrigation, maintenance, canal lining and closed conduits.

7.4.1 Land Forming/Shaping/Smoothing

Large-Scale Operations

When a system of surface irrigation is to be introduced, one of the first tasks is to shape the land surface so as to permit a uniform distribution of the irrigation water and to provide for the drainage of excess surface water. Attempts to irrigate land with an uneven surface generally result in a low efficiency of water use, excessive labour requirements, and poor crop yields.

Interesting figures have emerged from research on irrigated wheat (Tyagi 1984). This showed that with average deviations from mean field level of 1.5 cm and 6.5 cm, and with field application efficiencies of 85 and 45 per cent respectively, wheat yields were 3128 and 2246 kg/ha respectively.

Running the water deep in low points in order to wet the high points causes an uneven water distribution and erratic plant growth. Water flowing over land with non-uniform slopes may cause soil to erode from the steeper slopes and be deposited on the flatter slopes. Excess water resulting from rainfall or over-irrigation, if allowed to collect in undrained areas of a field for long periods, can become a habitat for mosquitoes and snails.

Land forming eliminates the major irregularities of the surface through grading or levelling. If wet paddy is grown, the surface is levelled. For furrow or border irrigation, a continuous grade has to be established, which requires very accurate grading. Various methods are available to calculate the grade of the future land surface and the quantities of earthmoving required (Agricultural Compendium 1985). One widely used method determines a plane with uniform slopes both downfield and across. The result gives the 'plane of best fit', with the minimum amount of earthmoving and the balance between cut and fill. Computer programs are also available for determining the 'plane of best fit' and doing the 'earthwork calculations' (ILRI 1982).

Any land-forming exercise – be it levelling to produce a horizontal surface for rice basin irrigation, or grading to create land with a specific slope or grade – should always have land smoothing as its final operation. Land smoothing – by land plane for large operations, or by a wooden bar pulled over the land surface for small operations – eliminates small surface irregularities. For seed-bed preparation after the land is ploughed, land smoothing should be repeated annually.

Small-Scale Operations

It would be a mistake to concentrate on large-scale operations and ignore the significance of the work done by the individual small farmer. His efforts to gradually level or grade his fields in a sequence of small earthmoving operations cannot be praised too highly. If he can be aided in such work by animal traction equipped with simple implements (Figure 7.5), extremely good results can be achieved in a relatively short time.

7.4.2 Field Irrigation Methods

Surface irrigation is practised on 90 to 95 per cent of the irrigated area. The various methods of surface irrigation are:

- Level irrigation on level fields (basins, level borders, level furrows, level corrugations);
- Graded irrigation on fields under a slope (graded borders, graded furrows, graded corrugations);
- Sprinkler irrigation;
- Drip irrigation;
- Wild flooding.

Obviously, the smaller the area of 'open water surface', the better for vector control. This is one of the main advantages of sprinkler and drip irrigation.

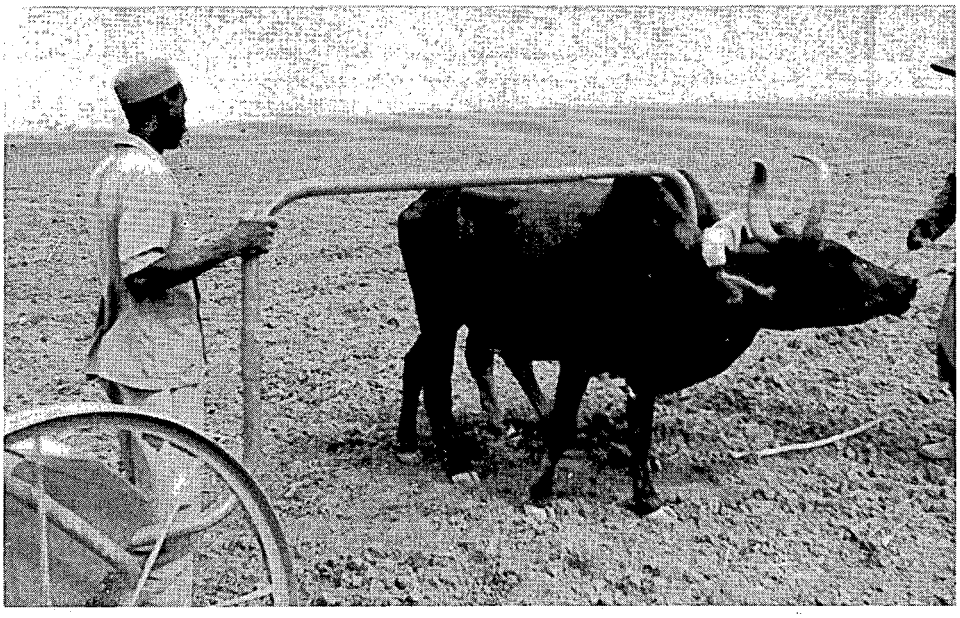

Figure 7.5 Elevated draw-bar facilitates the movement of oxen (after J. Boer 1985)

Selecting the right method of applying the water is critical. The wrong choice can damage the land, and may mean the failure of the irrigation scheme. The misuse of irrigation water can cause soil erosion, waterlogging (with the contingent creation of vector-breeding sites), and a build-up of soil salinity. It also wastes the funds spent on installing the irrigation system.

Each irrigation method is subject to a certain set of limiting conditions that govern its use. A thorough understanding of the soil, topography, water supply, and other factors that can affect irrigation is an important preliminary to selecting the proper irrigation method and the proper field layout.

Where surface irrigation is practised, its performance is generally poor. The main reasons for this are:

- More water is made available than is needed;
- The field is not properly laid out; its dimensions and its slope or grade are incorrect;
- The field application in incorrect, either in the stream size applied or the application time allowed.

When field irrigation requirements are being calculated, realistic values should be selected for the application efficiency. These values should be based on the assumption of a reasonably good performance, taking into account the irrigation method, the kind of soil, and the field layout. With good irrigators, there should then be only a small amount of 'unavoidable' waste, whilst poor irrigators will have an incentive to improve their performance.

For the assessment of field irrigation requirements, Table 7.1 presents indicative values for field application efficiencies (Roscher 1986).

Table 7.1 Indicative values for field application efficiencies

'Wet' crops: Continuous irrigation; 80% (not including percolation)
Intermittent irrigation; 95% (not including percolation)

'Dry' crops: Intermittent irrigation	Infiltration pattern		
	High	Medium	Low
Level irrigation, application depth < 50 mm	65%	70%	80%
Level irrigation, application depth > 50 mm	70%	75%	85%
Graded irrigation, without end check	65%	65%	65%
Graded irrigation, with end check	70%	75%	85%

7.4.3 Continuous or Rotational Delivery of Water

Usually, the water delivered to the tertiary unit is shared by a number of farmers. They may share the water by dividing the total flow among themselves, each obtaining his share as a continuous flow throughout the season. For a farmer with 'dry' crops, however, this delivery system causes problems. A more common practice, therefore, is to rotate the use of the full stream, supplying it to each farmer at intervals. The

time each farmer is allotted in the rotation is usually based on his irrigated area.

Sharing the water on a rotational basis is of particular value when a high irrigation efficiency is being aimed for. A comparative study of the efficiency of water distribution by continuous and rotational delivery was conducted in a tertiary unit of 40 ha. The calculations were made on the basis of net stream sizes and the normally accepted seepage rates. The results are presented in Table 7.2.

Table 7.2 Comparison between continuous and rotational delivery

	Continuous delivery	Rotational delivery
Stream size to tertiary unit	43.0 l/s	33.2 l/s
Distribution efficiency	70%	90%

Additional calculations of the distribution efficiencies for various canal discharges and lengths indicated the following:

- The larger the stream size, the higher the distribution efficiency;
- The shorter the canal length, the higher the distribution efficiency.

Because the stream size supplied to a farmer under rotational delivery is larger and the length of the canals simultaneously in operation is shorter, rotational delivery results in higher distribution efficiencies than continuous delivery. Rotational delivery also saves water. In the above-mentioned study, the stream size for rotational delivery was only 33.2 l/s, as against 43 l/s for continuous delivery – a saving of 9.8 l/s, or roughly 25 per cent.

Under continuous delivery, more water will percolate from the canals to the subsoil, increasing the hazard of a rising or perched watertable, which may eventually create waterlogged areas within the irrigation scheme or dangerous pooling elsewhere.

Altogether, there are many reasons for pursuing irrigation systems with rotational delivery, including their advantages for vector control. Take the question of bilharzia transmission, for instance. Field canals that follow a cycle in which water is present for 2 weeks and absent for 2 weeks are unable to support snail populations. This is so, even if the canals contain a few snails or cercariae washed in from upstream.

Mosquitoes require a different approach. Mortality in the larval stage is very high; so a dry period of a few days is sufficient to kill all the larvae. This fact can be put to use in field canals with rotational flow. If the rotation period for the application of water to a field can be reduced to 5 or 6 days on and 5 or 6 days off, the canals will not produce mosquitoes. But, if the rotation is lengthened to 15 days on and 15 days off, the water in the canal will become a habitat for mosquitoes, including those that transmit malaria.

Rotational irrigation has the disadvantage of involving higher investment costs, and may require the more frequent presence of the farmer, who may also have to irrigate at night. But the advantages so far outweigh the disadvantages that the conclusion should be a unanimous endorsement of rotational delivery.

7.4.4 Field drainage

There are many different types of drainage (Oosterbaan 1980). For example:
- Internal (or field) drainage versus external drainage (mainly disposal drains and outlets);
- Surface drainage (done by land shaping) versus subsurface drainage (done by subsoiling or moling, or by installing pipe drains, ditches, or tubewells);
- Gravity versus lift (or pump) drainage;
- Interception versus relief drainage (or dewatering);
- Temporary drainage versus permanent drainage.

Any drainage system can be characterized by the alternatives in these five categories, thereby offering a large number of options.

Drainage systems can fulfil various functions. Surface drainage, for instance, is most common in areas with high rainfall intensities or where soils have a low infiltration capacity, but it is also applied in irrigated lands to remove excess irrigation water or rainfall. Subsurface drainage in the temperate zone removes excess rainfall and maintains a well-aerated soil. In irrigated lands, it also helps to control soil salinity (e.g. by removing the water required for leaching). Temporary drainage systems are found in paddy fields where drainage is normally undesirable, but after exceptionally high rainfall or before harvest operations, the drainage system is put into operation.

The different types of drainage systems all have their own set of design criteria and require a separate research approach as to their effects.

7.4.5 Night Irrigation

Irrigation by night is possible, but because it may be inconvenient for the farmer to be present, night irrigation can mean poor irrigation. Furrow irrigation done in the traditional way, for instance, requires the farmer to be in attendance to regulate the flow to each individual furrow. Fairly simple measures, however, can reduce the farmer's duties to simple actions such as opening and closing gates.

One such measure is an equalizing basin installed at the head of a set of furrows (Figure 7.6). When the furrow inlets are fixed as to elevation and size by means of stones, grass sods, or spiles (and have been calibrated), the involvement of the farmer is reduced to opening and closing the inlet to the equalizing basin at the correct time and checking the water in the field ditch.

If desired, this method can be developed further by mechanization and automation (Humphreys 1986; Irrinews 1986). Drop-open and drop-close gates, commanded by a timer, for example, could be installed. The farmer can then pre-set the gates and the timer during the day, and the field irrigation will take place automatically. When the irrigation of one field is completed, the irrigation of the next will begin in accordance with the pre-set schedule.

With such simple measures, field irrigation can be done almost unattended. And, if proper stream sizes are provided and proper field delivery periods are adhered to, field irrigation can be done very well.

Another possibility is to change from surface irrigation to a pressurized sprinkler system. The energy costs of sprinklers, however, are high and their suitability in the

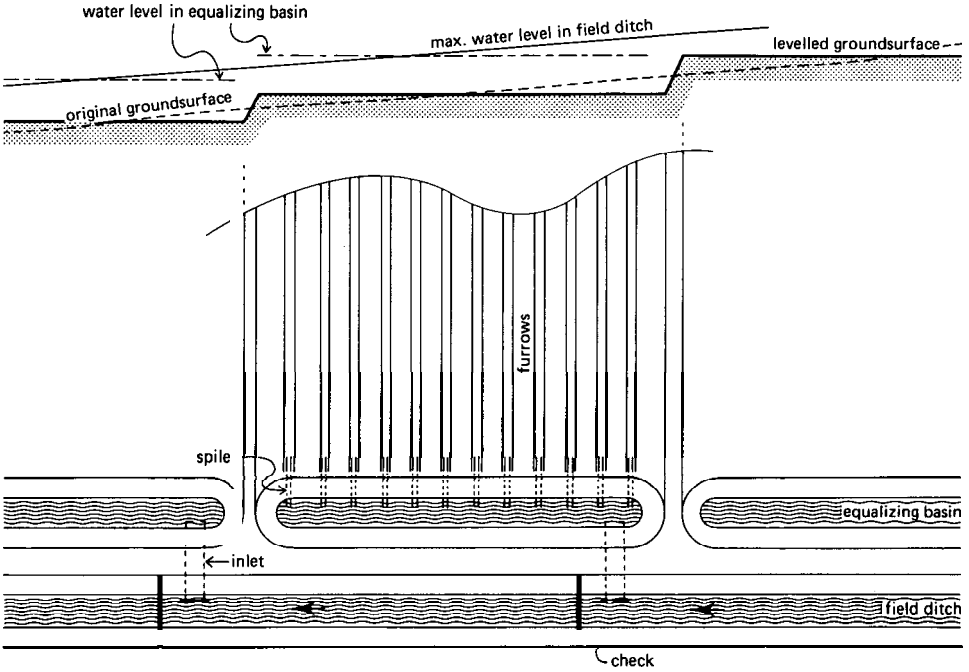

Figure 7.6 Equalizing basins for levelled strips of land (after Roscher 1986)

less developed countries is questionable. Besides, their relatively high capital costs argue against their wholesale application. When ways are being sought to improve water management systems, it might be wise to concentrate on the mechanization and automation of traditional surface irrigation methods, rather than to consider the more sophisticated methods of sprinkler or drip.

7.4.6 Night-Storage Reservoirs

If night irrigation is rejected, the alternative for large schemes is to incorporate night-storage reservoirs into the systems – an alternative that will certainly have repercussions in terms of vector proliferation. With siltation and the growth of aquatic vegetation, such reservoirs often become the sites of high densities of vectors. The risks can be reduced by using fewer, but larger-sized reservoirs, and emptying them completely during the day-time irrigation period. The reservoirs should be fenced to restrict human contact with the water, and the design should allow opportunities for maintenance and snail control.

The Bura Irrigation Project, Kenya

The Bura Irrigation Project in Kenya incorporates night-storage reservoirs in its design, which is shown in Figure 7.7 (MacDonald and Partners 1982; ILRI 1982).

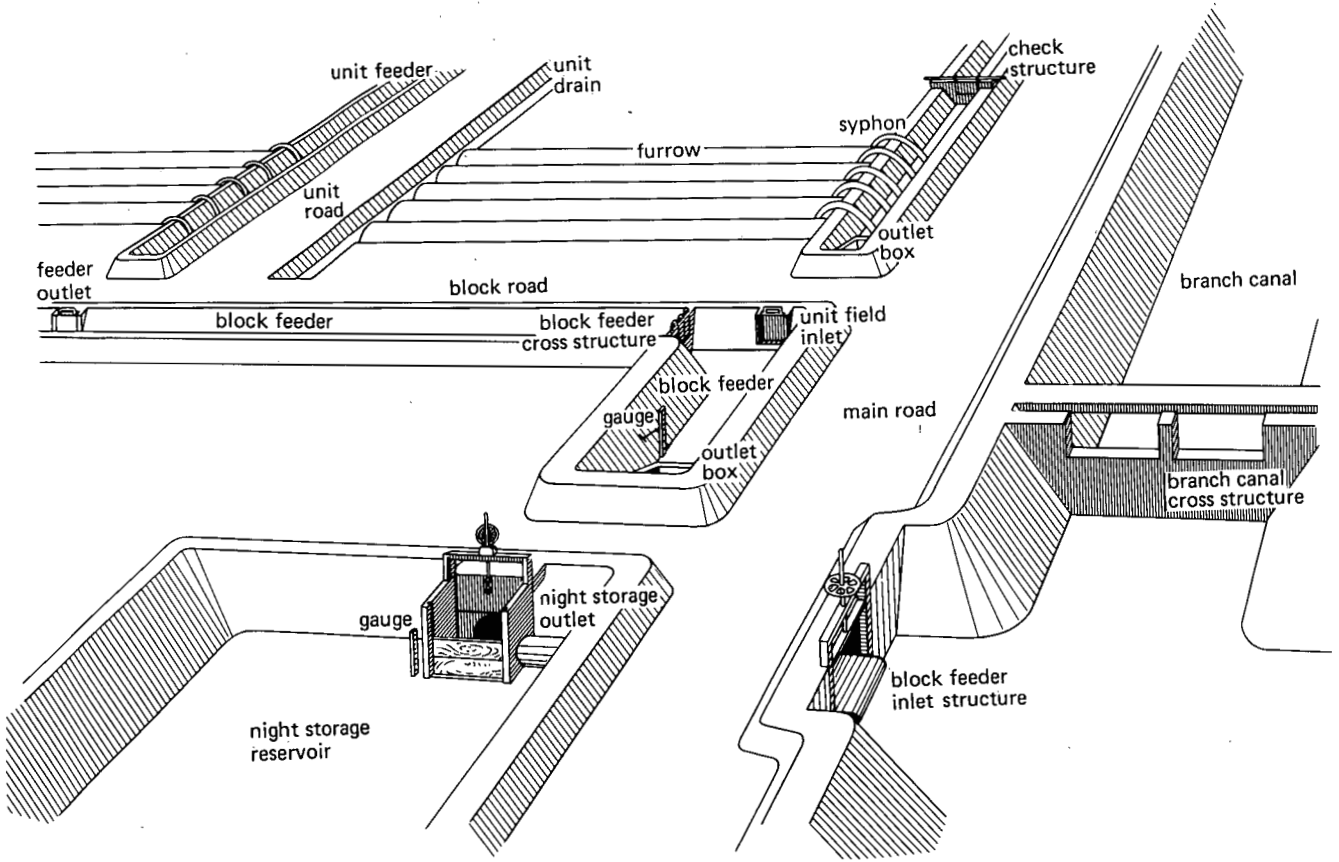

Figure 7.7 Layout of canals and structures, Bura Irrigation Project

In Bura, the main canal and all branch canals run continuously, whereas the block-feeder canals run only during the day. At night, water is diverted from the branch canals into the reservoirs. The storage capacity of an average-sized reservoir is 200 ha × 1.0 l/s/ha × 12 hours × 3600 s/hour = 8640 m^3.

The reservoirs have a live storage depth of 0.75 m between maximum and minimum operating level, and, to accommodate sediment, a dead storage depth of 0.50 m between minimum operating level and bed level. The top level of the reservoir's bank is the same as the top level of the branch-canal bank upstream of the cross regulator. This ensures that no overtopping of the reservoir banks can occur as a result of any ponding of water in the branch canal upstream of the cross regulator. Maximum operating level in the reservoir is set at 0.22 m below design water level upstream of the cross regulator.

For a live-storage depth of 0.75 m and the width of the reservoir set at 50 m, the length of the night-storage reservoir (in a direction parallel to the branch canal) comes to roughly 230 m. The location of the offtake structures was chosen to permit quantities of excavation and fill for the reservoir to more or less balance.

The inside banks of the reservoir slope 1 in 3 to reduce wave damage, and the bank top width is 3 m to permit occasional vehicular access. The reservoirs need periodic cleaning to remove accumulated sediment and a site is provided for dumping the material.

The block-feeder canals take off from a branch canal through a standard Romijn weir structure. The water then flows into an outlet box. This box also serves as the inlet to the night-storage regulator, which is used to control flow into the block-feeder canal. It is possible to isolate the reservoir and feed only from the branch canal or, conversely, to stop the supply from the branch canal so that flow into the block feeder comes only from the reservoir. This feature guarantees that the system can be maintained without the supplies to the fields being interrupted. The night-storage regulator has a vertical lift gate which is adjusted throughout the day at hourly intervals (or less frequently) as the reservoir level falls.

The design of the night-storage reservoirs offers good opportunities for maintenance by dragline excavation or dredging, and for the application of molluscicides. Unfortunately, the daily fluctuation of the water level does not help at all in snail control – the duration of the 'dry' periods being too short.

7.4.7 Ditch Maintenance

Apart from the tertiary canal proper, the tertiary unit contains many very small canals, which are more appropriately called ditches. In ditches, the flow velocity, the water depth, and the freeboard are small compared with those in canals. The consequences are: easier sedimentation of silt, more chance of weed infestation, greater risk of overtopping, and higher seepage rates just above the water line (because rodents find this an appropriate habitat and create macro-pores). Another point of difference between canals and tertiary-unit ditches is that the ditches have a proportionally greater number of small water-management structures and thus more chances of leakage.

To avoid seepage, overtopping, dangerous pooling, and the creation of snail habitats, the routine maintenance of tertiary-unit ditches is a must. The question of correc-

tive or curative maintenance is another point that may have to be considered, but now we move into the realm of renovation or rehabilitation, which more appropriately applies to canals.

7.4.8 Linings/Closed Conduits

To reduce seepage losses in the canals/ditches of the tertiary unit, they could be lined, although this may not be economically feasible. It may suffice to line only those sections where excessive seepage occurs. Under a rotational delivery regime, for example, Khepar and Rai (1979) found that by lining some 60 per cent of the total length of the ditches, about 90 per cent of the water otherwise lost through seepage could be saved.

The significance of canal lining in general, and for vector control in particular, are sound reasons for devoting attention to this topic. Lining, however, is more a concern for the major canal network, whereas, for tertiary-unit ditches, closed conduits (pipes, flexible hoses) are more relevant (Figure 7.8).

The Use of Closed Conduits

For the distribution of irrigation water in the tertiary unit, closed conduits or pipelines have a number of advantages over open ditches (Booker 1974). These are:

- They are as effective as concrete-lined ditches in reducing seepage losses;

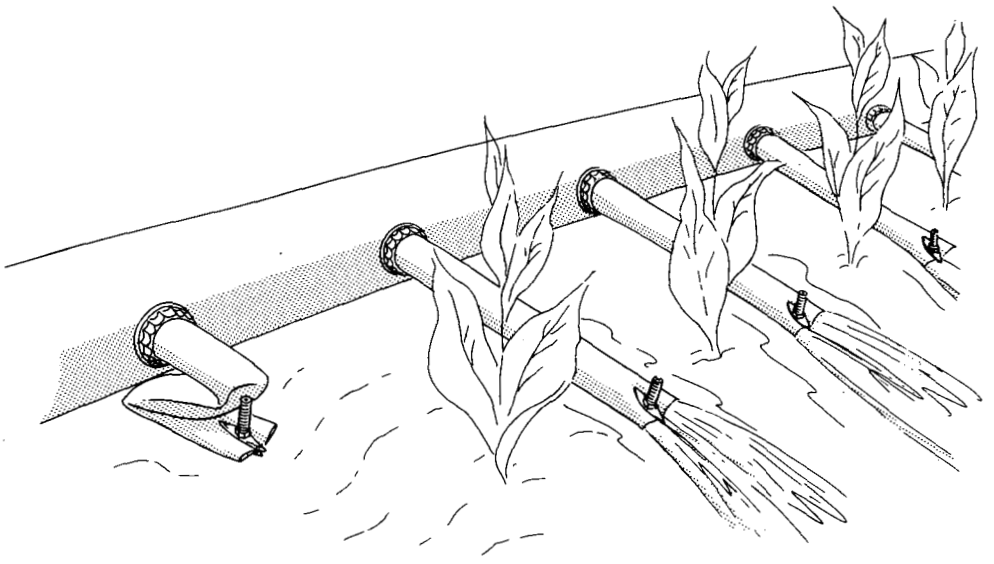

Figure 7.8 A flexible hose

- They eliminate evaporation losses;
- They eliminate the need for weed control along ditch banks;
- The area that would otherwise be occupied by ditches can be sown to crops;
- Pipe systems have lower maintenance and operational costs;
- By eliminating open water, they eliminate insect and snail breeding.

All these features make a pipe system very suitable for vector control.

The Demand Irrigation Schedule Pipe Line Project, Sri Lanka

An interesting experiment is the Demand Irrigation Schedule Pipe Line Project in Sri Lanka (Merriam 1980; Merriam and Davids 1986). This permits the farmer to take water at the frequency, rate, and duration that he believes he needs. All flow variations are controlled by him at his farm outlet. The maximum rate he can take is about 20 l/s.

The system consists of a farmer-controlled turnout with a 90 cm screw valve and a V-notch weir. The water is supplied from a closed or semi-closed, low-pressure concrete pipeline, which receives the water from an automatically controlled distributary pipeline or channel connected to the main canal.

The automation of the pilot projects is done by taking water at the 'demanded' variable rates from the main canal or a reservoir into level-top canals operating at the same level as the main canal. The Project uses an AVIO Neyrpic gate to maintain a constant water level in the level-top canals below the main canal or reservoir. The field pipe lines connect directly into the level-top canals and so their demands are transmitted back to the main canal. The flow fluctuation created by the demand schedule, which will largely permit day-time application, will be absorbed by the main canal flows (for the smaller projects) and by the reservoir (for the larger projects).

The benefits of this system are manifold:
- The farmer is assured of an adequate and timely water supply;
- The 'low-ender' problem of inadequate and erratic delivery is overcome;
- Disagreements among farmers and with the government over inequitable distribution of the water are eliminated;
- The farmers' propensity to take water illicitly and to damage structures is eliminated;
- The need for all farmers to plant the same crop at the same time is eliminated;
- Crop production is increased through better water management and through improved water availability for the 'low-end' farmers;
- The right-of-way widths are reduced;
- Operational spillage and seepage are reduced;
- Canal management problems are fewer;
- Maintenance of canals and ditches is reduced;
- Irrigation water requirements are lower.

The last four benefits, in particular, are also beneficial for vector control. The elimination of the small open ditches, which are usually the main culprits in providing habitats for vectors, means a vast reduction in habitat areas.

There may, of course, also be problems. Extra extension efforts will be needed,

for example, because the Project involves new techniques of farming and irrigating. There are also the costs: the investment costs for the Demand Irrigation Schedule were about U.S. $500/ha higher than the originally-planned typical system of earthen field channels, sloping distributary canals, and a rotation schedule. But, based solely on crop yield increases, this extra expenditure can be recovered in 2 to 3 years, and even more rapidly, if other benefits are included.

7.5 Summary of Control Measures

The basic premise is that anything that helps to promote good on-farm irrigation also helps to promote vector control. The following points are relevant:

- Proper field dimensions and layout:
  - In the case of graded irrigation, the introduction of end checks promotes uniformity of water application and reduces runoff losses;
- Field smoothing as part of seasonal land preparation:
  - This aims at an average deviation from mean field level of not more than about 3 cm;
- Rotational delivery for 'dry' crops, and rotational delivery and intermittent submergence for rice. This:
  - Reduces distribution losses in tertiary canals and ditches,
  - Creates operational stream sizes for efficient water application to fields,
  - Promotes equity in water delivery by time-sharing instead of stream-size-sharing, and
  - Increases the efficient use of rainfall;
- Night irrigation instead of night-storage reservoirs:
  - This requires simple measures to ease field application practices;
- Delivery schedules based on proper stream sizes and delivery times. This:
  - Results in the timely delivery of the required volume of water to each farmer,
  - Prevents the occurrence of soil moisture deficiencies or water excesses, and
  - Promotes an equitable distribution of the available water;
- Assessment of irrigation requirements:
  - The proper assessment of evapotranspiration values and of effective rainfall reduces unavoidable field application losses;
- Routine maintenance of canals/ditches within the tertiary unit:
  - A well-maintained ditch profile obviates the need to increase water depths to obtain the same flow, thereby avoiding extra seepage losses and their contingent hazards of creating waterlogging and vector habitats;
- Training operational personnel and increasing extension efforts to farmers:
  - Ditch riders and common irrigators should be trained in establishing appropriate delivery schedules, and
  - Field inspectors should be trained to advise farmers about field smoothing, border/furrow stream size, and field application time.

7.6 Practical Examples

Volume 2, Annex 5, presents three practical examples relevant to control measures in farm water management. These concern:

- Rice cultivation along the Niger;
- Asian bilharzia and rice in the Philippines;
- Irrigation and vector-borne diseases: a case study in Sri Lanka.

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8 Biological and Chemical Control

As was discussed in Chapter 1, integrated control is the simultaneous application of different methods of vector control. It is much to be preferred above one single method, whether this be control by environmental management, biological control, or, particularly, chemical control. From the preceding chapters, it will have become clear that chemical control should not be viewed as the first and foremost step in vector control. Instead, we advocate a comprehensive approach – one in which chemical control can have its place. Chemical control should always be used advisedly, and care should be taken that it does not interfere unfavourably with biological control.

8.1 Control of the Bilharzia Snail

8.1.1 Biological Control by the Snail – Marisa cornuarietis

Of South American origin, the *Marisa cornuarietis* is a large aquatic snail (6 cm in diameter), which eats the smaller bilharzia snails, competes with them for food, and safely absorbs the bilharzia larvae, thereby preventing them from developing in their normal snail hosts.

The *Marisa* has been used in streams, ponds, and reservoirs in Puerto Rico since the late 1950's, and was successfully studied under experimental conditions in Egypt in the 1960's. In 1975, it was introduced into Tanzania and, after laboratory studies, was placed in a pond near Moshi where it displaced the normal populations of bilharzia snails. In 1980, it was introduced into the Sudan for large-scale field testing. In the Sudanese studies, two other snails with a similar potential were tested as well. These were the smaller ramshorn snail from North America and an ampullarid snail from the Sudan. The results of this large, comparative trial should become available in 1988.

When these biological control agents are introduced into a new country, the evaluation of their effects proceeds slowly. Their reproductive rate is slow, and complex ecological studies are needed before they can be released into the field. Even so, for large reservoirs, they constitute a more rational method of bilharzia control than is otherwise available.

The introduction of a new aquatic snail species into any country or river basin should only be done with the permission of the national authorities, and the process should be carefully supervised. Initial trials should be aimed at evaluating the snails' ecological impact and should be restricted to enclosed habitats from which the snails can easily be eliminated if necessary. This means that large field trials cannot usually start until 2 to 4 years after the snails have been introduced.

The ampullarid snail *Marisa cornuarietis* has undergone 30 years of field evaluation since it was introduced into Puerto Rico, and has been under casual observations for about 20 years since being introduced into the Dominican Republic, St. Kitts in the eastern Caribbean, and Florida in the south of the U.S.A. No adverse effects have been reported from these locations. Neither has Egypt (Demian and Kamel 1973)

nor Tanzania (Nguma et al. 1982) reported any drawbacks with their imported snails. When *Marisa* was introduced into the Sudan in 1980, however, it was restricted to guarded enclosures, where it remained under test conditions until 1984. Field trials were then initiated, but only in irrigation canals that had no connections to drains or natural water bodies. After these field trials are completed, it may be possible to contemplate the wide-scale use of *Marisa*.

In Puerto Rico, *Marisa cornuarietis* has been studied thoroughly, both in the laboratory and in the field. Under laboratory conditions, *Marisa* preys freely on immature and adult *B. glabrata*, as well as on its egg masses. Other disease-bearing snails, such as *Lymnaea* and *Bulinus*, are similarly preyed upon by *Marisa*.

The amount of vegetation appears to be important. In early studies of farm ponds, *Marisa* displaced *B. glabrata* when there was a scarcity of macroscopic vegetation. The lack of vegetation may intensify competition for food and may also reduce the cover available to protect eggs and juvenile *B. glabrata* from predation by the ampullarid snail.

In the smaller reservoirs and night-storage ponds in Puerto Rico, this biological control method has proved its worth. For large lakes in the tropics, the logical solution would be to develop a biological method to control disease-bearing snails, and *Marisa* would appear to be an effective instrument.

Testing and Costs for Puerto Rican Night-Storage Ponds

For sugar cane irrigation in Puerto Rico, the water distribution is managed through a system of numerous night-storage ponds to reduce the labour required in operating the irrigation system. These earth-banked ponds have an average area of 0.5 ha, a design water depth of approximately 2 m, and a volume of 10,000 m^3. About 2 per cent of the ponds are lined with concrete. The ponds are filled to capacity at night and are emptied daily by gravity flow directly into the field laterals. Both bank-side and aquatic plants grow rapidly in these ponds and, when necessary, the plants are removed manually, mechanically, or chemically. Ponds choked with vegetation are dried out and cleaned with bulldozers.

An initial group of *Marisa cornuarietis* was collected and planted in 3 irrigation ponds, where the population development was evaluated every 2 months during 1956, and annually afterwards (Ruiz-Tiben et al. 1969). In 1957, *Marisa cornuarietis* were collected from the original 3 ponds and were seeded in 25 additional units. In turn, these 25 units provided *Marisa* for a further 66 units in 1958, 10 units in 1959, 2 units in 1960, 2 units in 1961, and finally, 3 units in 1963. Thus, a total of 111 units were stocked with *Marisa cornuarietis* from 1956 to 1963.

The *Marisa* snail began to displace *B. glabrata*, slowly at first, but later at a more rapid rate. Reseedings were necessary. Figure 8.1 shows the displacement situation in the 111 ponds.

The total effort required 111 seedings and 229 reseedings – a total of 179,700 *Marisa* snails. The total cost of planting and replanting in the 111 ponds was U.S. $5,467 over 9 years, or $5,467/111 \cdot 9$ = U.S. $5.5 per pond per year (U.S. $607 for 111 ponds per year). The cost per snail delivered in place was U.S. $0.03.

This technique required only the bare essentials in manpower and equipment: three

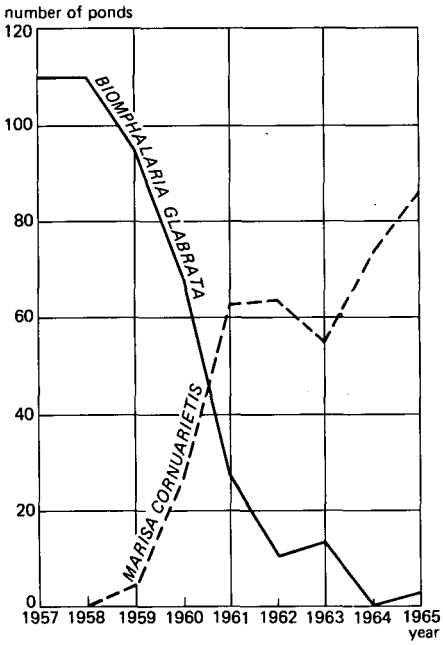

Figure 8.1 Control of *Biomphalaria glabrata* in irrigation ponds after the introduction of *Marisa cornuarietis*

unskilled labourers, one vehicle, snail dippers (Figure 8.2), and buckets for transporting *Marisa cornuarietis*. Unlike chemical control, it did not require weirs, dispensing devices, the handling of chemicals, power pumps, or specialized control personnel; nor did it present any of the problems inherent in the chemical control of *B. glabrata*.

The above-mentioned U.S. $607 (which included labour and transport costs, but excluded overhead and supervision costs) corresponds to a treatment of about 555,000 m^3 of water. If we compare this with the costs of chemical control by Na PcP (sodium penta chloro phenate), we find that those costs would run to some U.S. $9.70 per 100 m^3 of water treated, or U.S. $53,835 for 111 ponds (for a single treatment). The difference is very large.

There is a remote possibility that the effects of weed-control operations and fluctuations in the water level of the ponds caused the disappearance of *B. glabrata*. But weed control and pond-level fluctuations are inherent in an irrigation system of this type, and they occurred from 1914 to 1957 without eliminating the populations of *B. glabrata*. Thus it is difficult to believe that these routine happenings were responsible for the sudden disappearance of *B. glabrata*, coinciding as it did precisely with the introduction of *Marisa*. Nevertheless, these operational features may contribute in some way to the remarkable success of *Marisa* in dominating habitats, and to the low cost of this biological method of control (Jobin et al. 1973; Jobin et al. 1977; Jobin et al. 1984).

Figure 8.2 The large ampullarid snail *Marisa* can easily be harvested with dippers, enabling snails to be collected at a rate of 1000 per man-hour

Testing and Costs for Large Reservoirs

Especially in large reservoirs, the use of chemical pesticides for the control of bilharzia snails or malaria mosquitoes seems a woeful waste of money, given the continuous re-introduction of snails and insects. In the vast expanse of Lake Volta, methods that gave short-term success in bilharzia control were beyond the ability or resources of the Government of Ghana to continue, and the program was terminated, leaving the lakeside villages once again exposed to bilharzia infections.

The need for a more logical strategy for the long-term control of the bilharzia snail has long been recognized. The studies in Puerto Rico and elsewhere have indicated that such a strategy might be based on biological control by *Marisa cornuarietis*.

Before this ampullarid snail can be introduced into the large African reservoirs and lakes, there is a need for lengthy preliminary testing (Jobin and Laracuente 1984). Five important steps would have to be taken before the method could be applied, and each of these steps would have a significant cost. The five steps are:

1) Importation and establishment of a *Marisa* laboratory colony;
2) Controlled field trials to study the impact on bilharzia snails;
3) Controlled field testing to find any harmful ecological effects;
4) Establishment of a production facility;
5) Creation of a distribution system.

The two parts of Step 1, the importation of *Marisa* and the establishment of laboratory colonies, have been successfully completed in Egypt, Tanzania, and the Sudan, with about a thousand adult snails brought in by direct flights from Puerto Rico. The laboratory colonies were successfully established in simple aerated aquaria. The total cost of collection, importation, and establishment of each colony was less than U.S. $10,000. Annual maintenance costs (for labour and snail food) are less than U.S. $1,000 for a colony of 1,000 snails.

The controlled field trials of Step 2, in which the *Marisa* are placed in a small, isolated habitat that approximates conditions in the large lakes or irrigation canals, must be carefully monitored to ensure that the *Marisa* do not escape before their use is approved by the appropriate authorities. Steps 2 and 3 should proceed together because they may each require about 3 years to complete.

The trials of Steps 2 and 3 require supervision by a biologist with a doctoral degree and special training in malacology. The total cost of 3 years of studies is estimated at U.S. $200,000 (Table 8.1)

Table 8.1 Estimated costs of establishing biological control of bilharzia in Lake Volta

Step	Item	Estimated cost in U.S. $ (1985)					
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
1a	Importation	10,000					
1b	Colony	1,000	1,000	1,000			
2 + 3	Trials	100,000	50,000	50,000			
4	Production		100,000	100,000			
5	Distribution			50,000	50,000	50,000	50,000
Totals		111,000	151,000	201,000	50,000	50,000	50,000

Or overall total U.S. $613,000

Steps 4 and 5 (the production and distribution of *Marisa*) are necessary for large lakes because of the relatively low mobility of these large snails and their slow reproduction rate. Stocking Lake Volta would require colonies of 1,000 snails planted at intervals of roughly 1 km along the shoreline. Although this could be done fairly easily with a launch, it would require over 5 million adult *Marisa* to get a significant population within 2 or 3 years. Assuming that the population might be decimated by drought or other calamities every 10 years, a nursery or snail production facility would have to be maintained until the snail became permanently established in other habitats in the surrounding countryside.

A production facility could be organized in the same way as fish-cultivation ponds. It would require about 50 ponds, 1 m deep and 1 ha in area, with earthen sides, concrete bottoms that slope to a drain, and a reliable source of safe water to circulate through the ponds with a complete turnover once a week. The major operating cost would be for the addition of green vegetation for snail food, requiring about 100 kg of leafy vegetation for each pond each week. An edible vegetable, tuber, or salad green, locally

grown, would be satisfactory, the optimum being something similar to lettuce or watercress, or perhaps a weed from the lake itself, such as *Ceratophylum* from Lake Volta. The annual cost of constructing and operating these 50 ponds, which would require 10 labourers, a supervisor, and some equipment, is about U.S. $200,000 for 2 years (Table 8.1).

The final step, Step 5, is the creation of a distribution system (Figure 8.3). It requires a 4-wheel-drive pickup truck, an 8 m motor launch with 2 outboard engines, a captain and 3 assistants, plus sufficient fuel and supplies to make week-long trips to reach the entire protected shoreline of the lake. Assuming that the boat and vehicle would be needed for 2 years to plant the entire lake, and that the re-planting would be conducted at 10-year intervals, the total cost for the distribution system is estimated at about U.S. $50,000 yearly.

The completion of Steps 1 to 5 would take 4 to 5 years if the ecology of the area is suitable and reasonable care is taken by properly trained supervisors. In Puerto Rico in the 1960's and 1970's, such operations were done to spread *Marisa* to 28 mountain reservoirs, with successful colonies being established in 26 of them. There is no guarantee that the method will work in African lakes, but it is highly likely.

The total annual cost of U.S. $50,000 is significantly lower than the estimated cost of U.S. $1 million annually for chemical control, and most of the cost of the biological control is for local materials and labour. This makes it much more feasible for African countries than purchases of synthetic chemicals with hard currency.

In the initial planning stages for such large reservoirs – if bilharzia is anticipated

Figure 8.3 Distribution of *Marisa* in the Sudan, a process requiring only transport and containers

as a serious problem – the preliminary steps for developing the biological control method can be taken in cooperation with local health and fisheries authorities – the agencies most likely to have the expertise to handle such trials.

8.1.2 Biological Control by Fish

Research Approach Required and Some Results

In the fight against bilharzia, biological control by fish can also be successful. Possible bio-control species must first be identified and characterized, and then laboratory experiments will have to be done on the food preference of the molluscivorous fish.

A fish that is effective in bio-control must have a preference for snails, even if other food resources are abundant. On the other hand, the fish must be able to live on other resources too, if snails are temporarily absent (seasonality) or eradicated. Otherwise, the fish will disappear and the snails will rapidly re-establish themselves.

If a promising fish species has been found in laboratory experiments, small-scale field trials will give information about the efficacy of the fish against snails under more natural conditions. Finally, large-scale field trials will have to be conducted.

Background Information for Laboratory Investigations

In one of the earliest notes on the possible use of fish as a bio-control agent against snails, Oliver-Gonzales (1946) mentions guppies (*Lebistes reticulatus*). He reported that these fish fed actively on the egg masses laid by the snails, preferring egg masses of almost hatched snails. The disappearance of *Biomphalaria glabrata* snails from water bodies coincided with the occurrence of numerous guppies.

Other species predatory to snails are mainly *Cichlidae*, such as *Cichlasoma biocellatum* ('the crusher'), which originates in South America and is able to crush planorbid snails of at least 3 cm. Another is *Tilapia melanopleura*. One 45 cm-long specimen was able to eat snails up to 6 cm, but this fish prefers other food items.

Background Information for Small-Scale Field Trials

Promising results in the possible use of fish come from Zaire (de Bondt 1956). The fish is *Haplochromis mellandi* (a *Cichlidae*). De Bondt gives a detailed description of the experiments, in which several types of artificial water bodies were stocked with fish. Irrigation channels, for example, overgrown with *Potamogeton* and with a dense snail population, were stocked with *H. mellandi*. If one fish was released every 1 m, the channels were free of snails within 8 days; one fish every 10 m made the snails disappear in a fortnight.

Another successful field experiment was performed in Cameroon (Bard and Mvogo 1963; Gamet, Brottes, and Mvogo 1964). Two basins (85 m^2) were stocked with about 1600 *Tilapia nilotica* (now *Oreochromis nilotica*). One of the basins was also stocked with 69 *Astatoreochromis alluaudi*, imported from Uganda. At the moment of stocking,

the sides of both basins were covered with snails (*Biomphalaria camerunensis* and *Limnaea africana*). After 3 months, the basins were emptied of their water. The basin stocked with *A. alluaudi* no longer contained snails. Tank observations showed that all specimens, which were between 80 and 97 mm long, ate an average of one snail an hour.

The only large-scale field trial known from literature was performed in western Kenya in a number of basins. Because man and domestic animals used the water in these basins, chemical methods of snail control were not feasible (McMahon et al. 1958; McMahon 1967). The basins were stocked with *A. alluaudi*, with herbivorous species such as *Tilapia zilii* and *T. leucostica*, and with *Gambusia affinis*, which eats mosquito larvae. The Schistosoma intermediate hosts occurring in the water were *Biomphalaria pfeifferi*, *Bulinus physopsis africanus*, and *Bulinus forskali*. Densities of *Biomphalaria* snails decreased significantly over a period of 13 years, especially in the first 2 years. Densities of *Bulinus spp.* decreased, but not significantly. It seems that *A. alluaudi* is selective in its feeding habits. The other fish species stocked had no significant effect on vegetation or on snail and mosquito populations.

Research on the Grass Carp

Laboratory studies of the feeding habits of the grass carp, *Ctenopharyngodon idella*, an herbivorous species imported from China to control aquatic weeds, showed that the carp preferred to forage on herbs covered with egg masses of *Biomphalaria glabrata* and *Lymnaea stagnalis* (Neeft and van Schayk 1983; van Zon 1984).

In irrigation channels in Egypt, the bio-control of aquatic weeds by the grass carp also reduced the populations of *Biomphalaria alexandrina* and *Bulinus truncatus* (van Schayk 1982).

A problem with the grass carp is that it rarely propagates outside China.

Further Research Issues

Because of the lack of reliable data, there is an urgent need for field research (McCullough 1981a). This should be undertaken in cooperation with freshwater fisheries authorities. A combination of molluscivorous and herbivorous fish can probably give good results. Potential sites for such studies can probably be found in the Sudan, Kenya, Malawi, and Cameroon.

Where snail control by chemical or environmental methods is costly, the integrated control of schistosomiasis should always include fish (McCullough 1981b). Selective malacophagous fish species are recommended, possibly in combination with the grass carp.

In irrigated areas in the Sudan, where malaria and schistosomiasis have become major health problems, fish could play a useful role in the ecological management of the areas – controlling, as they can, not only aquatic weeds, but also parasitic disease vectors (Coates and Redding-Coates 1981; Redding-Coates and Coates 1981; Coates 1984).

In the integrated control strategy of the Blue Nile Health Project, some noteworthy

progress has been made in biological snail control (Daffalla et al. 1985). The Project has, for example, conducted laboratory and small-scale field experiments to study the malacophagous capabilities of the lungfish, *Protopterus annectans*. In the Sudan, this fish is known as the 'mudfish'. It is common in seasonal water bodies in western Sudan. As the water body dries up, the fish buries into the mud and survives by sealing itself into a cocoon about 0.5 m underground until the new rains flood the stream.

Conclusion

It is obvious that the biological control of snails by fish deserves more attention, but, given the dangers of introducing a new species into an area, proper research methods must be applied (Slootweg 1985). Most of the results we have described lack the necessary basic laboratory data, or have not yet progressed far enough to allow any predictions to be made about field situations.

Nevertheless, if fish are able to decimate snail populations, this must have consequences for the transmission of schistosomiasis. And, if this biological control method can be combined with medication campaigns, perhaps a long-lasting effect can be achieved with little effort, and at low cost.

8.1.3 Chemical Control by Mollusciciding

Basic Information

The following basic information on the chemical control of bilharzia has been taken from Jewsbury (1985).

The snail hosts of bilharzia are extremely adaptable and this, together with the great variety of aquatic habitats in which they occur, makes it virtually impossible to lay down hard and fast rules for the application of molluscicides which will be suitable in all situations.

In any mollusciciding program, a sequence of events is followed, which can best be summarized in a chart (Figure 8.4). A program such as this would take perhaps 2 to 3 years to establish effectively. Any shortcuts in the form of brief preliminary surveys, inefficient location of water bodies, inaccurate estimates of water volumes leading to under-treatment, etc., are completely counterproductive and may render the whole project totally useless as a control measure. It cannot be emphasized too strongly that efficient, comprehensive preliminary investigations over as much as 2 years are essential if a reduction in snails is to be achieved.

Once the optimum dosage rate and duration of application have been determined (the concentration-time product), the timing and frequency of the application need to be considered. Molluscicide applications should be timed to reduce snail populations immediately before the transmission seasons and, where practical, also before the periods of maximum breeding. The frequency of treatment depends on the rate of snail repopulation and this is determined by surveillance routines. Usually, it is necessary to treat relatively frequently in the early stages of a program, with treatments

	Comments
1. Mollusciciding programme decided upon and budget allocated	
2. Location and mapping of all water bodies	Requires diligent enquiry and searching
3. Comprehensive snail surveys of all these water bodies	Regular (e.g. monthly) quantitative surveys to establish population dynamics, infection rates in snails etc., to produce picture of epidemiology. Duration 1-2 years
4. Identification of transmission sites	Not all sites will contain snails; not all infested sites will be equally important in transmission
5. Selection of mollusciciding approach for each site	E.g. blanket, focal (contact point) or surveillance approaches, according to characteristics of site and degree of human contact and season
6. Detailed investigation of water at as many representative sites as necessary	To establish pH, amount and type of suspended matter, flow rates, and volumes to be treated, water usage pattern. Duration several weeks
7. Choice of molluscicide	May require more than one chemical in certain circumstances
8. Preliminary biological testing	Using local target snails in cages in natural environment where possible. Duration several weeks/months
9. Treatment regime	Dosage rate, duration, frequency, and timing of application
10. Calculation of volumes to be treated	
11. Choice of equipment	Drip feed applicators, sprayers etc. and training of operators, supervisors, etc.
12. Application	Frequent and close supervision essential
13. Evaluation	Snail surveys for short-term effects and to determine when reapplication is necessary; incidence and prevalence studies in human population
14. Costing	
15. Reconsideration of choice of molluscicide, treatment regime, equipment, etc.	

Figure 8.4 Sequence of events in a mollusciciding program (after Jewsbury 1985)

becoming more spread as the situation comes under increasing control.

There are two basic types of equipment for molluscicide application: the first is a constant-flow dispenser, designed to release liquid suspension or emulsion at a constant rate for different periods of time, according to design; the second type consists of power and hand-operated sprayers. The constant-flow dispensers are used mainly in applications to irrigation systems, but can also be used to treat rivers and streams. Sprayers are used in all situations where dispensers are not appropriate (including drains in irrigation systems) and to 'top up' molluscicide levels in areas where penetration of the chemical from dispensers is incomplete.

While the future status of mollusciciding in schistosomiasis control will depend on the type of control strategy adopted, which in turn will be determined by the local epidemiological, ecological, and socio-economic conditions, there is general agreement that judicious mollusciciding must remain among the methods of choice in any comprehensive schistosomiasis control program. Moreover, in certain circumstances, the control of the snail hosts alone, whether by chemical or environmental means, can confer substantial protection, although it is seldom that any single control measure can be advocated without reservation.

Finally, as stated by McCullough and Mott (1983), in the future, population chemotherapy, together with focal and appropriately timed mollusciciding, are most likely to spearhead schistosomiasis control programs in the endemic foci that merit high priority.

Types and Properties of Molluscicides

Various types of molluscicides are commercially available. The important ones at present are niclosamide (Bayluscide) and yurimin (a new molluscicide and particularly active against *Oncomelania*). Table 8.2 lists the properties of a number of these synthetic molluscicides (WHO 1965; 1973; 1980; 1983).

With respect to the stability of these chemicals, there is the question of their 'half-life', which is due to decomposition and to absorption in organic material and mud. Say, for example, that a molluscicide decomposes with a 'half-life' of 50 hours; then, if it takes, say, 30 hours for the molluscicide to reach the end of a canal, the toxic effectiviness at the end of the canal will be reduced by about 30 per cent, and the dosage must be increased to compensate for this natural detoxification.

A large snail population of high density can be controlled at the same cost per unit volume of water as a single snail. In fact, it is the unit of water that is treated, so, from all points of view, accurate estimates of volumes are very important. Estimating the volume flowing into an irrigation system from a single source is generally straightforward, but allowance has to be made for the capacity of dams and structures (e.g. long weirs) which cannot readily be drained. (It is of considerable help if systems are designed so that they can be drained down and filled with treated water.) Knowing the volume of water to be treated, one calculates the quantity of chemical to give the required snail kill in the time available. This is generally determined by the period during which water can be withheld from the crops, possibly between 24 and 48 hours. The chemical is then drip-fed into the supply system at the desired concentration, and the supply is managed so that treated water reaches all parts of the system in adequate concentrations. In complicated designs, this is no simple matter and achieving an effective treatment requires considerable skill in water management (NCAE 1983).

For *Bulinus* and *Biomphalaria* snails, the appropriate chemical seems to be niclosamide (Evans 1983). The dosage depends on the snail species, the temperature and pH of the water, the half-life of the chemical, and the contact time available. The longer the contact time, the lower the concentration of active ingredient needed for an equal degree of control. In a small impoundment that can be fully treated (e.g. a night-storage reservoir) and where a holding time of 24 to 48 hours is permissible,

Table 8.2 Properties of some molluscicides (Source: WHO 1965; 1973; 1980; 1983)

Characteristics	Niclosamide (Bayluscide)	N-trityl-morpholine (Trifenmorph)	NaPCP (Sodium pento-chlorophenate)	Yurimin	Copper sulfate	Nicotinanilide
Physical properties						
– Form of material	Crystalline solid	Crystalline solid	Crystalline solid	Crystalline solid	Crystalline solid	Crystalline solid
– Solubility in water	230 mg/l	very low	300 mg/l	Very low	320 mg/l	?
Toxicity						
– Snail LC_{90} (mg/l·h)*	3-8	0.5-4	20-100	4-5	20-100	5
– Snail eggs LC_{90}*	2-4	240	3-30	–	50-100	20-50
– Cercaria LC_{90} (mg/l)	0.3	No effect	–	–	–	?
– Fish LC_{90}(mg/1)	0.05-0.3	2-4	–	0.16-0.83	–	>30
Stability (affected by)						
– U.V. light	No	No	Yes	No		–
– Mud, turbidity	Yes	No	No	Yes		–
Formulations	70% W.P. 25% E.C	16.5% E.C. 4% granules	75% Flakes 80% Pellets 80% Briquettes	5% Granules	980 g/kg Pentahydrate crystals	Not yet formulated
Field dosage						
– Aquatic snails (mg/l·h)*	4-8	1-2	50-80	?	20-30	?
– Amphibious snails on moist soil (g/m^2)	0.2	–	0.4-10	5	Ineffective	?

* (mg/l·h) indicates that the figures given are the product of the concentration and the number of hours of exposure
LC Lethal concentration
LD Lethal dose
W.P. Wettable powder
E.C. Emulsifiable concentrate

Table 8.3 Comparison of molluscicide program costs for ten schistosomiasis control projects

Country	PUERTO RICO		ST LUCIA			BRAZIL		EGYPT	IRAN	TANZANIA
Locality	Vieques	Patillas	Guayama Arroyo	Cul de Sac	Sao Lourenco	Belo Horizonte	Taqua-rendi	Kom El Birka	Dez Scheme	Misungwi
Hydrology	i*	i and ii	i and ii	i	i	i and ii	ii	ii	ii	i
Annual rainfall (cm)	115	179	140	250	150	160	50	30	30	100
Controlled area (km^2)	130	122	207	18	80	200	2.5	52	220	100
Population	8,400	17,100	47,000	6,000	4,280	20,000	1,500	17,000	18,000	4,300
Annual volume of snail habitat treated (m^3)	65,000	89,000	106,400	182,000	80,000	39,000	15,000	1,354,000	500,000	200,000
Habitat volume per surface area (m^3/km^2)	500	739	514	10,000	1,000	195	6,000	16,000	2,300	2,000
Population density (persons/km^2)	64	140	227	333	54	100	600	330	82	43
Habitat volume per person (m^3)	7.8	5.2	2.3	30	18.5	2.0	10	80	28	46
Molluscicide	NaPCP	NaPCP	NaPCP	Niclo-samide	Niclo-samide	Niclo-samide	Niclo-samide	NaPCP + Niclo-samide	Niclo-samide	Niclo-samide
Cost period (years)	10	7	1	1.1	10	4	5	1	1	1
Currency	US$	US$	US$	US$	US$	US$	US$	Egypt pound	US$	Sh.T
Total cost of program	63,600	60,380	8,298	32,500	316,800	34,000	6,800	20,700	17,000	30,000
Base year for costs	1960	1960	1955	1972	1972	1968	1968	1963	1972	1972
Annual cost in 1972 US$	13,000	17,000	20,000	25,000	32,000	10,000	1,500	58,600	17,000	4,178
Annual cost per 100 m^3 treated	20	19	19	17	40	26	10	1.40	3.40	2.10
Annual cost per km^2	100	139	97	1,700	400	50	600	1,130	77	42
Annual cost per person	1.50	1.00	0.43	4.00	7.40	0.50	0.70	3.45	0.94	0.75
Program cost breakdown										
Labour	65%	61%		50%	80%	50%	36%	5%	6%	
Molluscicide	3%	6%	11%	12%	10%	11%	40%	85%	19%	25%
Transport and equipment	7%			16%	5%	15%	24%		21%	
Supervision	22%			16%		24%			54%	
Others	3%	33%	89%	6%	5%			10%		75%

*; Natural drainage systems, comprising small streams, pools, or small water collections (either natural or man-made), seepages and marshy areas
ii Irrigation systems

the concentration can be perhaps one-tenth or less of that needed in a flowing water system (e.g. a river or an irrigation system) where the contact time may be short. Preliminary experiments with caged snails are usual, and water samples are generally taken during application to ensure that adequate quantities of chemical are reaching all parts of the area being treated.

Herbicides that also have molluscicidal properties were discussed in Chapter 6, Section 6.9.3 (*The Management of Aquatic Vegetation*, Chemical Control).

There are also moluscicides of plant origin. Endod (*Phytolacca dodecandra*) remains the most thoroughly studied example (WHO 1970). Although Endod has been found to be somewhat less effective than niclosamide, its use can obviate the need to import synthetic chemicals because the substance does not require industrial synthesis and can easily be produced locally. The material has some advantages for self-help schemes, but its toxicity requires further investigation.

Costs of Control by Mollusciciding

For over 20 years, the preferred method of bilharzia control has been with the toxic chemical niclosamide, which was first used to kill snails around 1950. To obtain generalized cost information on snail control, ten well-documented and successful snail-control projects were analyzed in the late 1970's. All of them included mollusciciding, so a large body of information has been accumulated on chemical methods.

The projects covered a wide variety of endemic areas and snail habitats. To summarize the cost data in a form that allows cost estimates to be made for proposed national programs, the cost figures were analyzed according to various relevant parameters. This seemed more useful than simply reporting the mean costs and their upper and lower limits. Different strategies for snail control can thus be designed for individual epidemiological situations, and the least expensive strategy can be selected on the basis of these rough cost figures.

The cost comparison of the ten projects is presented in Table 8.3. The projects' snail habitats and schistosomiasis transmission sites can be classified under two headings: (i) natural drainage systems; and (ii) irrigation systems in which the irrigation water is led to the fields in open canals. Large irrigation systems are also provided with drains, which may add greatly to the schistosomiasis problem.

Seven of the projects represented natural drainage systems; three were in areas where both small-scale irrigation canals and natural streams represented transmission sites, although the irrigation canals were the main culprits from an epidemiological point of view. Six projects were in irrigation areas. Two of the projects were in arid areas with an annual rainfall of 400 mm or less; one area (St Lucia) is humid tropical forest; four others have distinct dry and rainy seasons.

The projects covered areas from 2.5 to 220 km^2, and had human populations ranging from 1,500 to 47,000. The population figure used in the Belo Horizonte Project in Brazil is a very conservative estimate. The area has a relatively dense population in its suburban district, but because of topographic conditions (steep hillside, limited access to transmission sites), only a certain proportion of the population (20 per cent) was considered directly involved in the transmission cycle.

The volume of water treated is based on the assumption that molluscicide was

applied at an effective concentration or dose. It is a common feature of the snail habitats to dry up during the period following the rains, so the volume of water in a given area shows cyclical (seasonal) fluctuations, which are accompanied by cyclical changes in molluscicide consumption.

The distribution of snail habitats in an area can be characterized with the index: 'cubic metres of habitat per square kilometre'. The different projects showed a wide range in this parameter: from a very low 195 m^3/km^2 in Belo Horizonte to a high of 16,000 m^3/km^2 in the Egyptian irrigation system (Ministry of Health, United Arab Republic of Egypt 1975). This parameter is an indication of the difficulty of reaching the snail habitats in terms of travelling over a given area. Low values of the term indicate a lot of travelling to reach a small volume of snail habitat, which means a costly program in terms of the results achieved.

Two molluscicides, niclosamide and NaPCP, were used. The usual strategy was to cover the whole area one or more times (blanket treatment), followed by spot treatments wherever snail colonies appeared (surveillance). In Belo Horizonte, because of local epidemiological factors, the surveillance system was used exclusively. This method consists in restricting the chemical treatment to the main transmission sites and to the transmission season. In the surveillance system, the control team worked independently of the snail-survey team, applying molluscicide at intervals of 5 to 6 weeks.

Project duration varied from 1 to 10 years. Six projects are still going on. Average annual costs of these projects ranged from U.S. $1,500 to U.S. $58,650. These figures have been adjusted to a dollar value for the year 1985.

In analyzing mollusciciding costs from these diverse areas, a geographical parameter was found, by trial and error, to be proportional to cost. This parameter would seem, logically, to reflect the difficulty of snail control. The parameter is the volume of snail habitat per unit land area, divided by the annual rainfall; it is dimensionless (Table

Table 8.4 Cost of chemical control for various projects as a function of habitat volume, area of endemic zone, and annual rainfall

Project	Cost in 1972 (in 1985 US $ per 100 m^3 treated)	A m^3 of habitat per km^2 of perendemic zone ($A = m^3/km^2$)	B Annual rainfall in m ($B = m$)	Geographic parameter $\frac{A}{B}$ ($m^3/m^3\ 10^6$
Puerto Rico				
Vieques	20	500	1.15	435
Patillas	19	739	1.79	413
Guyama	19	514	1.40	367
St Lucia	17	10,000	2.50	4,000
Brazil				
Sao Lourenco	40	1,000	1.50	667
Belo Horizonte	26	195	1.60	122
Taquarendi	10	6,000	0.50	12,000
Egypt	1.40	16,000	0.30	53,333
Iran	3.40	2,300	0.30	7,667
Tanzania	2.10	2,000	1.00	2,000

8.4). When control costs are plotted against the logarithm of this parameter, most of the data cluster along a straight line (Figure 8.5). This probably indicates the validity of the geographical index selected for analysis.

The cubic metres of habitat per square kilometre reflect the distance a control crew has to travel to reach the habitats. If the water and snails are all in one place, control is much easier than if the habitats are small and widely dispersed. The inverse effect of rainfall on cost of control is probably due to the extra humidity and protection afforded to the snail by heavy rainfall. Low rainfall lowers the snail's survival and reproduction rates.

The composition of the costs shows two extremes in the proportion of expenditures on chemicals: in Egypt, this was 85 per cent, whereas in Puerto Rico it was only 3 per cent. In the other projects, the chemical cost varied from 10 to 40 per cent. The expenses disbursed in transportation varied from 7 to 24 per cent. The balance of the yearly total cost was spent on labour, supervision, and overhead, which were sometimes not reported separately and make up 8 to 88 per cent of the annual costs. In the case of irrigation systems such as Egypt or Taquarendi, the foreign exchange costs due to the program became very significant, whereas in Puerto Rico or Sao Lourenco most of the expense went to local labour with a salutary impact on the national economy instead of a loss in foreign exchange.

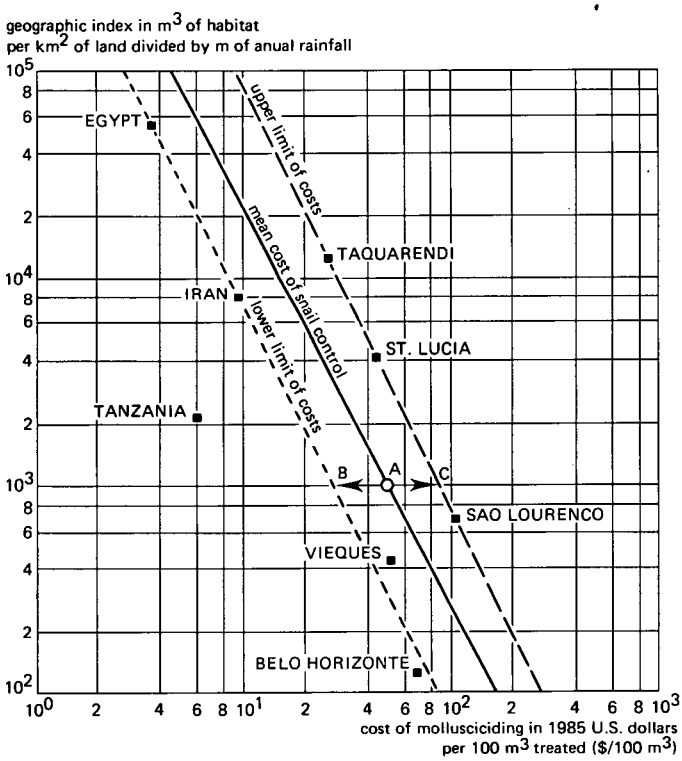

Figure 8.5 Cost of mollusciciding as a function of geographical parameters

It has been shown that the volume of snail habitat plays a role in the cost of molluscicid-ing. Reducing the volume of water held in channels and reservoirs speeds up the flow and keeps the potential breeding places to a minimum. Extra large canals that serve as longitudinal storage reservoirs require enormous quantities of molluscicide. As well, the flow in them is slow and the molluscicide does not mix easily with the water.

Example of an Application Prodecure

From an irrigated sugar cane estate in Tanzania, Fenwick (1970) presents an example of an application procedure. He discusses the factors associated with mollusciciding (e.g. duration, frequency, application methods for irrigation canals and drainage ditches).

A series of experiments were conducted to determine the optimum methods of apply-ing the molluscicide to the snail habitats so as to achieve a level of snail control that might lead to a complete break in the transmission of *S. mansoni*. Important questions were 'What are the optimum number of days per treatment to kill all adult *Biomphalaria* snails?' and 'What frequency of treatment is necessary to give effective control and hence break the transmission cycle?' From the experimental results, it is clear how persistent snails are in re-appearing and how carefully mollusciciding has to be done.

Treatments were effected at the intake for the irrigation network. Two 200-litre drums were connected in parallel to one exit pipe with a nozzle to give a flow of 400 l per 24 hours. The water flow at the intake was measured and 2.3 l trifenmorph (a chemical no longer used) was placed in each drum per 354 l/s of flow. In this way, a concentration of 0.025 ppm was achieved ($4.6 \cdot 0.165/354 \cdot 864{,}000 \cdot 10^{-6} = 0.025$ ppm).

The drums were topped up with water and the chemical was allowed to flow out. A steady emission rate was maintained with the constant-head principle. The drums were recharged every 24 hours for the duration of the treatment. From the experiments, it was concluded that 5-day applications (of trifenmorph) at 0.025 ppm every 7 weeks might lead to a break in transmission.

For the drainage ditches (main ditches), drip-feed equipment was used (trifenmorph application in a concentration of 1 ppm for 3 hours). While this was being applied, all of the smaller ditches were sprayed with knapsack sprayers.

8.2 Control of Mosquitoes

8.2.1 Biological Control Measures – General

Since larvae and pupae of the species *Aedes*, *Anopheles*, and *Culex* must breathe from the atmospheric air, it was – in earlier days – a logical step to prevent this air from reaching the larvae by oiling the water surface. This suffocated the larvae and pupae and prevented adult mosquitoes from laying eggs. The method proved successful and is nowadays still being applied on a limited scale. After World War II, oils (and other chemicals like Paris green) were largely replaced by newer and more effective larvicidal

compounds such as temephos and fenthion. From an ecological point of view, however, such chemical methods are unacceptable. Moreover, they are costly and labour-intensive. Besides, the phenomenon of resistance became an established fact. The decision to apply chemicals should be made with caution and, because they may be toxic to fish, great care should be taken in using them.

With these facts in mind, current thinking on mosquito control is moving towards a more biological approach. WHO (1982) mentions the following biological methods:

- Use of larvivorous fish;
- Use of bacteria;
- Genetic control;
- Release of nematodes;
- Release of invertebrate predators.

8.2.2 Biological Control by Fish

As in snail control by fish, one of the first fish species used to control mosquitoes in the tropics was the guppy (*Poecilia reticulata*), a fish well known in Trinidad. In the latter half of the last century, the fish was introduced into the Far East and East Africa, mainly by British health authorities.

American scientists gave their attention to a local (U.S.A.) species, *Gambusia affinis*, a small fish able to penetrate almost inaccessible places in shallow waters. Being small, the fish has little value for human consumption. The species is tough, easily adapts to different conditions, and multiplies rapidly. *Gambusia affinis* was (and perhaps still is) considered an excellent fish in the fight against malaria mosquitoes. It was spread from the U.S.A. all over the world.

There are problems, however, one of which is that the fish is not able to penetrate dense masses of aquatic vegetation so, for it to be effective, a certain amount of vegetation control is necessary (Wildekamp 1985). From investigations in Gezira irrigation canals, Salah El Safi (1985a) concluded that both *G. affinis* and *Oreochromis niloticus*, as mixed stock, are of great benefit in controlling mosquito larvae. The large *O. niloticus* feed on aquatic vegetation, thereby destroying the hiding places of the larvae. But *Gambusia* is not effective in aquatic habitats that dry out periodically, making repeated re-introductions a necessity. Moreover, *Gambusia* has an impact on some natural predators of immature mosquitoes and forms a menace to the local fish population (brood predation, heavy competition for food) (Salah El Safi 1985b). As a consequence of the introduction of *Gambusia*, some useful fish species disappeared or their numbers were severely reduced.

Keeping in mind the problems with *Gambusia*, India is making use of local species such as *Aplocheilus* and, for brackish waters, *Aphanius dispar*. But there, too, the big problem lies in the periodic drying out of the habitats and the need for re-introductions.

Promising small-scale experiments have been set up with 'seasonal' fish, of which *Notobranchius guentheri* from Zanzibar appears to be of particular value. The fish is able to bridge long periods of dryness because its eggs remain 'dormant' in the soil. With the onset of the monsoon, the eggs hatch and the fish grow rapidly. Such experiments are difficult to conduct successfully, however, because of a lack of knowledge on the biology of the fish and its specific environmental conditions.

Other promising experiments have been set up in South Somalia with some local *Notobranchius* species. That research was stimulated by the success achieved in experiments in the northern desert areas of Somalia (Alio and Isaq 1982).

The Fish Oreochromis spilurus spilurus

Probably the first trial of its kind to be scientifically planned, executed, and evaluated is the trial on the impact of the local larvivorous fish, *Oreochromis spilurus spilurus*, on malaria transmission in Burao District of Togdheer Region in Northern Somalia (Alio and Isaq 1982). This large-scale field trial has proved beyond doubt the effectiveness of this fish in controlling mosquito breeding in the man-made, excavated, ground-level, cement-lined water tanks, called *barkits*, which are the only source of water in the trial area.

For years, the control of malaria among the nomadic pastoral population of semi-arid northern Somalia has been a problem, with related economic and health implications that could not be resolved by contemporary anti-malaria measures. After the introduction of the fish into the Experimental Area 'A', a well-marked, sharp, and sustained decline was observed in vector density and slide positivity rate (i.e. the percentage of people with a negative blood-slide for malaria parasites). This was maintained from the first months of the trial up to the time it ended in June 1982.

The benefits of the trial were so tangible that they guaranteed the cooperation of the local community in distributing and maintaining the fish. When the achievements of the trial are extrapolated to other identical areas, similar public enthusiasm can be expected. An additional benefit is that the adult fish, which grows to a length of between 15 and 20 cm, is a good source of protein for the people.

The reason for the enthusiasm and satisfaction of the local population is not only the decline in malaria morbidity and a reduction of the mosquito nuisance, but also that the treated *barkits* are free from all sorts of aquatic insects and vegetation. This means that *Oreochromis spilurus spilurus* is voraciously omnivorous, and leaves the water clean. Moreover, it is very tolerant and hardy, being able to withstand difficult long-distance transportation and to survive in diverse types of permanent water bodies. Although a cost-effective comparison of the use of fish and other control methods has not yet been done, the trial clearly demonstrates that the method is very economical, besides being devoid of all the hazards and complications of residual insecticide applications.

A word of warning, however, is not amiss here. Whereas the introduction of this *Cichlide* into the strictly isolated *barkits* will not create problems, one should not forget that *Oreochromis spilurus spilurus* is a voracious fish indeed and its introduction into open waters should only be done after thorough investigations have proved that no harmful consequences will ensue for the local habitat.

It is easy to make mistakes. At the beginning of 1973, *Oreochromis* was introduced into some waters in south Somalia. Malaria prevalence was strongly reduced, but all the frogs disappeared (Figure 8.6).

Another mistake occurred when, after *Oreochromis* had been introduced into irrigation canals in the Coriole district in Somalia, the fish escaped from the canals into some neighbouring marshes. In these marshes, mosquitoes were kept under control

Figure 8.6 Source and stream of the Manaas in southwest Somalia, stocked with *Oreochromis spilurus spilurus*, but all the frogs disappeared

by *Notobranchius jubbi*. After two seasons, the *Notobranchius* had disappeared, but so too had the *Oreochromis*, not being adapted to the marshy environment. As a result, the area was rapidly infected with mosquitoes again.

The Cost of Introducing Gambusia

In 1983, the larvivorous fish *Gambusia* was introduced for larval mosquito control into the 10 villages identified in the Study Zone of the Blue Nile Health Project (BNHP). This zone was not sprayed with fenitrothion, and larval control was continued as a basic element in the strategy. The fish grew in artificial ponds, requiring the maintenance of the water level. The fish were distributed by the Entomology Team operating in the Study Zone, who devoted 10 per cent of their time to growing, distributing, and monitoring the *Gambusia* fish. The annual costs for the larvivorous fish program were U.S. $1400 (1983) or U.S. $0.07 per capita (U.S. $140 per village).

Concluding remark

Notwithstanding all the problems that can arise and all the possible errors that can be made, the use of fish in the fight against tropical diseases can be considered a promising and cheap method (Figure 8.7). But, their introduction must be preceded by thorough research.

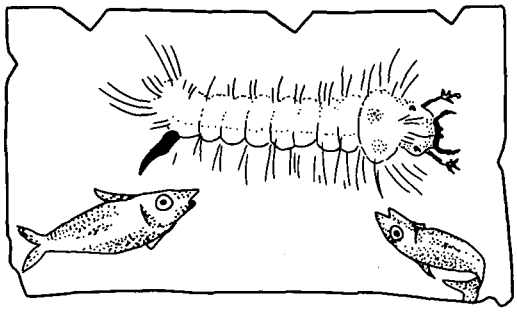

Figure 8.7 Wall painting depicting malaria control by fish, Ministry of Health, Mogadishu Somalia (after Wildekamp 1985)

8.2.3 Biological Control by Bacteria, Nematodes, Invertebrate Predators, and Genetic Control

Bacteria

Some spore-forming bacteria, and in particular certain strains of *Bacillus thuringiensis* and *B. sphaericus*, produce bacterial toxins that are lethal to mosquito larvae, but are innocuous to most non-target aquatic organisms and to vertebrates (WHO 1982). They therefore constitute environmentally safe larvicides. Larvicide formulations derived from the serotype H-14 of *B. thuringiensis* are already being used and those based on the strain 1593 of *B. sphaericus* may soon be on the market.

Nematodes

Memithidae are a family of elongated round-headed nematode worms. A large number of mermithid species have been described. One of these, *Romanomermis culicivorax*, has been mass-produced for large-scale evaluation. The potential of the mermithids for the control of ground-pool and rice-field mosquitoes could be rather high, wherever they can be recycled at operational levels after having been introduced (Mather and Trin Ton That 1984; WHO 1982).

Invertebrate Predators

Invertebrate predators play an important role in the natural regulation of mosquito populations (WHO 1982), but mass-production for biological control is extremely difficult. One outstanding exception is represented by mosquitoes of the genus *Toxorhynchitus*, but more investigations are required.

Genetic Control

Several genetic methods of mosquito control are being studied under laboratory conditions. A few, including the release of sterile males to reduce fertility, have been tested in field trials (WHO 1982).

8.2.4 Chemical Control by Larviciding and Insecticiding

The Use of Chemicals in Insect Control – Some Basic Information

The chemical control of insects forms a subject of great complexity, and local advice on the best methods to use should always be sought.

The question of resistance is a crucial one. Resistance can be accelerated by low dosages of insecticides or by the use of insecticides for other purposes (e.g. spraying rice fields with DDT against a rice pest). Thus, a vector species may become resistant to a given insecticide before it has ever been used specifically against it.

Insecticides may be effective by contact (as a stomach poison) or may have a fumigant effect. They have two application characteristics: persistence and non-persistence. In a persistent application, the objective is to apply a layer of insecticide to a surface so that the surface will remain toxic for weeks or even months (residual spraying or application). Usually, non-degradable insecticides are used (e.g. DDT, Dieldrin, BHC). These are usually applied as coarse or fine sprays of oil solutions, emulsions, dusts, or wettable powders. Slow-release mechanisms may also be classed as persistent and include paints and lacquers, plastic strips, encapsulated formulations, briquettes, and granules.

Non-persistent applications aim at hitting the insect with a droplet or placing a temporary layer on a surface that the insect will touch or eat. These are usually applied in fine sprays, mists, and aerosols of oil or water solutions (NCAE 1983; Kumar 1984).

An insecticide may have three different names:
- A trade name under which the chemical is marketed;
- A name that denotes the chemical structure;
- A common name approved by an International Organisation for Standardization.

The principal groups of insecticides currently in use in agriculture and public health are:
- Chlorinated hydrocarbons (e.g. DDT, Chlordane, BHC, Aldrin, Dieldrin, Endrin, and Toxaphene);
- Organophosphates (e.g. Parathion, TEPP, Malathion, and Diazinon);
- Carbamates (e.g. Sevin, Ortho-Bux, Elocron, and Baygon);
- Organic insecticides of plant origin (e.g. Pyrethrum, Rotenone);
- Certain dinitro and fluorine compounds, and a variety of special fumigants (e.g. ethylene dibromide and dichloride);
- Hormones and pheromones.

Some of the Carbamate compounds have been tested and used as molluscicides and mosquito larvicides (see Chapter 6, Section 6.9, *The Management of Aquatic Vegetation*, Chemical Control).

Insecticides, in general, are used in extremely small dosages. The active ingredient(s) of an insecticide formula must be distributed as evenly as possible over a wide area. Formulation is the science or art of evenly diluting the insecticide in a manner suitable for application through appropriate machinery, and ensuring that this is done conveniently, efficiently, safely, and in forms that are toxic. Common types of formulations are: dusts, granules, wettable powders, emulsifiable concentrates, aerosols, fogs, fumigants, smokes, encapsulations, and baits.

The choice of equipment for application must be consistent with the method of control. There are sprayers (manually-operated knapsack sprayers, pressurized knapsack sprayers, motorized knapsack sprayers, tractor-mounted sprayers, aerial sprayers, and ultra-low-volume sprayers) as well as dusters and granule applicators.

Malaria Control by Residual Insecticide Spraying and Larviciding

There are several approaches to malaria control, depending on the climate, epidemiology, terrain, and the mosquito species. Basic components of a control program are

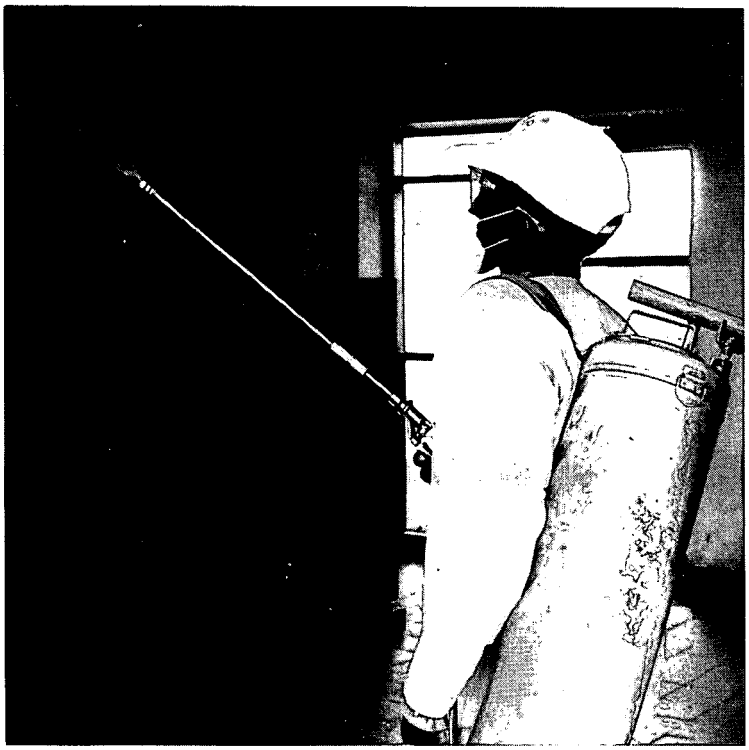

Figure 8.8 Spraying indoor resting sites of malaria mosquitoes and screening sleeping quarters are the two direct methods of attacking the malaria transmission cycle. People living in well-constructed houses with smooth plaster walls, tight-fitting windows, and screened doors can be effectively protected from malaria-transmitting mosquitoes, provided the people sleep indoors

residual spraying and larval control with chemicals.

Spraying the interior walls of houses with a residual insecticide is a highly effective and relatively cheap way of controlling transmission by killing resting mosquitoes (Figure 8.8). In 1981, in the Gezira Scheme in the Sudan, a large-scale spray-round cost 555,370 Sudanese pounds to spray 885,000 rooms and protect slightly over 1 million people. Fenitrothion, a new and expensive insecticide, was used out of necessity because the mosquito *Anopheles arabiensis* had developed resistance to all the cheaper residual insecticides such as DDT and malathion. The application of a dosage of 1 gram of active ingredient per square metre of wall cost 0.52 Sudanese pounds per capita protected. Its effect lasted 18 weeks. The operation required 1100 men and 62 vehicles.

In a malaria control project in Maharashtra, India, the annual cost of larviciding with abate was 16.4 rupees per capita and, for residual house-spraying with Malathion, the cost was 4.52 rupees per capita (1980 prices). The combination of these two measures resulted in a 78 per cent reduction in the malaria mosquito *Anopheles culicifacies* and a 25 per cent reduction in malaria infections in people (Vittal et al. 1982).

Prior to the comprehensive trial strategy in the Study Zone of the Blue Nile Health Project, the larvae of malaria mosquitoes were controlled by a weekly spraying of breeding sites near villages during the dry months of November to May. Sixty U.S. gallons of abate 50 per cent emulsifiable concentrate were used each week. The annual cost of this method was $0.09 per capita in 1982 dollars (Table 8.5). The cost of foreign purchases was $0.03 per capita, 32 per cent of the total. This practice continued until December 1982 when it was terminated because the chemical stock was depleted. To reduce costs, the larviciding was done in conjunction with focal spraying of bilharzia snails.

Table 8.5 Annual cost of larval control of anopheline mosquitoes (chemical control with abate) in 31 villages in the Study Zone of the Blue Nile Health Project, 1982

Activity	Personnel	Transport	Supplies	Total
Larviciding near villages	50% · 40.8 man-months = $ 3130	$ 259	$ 1560	$ 4949
Cost per capita (1982 U.S. $)				$ 0.09
Cost per village (1982 U.S. $)				$ 160

Control of Filariasis Mosquitoes

The filarial infections of man are spread by mosquitoes, mainly by *Culex pipiens fatigans, Culex quinquefasciatus*, and *Aedes aegypti*. Theoretically, the best strategy for control is by local programs of environmental sanitation and drainage. Thus, the cost of such programs would depend primarily on the amount of local volunteer labour contributed. Unfortunately, most urban control attempts have been based on space-spraying to kill adult mosquitoes and on larval control with chemicals. These methods have very limited success, but their costs can be estimated as approximately equal

to mosquito control operations against malaria.

In the urban type of filariasis, *Culex quinquefasciatis* is one of the main vectors. It favours breeding sites in pit latrines. Properly designed latrines (VIP-design) with screened vent pipes are a part of integrated control. (See further in Chapter 9.)

8.3 River-Blindness Blackfly Control

Very little information has been published on the costs of current programs to control the blackfly that transmits river blindness in West Africa and Central America. An exception is the annual budget of the WHO Onchocerciasis Control Programme, which has been operating in West Africa since 1975. It uses a toxic chemical, abate, to spray breeding sites in the rivers and streams of a large portion of West Africa. Each year, more than 200,000 litres of larvicide are sprayed over an area of 764,000 km^2 by helicopter and fixed-wing aircraft, flying 5,000 to 7,000 hours. The program cost was estimated at $21 million for the year 1985. The total protected population is about 13 million (in the French-speaking part of West Africa). Thus, the annual operating budget is about $1.60 per capita or $27.50 per km^2.

The direct contract costs for vector control are hard-currency expenditures. Estimates for 1985 were $14.5 million, roughly $1 per capita. There is a basic difficulty in future projections with these figures because the hard-currency requirements are rapidly increasing and the strategy implies that vector control must be continued indefinitely (Prost and Presscott 1984).

In 1956, river blindness was controlled in Western Kenya by the eradication of the blackfly *Simulium neavei* with DDT in an area of about 40,000 km^2 (McMahon et al. 1958). The annual cost of control in current prices is difficult to estimate from the figures available, but it was about $8 per km^2. The Kenyan control effort achieved eradication within the national boundaries and was thus suspended, whereas the program in West Africa does not offer that hope. The blackfly in Kenya has a shorter flight range and a somewhat different ecology from that of *Simulium damnosum*, the blackfly in West Africa. Data from Nigeria indicate that the annual present-day costs would reach about $6 per km^2.

Chapter 2 mentions the use of a new drug, Ivermectine, which kills the microfilariae in onchocerciasis patients. This drug could be used to halt transmission and obviate the need for continuing attempts to kill the fly (TDR 1988).

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9 Disease Control in the Domestic Environment

9.1 The Primary Health Care Approach

The concept of Primary Health Care (PHC) emphasizes coordination between different sectors, thereby acknowledging that public health depends not only on the health services, but also on such sectors as agriculture and public works.

At the 1978 Alma-Ata Conference, eight fundamental components of Primary Health Care were identified. They are:

- Prevention and control of locally endemic diseases;
- Provision of an adequate supply of safe water;
- Provision of basic sanitation;
- Promotion of proper nutrition;
- Immunization against major infectious diseases;
- Treatment of common diseases and injuries;
- Education in local health problems and methods of prevention and control;
- Mother and child care and family planning.

PHC workers have a major task to perform in providing these components. In addition, by collecting the data needed for epidemiological surveillance, they can help in planning control measures to reduce the transmission of diseases.

In this chapter, we present components of PHC in which engineers are involved. It is our intention to make them aware of the significance of these components in the integrated control of vector-borne diseases and in the promotion of health in general.

In tropical irrigation schemes, where many people live together and the standards of living and environmental hygiene are often low, the control of diseases in the domestic environment depends largely on improvements in housing, sanitation, and diet (PEEM 1986; Fernando 1984; Martin 1977; Scudder 1975). The health problems common to irrigation schemes often resemble those in refugee camps (Simmonds et al. 1983). Both have populations whose resistance to disease is reduced by poor nutrition and mental stress, leading not only to an increased transmission of vector-borne infections, but also to diarrhoeal and respiratory diseases.

Health goals have, for the most part, been looked upon as implicit by-products of improved housing (Stephens et al. 1985; Mason and Stephens 1981). This assumption has meant that, in the planning stages of low-income housing schemes in tropical countries, design features of housing and domestic facilities that could help to reduce disease transmission are not given enough emphasis. Often, the consequence is that, despite substantial investments, health goals are not achieved. This negative experience teaches us two lessons: the first is that health goals should be disease-specific, taking the local health situation into account; the second is that the design features of housing and domestic facilities should be tailored to fit that local situation.

Table 9.1 presents design features of housing schemes that are fundamental to good health planning. As can be seen, many of these features have a relationship with certain

diseases or health problems. If engineers are well informed on the major local health issues, they can make use of these relationships to improve public health without increasing costs.

Table 9.1 Design features of housing schemes and the diseases or health problems they can help to reduce

Design feature	Diseases/health problems reduced
Well-chosen sites for houses, schools, villages	Schistosomiasis, malaria, filariasis, sleeping sickness, leishmaniasis, Chagas' disease
Domestic water supply:	
– In adequate quantity	Trachoma, skin infections, diarrhoeal diseases
– Microbiologically safe	Typhoid fever, cholera, diarrhoeal diseases
– Bathing/Washing facilities	Schistosomiasis, trachoma, diarrhoeal diseases
– Safe water-collection points	Guinea worm, schistosomiasis, malaria, sleeping sickness
– Safe water storage	Diarrhoeal diseases, yellow fever, dengue fever
Domestic excreta disposal	
– Construction of latrines	Intestinal worm infections,
– Waste disposal	schistosomiasis, diarrhoeal diseases
Improved facilities for cooking/heating:	
– Stoves/ovens that burn less biomass fuel and reduce indoor smoke	Acute and chronic respiratory disease, respiratory malignancies
– Adequate ventilation for open indoor fires	Acute and chronic respiratory disease
– Control of open fires/Safe storage of kerosene	Burns
Preventive measures for housing:	
– Screening/Mosquito netting	Malaria and other mosquito-borne infections
– Adequate living space and ventilation	Air-borne and contact infections, epidemic meningococcal meningitis
– Minimum use of mud walls and thatched roofs	Chagas' disease, leishmaniasis
Adequate food supply:	
– From home gardens/Livestock raising	Malnutrition, undernourishment, vitamin A deficiency, iron
– Safe food storage	deficiency
Health care services:	
– For vaccinations	Measles, poliomyelitis, tetanus, whooping cough, diphtheria, meningitis, yellow fever
– For case finding and treatment	Malaria, schistosomiasis, and other infections
– For education in hygiene	Most of the above

9.2 The Siting of Settlements

The first step in the integrated strategy for controlling vector-borne diseases is to select suitable sites for housing and schools. Siting settlements away from vector habitats will reduce man-vector contact and, hence, disease transmission (WHO 1980; 1985; 1986; 1988). Although this principle applies to all vector-borne diseases, most of our

remarks in this section concern schistosomiasis, or, as it is more commonly known, bilharzia.

9.2.1 Vector Habitats and Human Travel Ranges

The selection of a site should start with a definition of likely vector habitats, which can then be pinpointed from an inspection of the design characteristics of the planned canals and drains, with the flow velocities as one of the major environmental determinants.

Once the potential vector habitats have been identified, the range of dispersal of the vectors should be demarcated. This information can be plotted on a map of the proposed irrigation scheme (Dalton and Pole 1978; Kloos et al. 1983). Human habitations will be surrounded by a zone of 'travel range' (about 1 km), which corresponds to the movements of the inhabitants. The travel range of certain epidemiologically important groups (e.g. schoolchildren and agricultural labourers) may be different. For the various age groups of schoolchildren, the travel range will be dictated by the location of their schools. For agricultural and irrigation workers, it will be dictated mainly by the land distribution system or the pattern of crop rotations. The housing and travel ranges of each ethnic or occupational group in a community should be examined separately, because these often differ. A separate analysis should be made for school-age and adolescent boys, who, being restless travellers, cover a range closer to 5 km.

The various possible sites for villages and housing should then be plotted on the map. Where the travel ranges of the people overlap the habitats and ranges of dispersal of the vectors, this should be noted. These overlapping zones represent the risk areas where people can infect snails or become infected themselves, or where mosquitoes can transmit the malaria parasite from one person to another.

9.2.2 Safe Distance of Housing from Bilharzia Snail Habitats

The concept of travel and dispersal ranges emerges most clearly in the transmission of bilharzia. If we assume that the general travel range for people of all ages is 1 km from their homes, and that bilharzia snails are found only in those portions of the irrigation system that are used for night storage, we can determine the safe distance of housing from these bodies of water with a simple mapping exercise. Examples from two irrigation schemes are presented below.

The Gezira-Managil Irrigation Scheme, Sudan

In the Gezira Scheme, the minor canals are used for night storage, but flow in the main canals is continuous and fairly fast, so they are not as conducive to weed growth or snail infestation. Thus, for a typical portion of the minor canals, the snails' habitat and dispersal range are easy to specify. Figure 9.1 shows the overlap of the human and snail ranges around two villages in the Scheme. Village A is located near a major

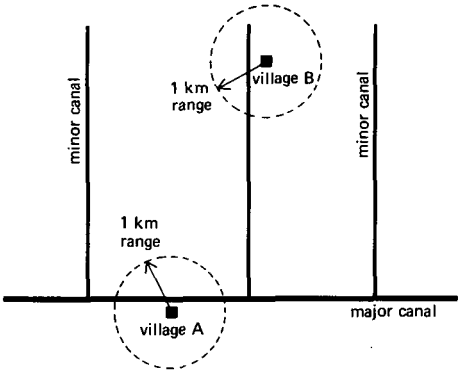

Figure 9.1 Overlap of human and snail travel ranges around two villages in the Gezira-Managil Irrigation Scheme

canal, exactly in the middle of the reach between two minor canals that are spaced 3000 m apart. The normal human travel range for this village overlaps only slightly with any of the normal habitats of the snails, so serious persistent transmission should not be a problem. Nevertheless, the secondary-school children of Village A must cross the snail-infested minor canal to reach their school in Village B. Therefore, the secondary-school children in Village A can be expected to have a significantly higher prevalence of bilharzia infections than other age groups in their village.

In contrast to Village A, everyone in Village B lives near the tail of the minor canal, which is a principal zone of bilharzia transmission. This canal carries a double risk: it is used for night storage and it is extremely stagnant, offering in both cases a favourable environment for aquatic weeds and snails. The inhabitants of Village B are in daily contact with the snail-infested water. As expected under such conditions, the prevalence of infection is extremely high – approaching 96 per cent. In Village A, this rate is less than 50 per cent.

The Hippo Irrigation Scheme, Zimbabwe

In the Hippo Scheme, bilharzia is also a serious problem. The Scheme's layout, however, is geared to irrigated sugar cane and so is quite different from that of the Gezira. Housing is also arranged differently, producing a geographic pattern of infection related primarily to the night-storage reservoirs and the drainage system. The night-storage system makes use of small reservoirs scattered throughout the fields. These reservoirs, which are ideal habitats for snails, make very attractive places to bathe or swim. For various reasons, the drainage system in the Hippo Scheme is quite extensive, and the lower portions are traversed by several small rivers that collect water from the agricultural drains.

Most of the distributary canals are lined and the flow velocity in them is very fast, making them unsuitable habitats for snails. The canals or field ditches downstream of the numerous reservoirs are unlined, but the flow is turned off every night, making them equally unsuitable as snail habitats.

In the villages near the night-storage ponds, and in the dormitory housing for single men, bilharzia is a serious problem. In housing near the main distributary canals, however, the incidence of the disease is lower; the swift flow in those canals prevents colonization by snails and reduces human-water contact because of the danger it poses to poor swimmers.

Not all of the men in the labour force are single – some come with their families, even though housing is not provided by the Scheme management. These men sometimes build a family home on the unused lands near the drains or near the natural stream system into which the drains enter (Figure 9.2). This often results in severe infections among the families, especially in those areas where the drains flow often enough during the year to make snail infestation possible. Where schools are located near these drains, the schoolchildren are at additional risk of infection while travelling to and fro or playing around the school building, regardless of the location of their homes.

Various estimates have been made of the safe distance of villages from infective snail habitats, but perhaps the most reliable one comes from the recent studies in the Blue Nile Health Project, which were made in the Study Zone of the Gezira Scheme (see Volume 2, Annex 4).

9.2.3 Infection in Snails as a Function of Their Proximity to Housing

In addition to man-vector contact, the intensity of bilharzia transmission also depends on the relationship between the prevalence of infection in snails and the proximity of their habitats to human dwellings. Tiglao and Camacho (1983) illustrated this relationship with data from a study of water-contact behaviour among people in an area

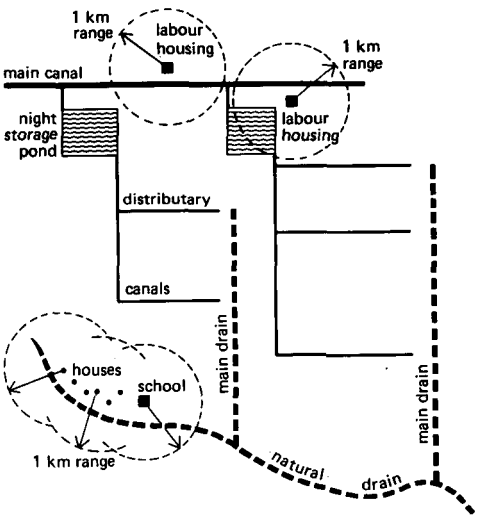

Figure 9.2 Typical housing situation in the Hippo Irrigation Scheme, Zimbabwe

of The Philippines where *Schistosoma japonicum* (Asian bilharzia) is prevalent (Figure 9.3). The data show that, around the houses of people with bilharzia, the contamination of soil and water by infected faeces and urine decreases drastically with distance, thus reducing the infection pressure on the snail population. The prevalence of infection in the snail population falls off very rapidly in the first 100 m from the houses, but does not decrease significantly thereafter.

9.3 Adequate Supply of Safe Water

The basic function of water in human well-being is twofold: it satisfies physiological requirements and it facilitates hygiene. If a water supply does not meet certain minimum standards of the quantity available per person per day or of microbiological and chemical safety, public health will progressively deteriorate (McJunkin 1982).

The 'social costs' of water supply can be expressed in terms of the occurrence of water-related diseases or of the time and energy expended by women, whose duty it is to collect water for the household (van Wijk-Sijbesma 1985; Feachem et al. 1978).

In 1985, only about 42 per cent of the people living in rural areas of developing countries had reasonable access to safe drinking water. Although this percentage compares favourably with the estimated 31 per cent in 1980, the number of people without safe drinking water (around 1000 million) remained nearly the same because of population growth. For these people, the drinking-water situation will be about the same as the classical situation described by White et al. (1972) for East Africa. In those circumstances, it is common for the 'water-collection journey' to demand 2 to 4 or more hours each day of a housewife's time. The average time needed to fetch water in 12 East African rural villages was 46 minutes per household per day. Times for individual households, however, ranged from 3 to 264 minutes per day. The average energy expenditure was 240 calories per household per day, with a range from 0 to 1930 calories.

On the basis of annual reports from ministries of health in East Africa, it was found

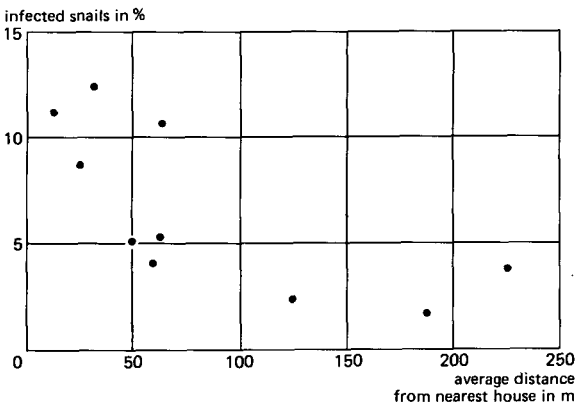

Figure 9.3 Relationship between the prevalence of *S. japonicum* in *Oncomelania quadrasi* and the proximity of snail habitats to housing (Palo, Leyte, The Philippines)

Table 9.2 Environmental classification of water-related infections

Category	Infection	Pathogenic agent	Preventive strategy
1) Faecal-oral (water-borne or water-washed)	Diarrhoeas and dysenteries		
	Amoebic dysentery	P	
	Balantidiasis	P	
	Campylobacter enteritis	B	
	Cholera	B	
	E. coli diarrhoea	B	Improve quality of drinking water
	Giardiasis	P	
	Rotavirus diarrhoea	V	Prevent casual use of other unimproved sources
	Salmonellosis	B	
	Shigellosis (bacillary dysentery)	B	
	Yersiniosis	B	Improve accessibility and reliability of domestic water supply
	Enteric fevers		
	Typhoid	B	
	Paratyphoid	B	Improve hygiene
	Poliomyelitis	V	
	Hepatitis A	V	
	Leptospirosis	S	
	Ascariasis	H	
	Trichuriasis	H	
2) Water-washed:			Increase water quantity used
a) skin and eye infections	Infectious skin diseases	M	
	Infectious eye diseases	M	Improve accessibility and reliability of domestic water supply
b) other	Louse-borne typhus	R	
	Louse-borne relapsing fever	S	
			Improve hygiene
3) Water-based:			
a) penetrating skin	Schistosomiasis	H	Decrease need for contact with infected water
b) ingested	Guinea worm	H	
	Clonorchiasis	H	
	Diphyllobothriasis	H	Control snail populations
	Fasciolopsiasis	H	
	Paragonimiasis	H	Reduce contamination of surface waters by excreta
	Others	H	
4) Water-related insect vector			
a) biting near water	Sleeping sickness	P	Improve surface water management
b) breeding in water	Filariasis	H	
	Malaria	P	Destroy breeding sites of insects
	River blindness	H	
	Mosquito-borne viruses		Decrease need to visit breeding sites
	Yellow fever	V	
	Dengue	V	Use mosquito netting
	Others	V	

B = Bacterium P = Protozoon R = Rickettsia V = Virus
H = Helminth M = Miscellaneous S = Spirochaete

Adapted from Cairncross and Feachem (1983)

that diseases potentially related to water supply are responsible for 11 per cent of hospital deaths, 12 per cent of in-patient diagnoses, and 21 per cent of out-patient diagnoses. Against this background, a tragic linkage between inadequate supplies of safe water and high levels of disease and high rates of infant and child mortality is inescapable.

Bradley (1974) differentiated four categories of water-related infections. They are presented in Table 9.2.

9.3.1 Water-Supply Systems and Rates of Water Consumption

The total daily per capita consumption of water is determined by many factors: the availability of water, its quality, its cost, the income and size of the family, regional customs, standard of living, ways of water distribution, and climate (Cairncross and Feachem 1978; DHV 1979a, 1979b; Hofkes 1986; USAID 1982; Wagner and Lanoix 1959). Table 9.3 presents the average per capita rate of domestic water consumption in rural areas of developing countries according to the method of supply – by communal water point (village well or public standpipe) or by individual home outlet (single tap or multiple taps). Planners should add about 20 per cent to the figures to cover the demand for non-domestic purposes (e.g. water for gardens, livestock, handicrafts, and light industry). The ultimate design capacity will be determined by the design consumption figure plus an allowance for losses and wastage (about 25 per cent) and the mode of operation of the water supply system (continuous or intermittent). Planners should tailor a water policy to fit the circumstances of a particular country rather than aim for universal solutions.

Table 9.3 Average daily rate and range of domestic water consumption for water-supply systems in rural areas (in litres per capita)

Water-supply system	Average daily rate of consumption	Average daily range of consumption
Communal water point		
Well (unpiped supply)	15	5 – 25
Standpipe (piped supply)	30	10 – 50
Individual home outlet		
Single tap (piped supply)	50	10 – 100
Multiple taps (piped supply)	150	50 – 300

Source: Feachem et al. (1977)

Communal water points can be wells or boreholes, or a system of public standpipes. In general, if a well or borehole is the water point, no piped distribution system is installed. Public standpipes, however, will require such a system. Table 9.4 gives the recommended criteria for communal water points.

Table 9.4 Recommended criteria for communal water points

Basic consideration	Recommended criterion
Average demand	40 l/capita/day (includes allowance of 25% for losses and waste)
Demand pattern	2 peak periods daily of 3 hours each
Maximum walking distance to water point	500 m
Maximum number of people supplied by water point	250 people for each l/s (at effective utilization rate of 50%
Maximum number of households supplied by water point (average size of household: 7)	35 households for each l/s (at effective utilization rate of 50%)

The investment costs of community water-supply schemes are determined mainly by the costs of materials and labour. These can vary widely, depending on regional and local circumstances, the size of the scheme, and the type of technology applied. Table 9.5 compares construction costs, water costs, and water consumption rates (both the design rate and the actual rate) in rural areas around the world.

Table 9.5 Comparison of water consumption rates and water costs in rural areas around the world

Region	Design rate of consumption (in l/cap/day)	Actual rate of consumption in 1985 (in l/cap/day)	Unit costs of construction (in (U.S.$/cap*)	Average water costs (in U.S.$/ m^3*)
Africa	35	24	$ 40.00	$0.50
Latin America	130	94	$ 88.00	$0.11
S.E. Asia	55	47	$ 14.00	$0.16
E. Mediterranean	128	62	$142.00	$0.40
W. Pacific	104	83	$ 49.00	$0.32
Least-developed nation			$ 39.00	$0.40

* Median values of national averages. After WHO (1986). The International Drinking Water Supply and Sanitation Decade (1981-1990). Review of National Progress (as of December 1983)

9.3.2 Per Capita Consumption of Safe Water and Public Health

Useful data correlating the incidence of bilharzia and diarrhoeal diseases with the rate of daily per capita consumption of safe water have been collected from the Study Zone of the Blue Nile Health Project. The village water-supply systems in the Study Zone were monitored for one year before any engineering improvements were made to them. The monitoring was done by the pump operators, who kept daily records of the hours of operation, the amount of water pumped, the amount of fuel or electricity used, and any operational problems. At the same time, test villages were selected

and a census was taken. The villagers were given check-ups and stool samples were examined.

The data revealed that when the daily per capita consumption of safe water was increased from 40 litres to 70 litres, the following occurred:

- The incidence of diarrhoeal diseases dropped from 60 per cent to 35 per cent, accounting for an appreciable decrease in infant mortality;
- The incidence of bilharzia dropped from 50 per cent to 40 per cent.

(For a more detailed account of the findings from the Study Zone, see Volume 2, Annex 4.)

9.3.3 Costs of Village Water-Supply Systems

Several recent reports (e.g. Tamein et al. 1985) have listed the costs of constructing or improving village water-supply systems to prevent bilharzia and diarrhoeal diseases. The costs of four of these systems – two on the Gezira Plain of central Sudan and two on the hilly Caribbean islands of St Lucia and Puerto Rico – are compared below.

The Study Zone of the Blue Nile Health Project

The entire population of the Study Zone was at risk of being infected with bilharzia or a diarrhoeal disease, especially those who lived outside the 26 villages of the Study Zone and were obliged to obtain unsafe water from canals and shallow wells. The 26 villages are supplied from a typical deep bore-well system, which includes a pump and an elevated storage tank with a capacity of 45 m^3. In 1982, the combined costs of capital, operation, and maintenance amounted to U.S. $196,000, or U.S. $3.44 per capita for a population of 57,000. In that year, the total daily consumption of safe water from the 26 village supply systems was 2491 m^3, or a daily per capita mean of 44 litres.

A plan was made to improve the capacity and reliability of the existing supply systems so that the mean daily per capita consumption of safe water could be raised to 70 litres by 1985. The resulting total annual cost increase for extra capital investment in, and more intensive use of, the supply system worked out to about U.S. $1.10 per capita, in 1984 prices. If this amount is added to the initial annual per capita cost of U.S. $3.44, the final cost of the increase in water consumption is about U.S. $4.50 per capita, in 1984 prices.

If the cost of the improvements is divided equally among the three benefits of a safe water supply – lowered incidence of bilharzia, lowered incidence of diarrhoeal diseases, a reduction in labour – then the price of any one of these benefits is 1/3 of U.S. $1.10, or an extra U.S. $0.37 per capita annually.

These figures are set out in graphs in Volume 2 (Figures 4.5 and 4.8). Planners can use these figures – or other figures obtained from their own experience and expressed in relation to daily per capita consumption – to compare the cost effectiveness of improving a water-supply system with that of other disease-control methods. The figures are also suitable for assessing the net cost effectiveness of a community water-supply system.

Cost figures require constant re-assessment, but the relationship between disease prevalence and daily per capita consumption rates of safe water is generally applicable throughout the Sahel and in similar areas where intestinal bilharzia is endemic.

The Rahad Irrigation Scheme, Sudan

Although the Rahad Irrigation Scheme and the Study Zone are in the same part of the Sudan, their village water-supply systems are quite different. Because subsurface water is not readily available in the Rahad Scheme, most of the villages use canal water that first has been allowed to settle and then has been filtered through sand and chlorinated.

In 1980, from the Rahad Scheme's budget for construction, operation, and maintenance of all village water-supply systems, U.S. $314,000 was allocated for bilharzia prevention. By 1983, the rising value of the U.S. dollar against the Sudanese pound had reduced this amount to U.S. $136,000 (see Table 9.6). The unfavourable rate of exchange also curtailed the purchasing power of the Sudanese pound in the international market, leading to shortages of spare parts and fuel in the Scheme. The major cost component in the Scheme's budget for water-supply systems is construction – about 60 per cent of the total.

The total cost of water supply in the Scheme in 1983 was U.S. $408,000 (3 times the amount for bilharzia control) for a population of 110,000, or U.S. $3.71 per capita. Precise figures were not available for per capita consumption in 1983, although the design figure is 100 litres per capita daily. That may have been the consumption rate in 1980, when the systems were quite new, but the annual per capita cost was much higher then because the population was only 80,000. By 1983, the performance of the systems had deteriorated because of malfunctions and frequent blocking of the sand filters. A good estimate of daily per capita water consumption in that year would be about 75 litres, at an annual per capita cost of about U.S. $4, about the same as in the Study Zone.

The St Lucia Scheme, Windward Islands

On the mountainous Caribbean island of St Lucia, where intestinal bilharzia transmission was occurring in several valleys, it was decided to control transmission by providing safe water for domestic use. Accordingly, an experimental scheme to pipe water from safe, upstream sources to individual households was implemented in Riche Found Valley. Prior to the scheme's implementation, these households had obtained all their domestic water from nearby streams that contained infected bilharzia snails. Jordan et al. (1978; 1982) evaluated the cost of the scheme and the effect of a safe water supply on bilharzia transmission.

The St Lucia Scheme was planned to serve about 2000 people in 5 rural settlements. It took 2 years to complete – from 1970 to 1972. The Scheme was especially intended to encourage the women to do their laundry at home rather than in the snail-infested streams. In the villages with the new water systems, the incidence of bilharzia dropped from 56 per cent in 1970 to 38 per cent in 1975. The intensity of infection (i.e. mean

Table 9.6 Number of village water-supply systems in the Rahad Irrigation Scheme, their costs, and the total costs for bilharzia control* (1980-1983)

	1980	1981	1982	1983
Number of village water-supply systems	43	47	47	47
Investment costs, depreciation, & interest				
• Investment costs[1]	3,844,000	4,014,000	4,064,000	4,164,000
• Depreciation & interest[1] (50 years at 10% interest)	461,000	481,000	487,000	499,000
• 1/3 of depreciation & interest for bilharzia control[1]	154,000	160,000	162,000	166,000
Operation & maintenance, Foreign costs				
• Personnel costs[1]	91,000	99,000	99,000	99,000
• 1/3 of personnel costs for bilharzia control[1]	29,000	30,000	30,000	33,000
• Foreign costs[1] (e.g. machinery)	255,000	252,000	180,000	108,000
• 1/3 of foreign costs for bilharzia control[2]	85,000	84,000	60,000	36,000
Summary of costs for bilharzia control				
• 1/3 of depreciation & interest[1]	154,000	160,000	162,000	166,000
• Personnel costs[1]	29,000	33,000	33,000	33,000
• Local costs[1]	183.000	193.000	195.000	199.000
• Free market value of U.S.$[1]	.80	.90	1.25	2.00
• Local costs[2]	229,000	214,000	156,000	100,000
• Foreign costs[2]	85,000	84,000	60,000	36,000
• Total costs for bilharzia control[2]	314.000	298.000	214.000	136.000

* Calculations are based on the assumption that domestic water-supply systems bring three major benefits: prevention of bilharzia, prevention of diarrhoeal diseases, reduction of labour. Costs for bilharzia control have therefore been reckoned as one-third of the total cost of a domestic water-supply system

[1] Price in Sudanese pounds

[2] Price in U.S.$

egg counts in the remaining infections) also decreased. Thus the contamination potential of the community – the sum of the products of prevalence and egg counts for each age group – declined steadily until, by 1975, it was 68 per cent lower than in 1970. Although a small drop in this index was also measured in nearby untreated

villages, most of the decline in the Scheme villages can be ascribed to the availability of safe water.

The water piped to the individual households was used extensively to meet domestic requirements, and collection of water from the river ceased. Yet even with running water available, not all of the women wanted to do their laundry at home. Those who lived near the river still preferred to use the traditional washing site, where they could also socialize. When the initial laundry and shower units, which had been built to serve the houses high above the river, proved immediately popular, others were built near the river, on sites agreed to by the women. These units, too, became very popular. They are believed to have been essential to the Scheme's success. In particular, their use meant that the children accompanying the women no longer had occasion to play in the river and, eventually, that many children were bathed in the laundry tubs instead of in the river.

In 1975, the water-supply system delivered 65 litres per capita daily at a total approximate cost of U.S. $8.90 per capita (Table 9.7), and the incidence of bilharzia dropped to less than 38 per cent. This prevalence-consumption relationship coincides with the curve measured in the Gezira Scheme (Volume 2, Figure 4.6), where a daily water-consumption rate of 60 litres per capita corresponds to a bilharzia-incidence rate of 40 per cent.

Table 9.7 Expenditures of the St Lucia Scheme for 1975 (in U.S.$)

Item	Cost	Per capita cost
Capital Investment		$1.30
Operation		
– Electricity	$ 3171.00 (35%)	
– Materials/equipment	1319.00 (14%)	
– Labour		
• Caretaking/Pool maintenance	3791.00 (41%)	
• Emergency work	869.00 (9%)	
• Other	31.00 (.3%)	
Total	$ 9181.00	or 9181/2000 = $4.59
Supervision		
– Principal engineer		6000/2000 = $3.00
Total		$8.89
Repayment		$ .15

Puerto Rico

The St Lucia study of the impact of safe water supplies on bilharzia transmission was expanded to include an island-wide operational program on Puerto Rico. This program's water-supply systems delivered 330 litres per capita daily to almost 3 million people, at an annual cost – including capital, operation, and maintenance – of about

U.S. $50 per capita (1984 prices).

The per capita cost of water on Puerto Rico corresponds to a bilharzia prevalence rate of only 4 per cent. This rate does not correspond to the prevalence-consumption relationship found in the Sudan, because the Puerto Rican study included data from large urban areas – where there are no vector snails – and from some irrigation schemes where active bilharzia control was practised.

The costs of the four village water-supply systems and their impact on bilharzia transmission are presented in Table 9.8. In the two Sudanese irrigation schemes, where the water-supply systems serve villages of over 1000 people and the topography is very flat, the per capita costs are about U.S. $4. These costs cover multiple benefits (e.g. prevention of bilharzia, prevention of diarrhoeal diseases, and reduction of labour). On the mountainous islands of Puerto Rico and St Lucia, where the systems are small and serve houses on hillsides, the total annual per capita cost rises to U.S. $20 or more. Although the per capita cost on Puerto Rico is about 3 times that on St Lucia, the Puerto Rican systems deliver about 5 times more water per capita than the St Lucia systems.

Table 9.8 Comparison of per capita costs of water-supply systems and the incidence of intestinal bilharzia in the Sudan and the Caribbean Basin

Location	Year of observation	Total per capita cost (U.S.$)	Mean rate of of water consumption (l/cap/day)	Incidence of intestinal bilharzia (%)
Sudan				
Gezira	1982	$ 3.39	40	35%*
Gezira	1984	$ 4.54	70	(10-20%)
Rahad	1983	$ 3.71	73	10%*
Caribbean Basin				
St. Lucia	1974	$ 8.90	65	38%
Puerto Rico	1975	$27.00	330	4%

* Percentage in large areas that included non-endemic villages. This rate does not illustrate the precise consumption-prevalence relationship observed in villages in the Study Zone and on St Lucia, which were all in heavily endemic areas

9.4 Basic Sanitation

Excreta disposal and waste collection are common problems anywhere in the world. In developed countries, they have been solved by vast investments in technologically advanced solutions. Small-scale waste-disposal technology, appropriate for the rural parts of developing countries, has lagged behind (Pacey 1980).

In many parts of the developing world, human excreta are regarded as valuable commodities and are carefully collected and sold for use in fish farming and agriculture. In other countries, the majority of the rural population defecates in the immediate vicinity of houses and in fields. These time-honoured and culturally accepted practices are difficult to change. They form a major impediment to the improvement of environ-

mental sanitation and, hence, to the control of diarrhoeal diseases, schistosomiasis, hookworm, and other infections. In 1985, only 18 per cent of the rural population in developing countries had adequate excreta-disposal facilities, and this figure was based on a very modest definition of 'adequate'!

Feachem et al. (1983) have identified six classes of excreta-related infections. They are presented in Table 9.9.

Rural sanitation is no longer primarily a technical problem. Appropriate and cheap designs for pit latrines and composting pits, suitable for application in rural situations, are now available (Feachem et al. 1977; Cairncross and Feachem 1983; World Bank Technical Notes 1-14).

Excreta-disposal systems should meet the criteria of Wagner and Lanoix (1958). In order of priority, these are:

- The system should be simple and inexpensive to construct, operate, and maintain;
- The handling of fresh excreta should be kept to a minimum;
- Excreta should not be accessible to flies or animals;
- The contamination of wells and springs should be avoided;
- Surface water should be safeguarded against pollution;
- The surface soil should not be contaminated;
- There should be freedom from odours and unsightly conditions.

Improving sanitation for the millions of villagers in developing countries is one of the greatest challenges for health planners. Cairncross and Feachem (1983) summarized the guiding principles of a rural sanitation program as follows:

- Excreta disposal is a sensitive matter about which people have strong cultural preferences. Therefore it is imperative to achieve the maximum involvement of the community in the design and implementation of any latrine programme. Solutions imposed from the outside are unlikely to succeed. Often, a modification of an existing practice or type of latrine may be much easier to implement than a completely new package of technology;
- People require a reason or a motivation for using a new kind of latrine. In general, health improvement will not provide such a motivation because the connection between latrine usage and health will not be perceived. Experience in South East Asia indicates that an economic motivation (e.g. the use of excreta in agriculture or fish farming) may sometimes provide the necessary incentive. Another motive might be the desire for privacy;
- Any type of latrine needs good maintenance and will become fouled and offensive without it. If this is allowed to happen, the latrine will either not be used or will become a major health hazard in itself. There is evidence that the use of a fouled latrine in rural areas provides a greater health hazard than the practice of casual defaecation in the surrounding bush.

9.4.1 Excreta-Disposal Systems

The many systems of excreta disposal are all variants of three basic systems: infiltration, destruction, and removal (Cairncross 1988; USAID 1982).

Table 9.9 Environmental classification of excreta-related infections

Category	Infection	Pathogenic agent	Dominant transmission mechanics	Major control measures (engineering measures in italics)
1) Faecal-oral (non-bacterial) Non-latent, low infectious dose	Poliomyelitis	V	Person-to-person contact	*Domestic water supply*
	Hepatitis A	V	Domestic contamination	*Improved housing*
	Rotavirus diarrhoea	V		*Provision of toilets*
	Amoebic dysentery	P		Health education
	Giardiasis	P		
	Balantidiasis	P		
	Enterobiasis	H		
	Hymenolepiasis	H		
2) Faecal-oral (bacterial) Non-latent, medium or high infectious dose, moderately persistent and able to multiply	Diarrhoeas and dysenteries		Person-to-person contact	*Domestic water supply*
			Domestic contamination	*Improved housing*
	Campylobacter enteritis	B	Water contamination	*Provision of toilets*
	Cholera	B	Crop contamination	*Excreta treatment prior to re-use and discharge*
	E. coli diarrhoea	B		
	Salmonellosis	B		Health education
	Shigellosis	B		
	Yersiniosis	B		
	Enteric fevers			
	Typhoid	B		
	Paratyphoid	B		
3) Soil-transmitted helminths Latent and persistent with no intermediate	Ascariasis	H	Yard contamination	
	Trichuriasis	H	Ground contamination in communal defaecation area	*Excreta treatment prior to land application*
	Hookworm	H		
	Strongyloidiasis	H	Crop contamination	

tapeworms			Field contamination	*Excreta treatment prior to land application*
Latent and persistent with cow or pig intermediate host			Fodder contamination	Cooking and meat inspection
5) Water-based helminths latent and persistent with aquatic intermediate host	Schistosomiasis	H	Water contamination	*Provision of toilets*
	Clonorchiasis	H		*Excreta treatment prior to discharge*
	Diphyllobothriasis	H		
	Fasciolopsiasis	H		Cooking
	Paragonimiasis	H		
6) Excreta-related insect vectors	Filariasis (transmitted by mosquitoes) *Culex pipiens*	H	Insects breed in various faecally-contaminated sites	*Identification and elimination of potential breeding sites*
	Infections in Categories 1-6, especially 1 and 2, which may be be transmitted by flies and cockroaches	M		Use of mosquito netting

B = Bacterium P = Protozoon V = Virus
H = Helminth M = Miscellaneous

Source: Cairncross and Feachem (1983)

Infiltration

Infiltration is the absorption and dispersion of excreted materials into the soil or groundwater. This type of system is commonly used in rural areas, where a sewerage system is often impracticable and the population density is low. It is a potential source of contamination of the water supply. Low-cost options for sanitation improvement include:

- Pit latrines, which are essentially nothing more than a hole in the ground. These latrines are commonly used as a temporary excreta disposal method or as a first step in the development of a village sanitary system. The cheapest improvement to a pit latrine is a prefabricated floor in the form of a squatting slab with a lid to cover the hole. In some countries, a seat is more acceptable than a squatting slab, although the cost is higher. Pit latrines often become breeding sites for flies and mosquitoes. Odour is a persistent problem;
- Ventilation-Improved Pit latrines (or VIP latrines), which alleviate the two principal disadvantages of conventional pit latrines. The vent pipe reduces odours, and its spiral-shaped superstructure, covered by a fly screen (mesh 1 mm), reduces the numbers of flies that can enter (Figure 9.4).

  In controlled experiments in Zimbabwe (Morgan 1977), 13,953 flies were caught during a 78-day period from an unvented pit latrine, but only 146 were caught from a vented (but otherwise identical) pit latrine. An additional device effective against flies and mosquitoes is a fly trap, which is placed over the drophole instead of a cover.

  Although the single-pit VIP latrine can be designed for long use, it is often more convenient (and possibly less expensive) to use a twin-pit VIP latrine. In this version, one pit is used until it is full; then the second pit is put into use. When that pit is full, the first is emptied and used again;

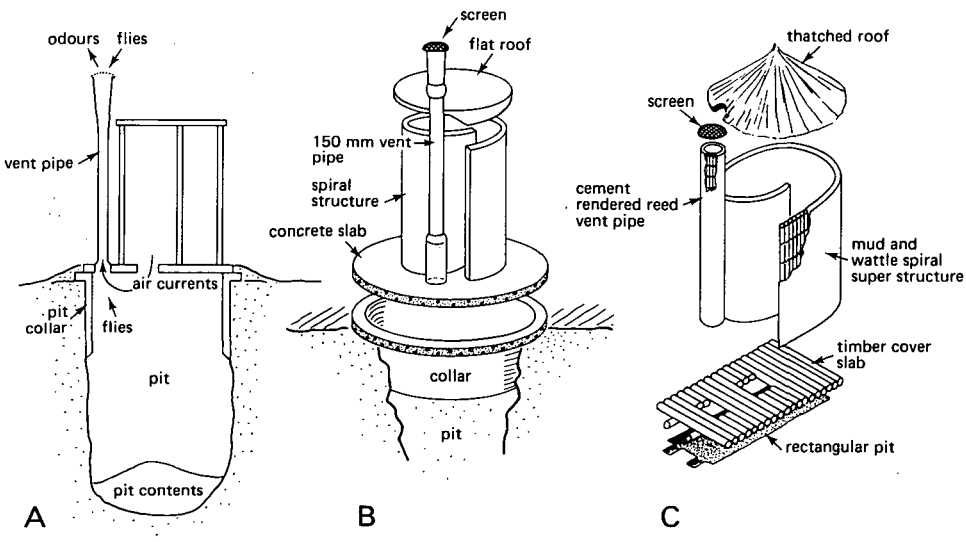

Figure 9.4 A Ventilation-Improved Pit Latrine (or VIP latrine)

- Pour-flush toilets, which offer the further improvement of a water seal below the seat or squatting pan. The water seal – a U-shaped pipe filled with water – completely prevents the passage of flies and odours. While the small quantity of water used in pour-flush toilets is not enough to operate them on a conventional sewerage system, it is nevertheless enough to carry excreta to a soakage pit up to 8 m away;
- Septic tanks, which are watertight settling tanks to which wastes are carried by water flushing down a short sewer. A septic tank does not dispose of wastes; it only helps to separate them and digest the solid matter. The liquid effluent flowing out of the tank remains to be disposed of, normally in a soakage pit or drain field, and the accumulating sludge must be periodically removed. Certain modifications will make the septic tank suitable for use in areas where the population density is 200 to 300 people/ha.

Communal latrines are usually cheaper to build than individual household latrines. They have many disadvantages, however, and the decision to introduce them should not be taken lightly.

Destruction

Destruction is the conversion of excreta and other wastes into useful and harmless substances. This system is based on:

- Composting toilets, which use dry composting techniques to destroy wastes and provide an inoffensive, stable soil conditioner. The twin-vault VIP is, in fact, a kind of composting latrine with a prolonged decomposition time. Designs for composting toilets in which the composting process is accelerated, thereby permitting a smaller chamber and more frequent emptying, have been used successfully in Vietnam and Guatemala. In the Vietnamese double-vault composting latrine, urine is collected separately and ash is added after use. When full, a chamber is sealed for two months, after which the compost is removed and applied to the land. Latrines of this type cannot be introduced into an area without an enormous supporting effort to ensure that they are used properly.

Removal

Removal is the collection and transportation – either manually or through a sewerage system – to a discharge site or central facility for further processing. Waste-disposal systems relying on excreta removal are used mostly in urban areas. They are:

- Bucket latrines, which consist of a squatting slab or seat placed immediately above a bucket. The bucket is positioned in such a way that it can be removed from the back of the cubicle. It is filled within a few days by the excreta of an average family. A collector calls regularly (once or twice a week) to empty the bucket. The wastes are carted off or carried away by truck. This is one of the oldest, and generally least hygienic, of the sanitation systems. The handling and spillage of the wastes typically results in heavy contamination of the site and of the depot where the contents are emptied for treatment, composting, or use in agriculture. A bucket system can only work well under situations of tight institutional control, where all opera-

tions are carefully supervised. It should be considered a temporary measure, to be used only while more permanent solutions are being sought;
- Aquaprivies, which are essentially septic tanks located directly underneath a squatting plate. VIP latrines and pour-flush toilets are less expensive than aquaprivies and less prone to malfunctioning;
- Cesspools, which are covered chambers that receive all waste water from a dwelling or dwellings.

9.4.2 Selection of an Excreta-Disposal System

An excreta-disposal system should never be imposed on a community from outside. Technical criteria for the selection of an excreta-disposal system are the size of the area to be served, the density of population and housing, the cultural patterns, the level of development, and the soil-drainage conditions. The most critical consideration is the effect an excreta-disposal system will have on the per capita rate of water consumption. Pour-flush toilets and aquaprivies use moderate amounts of water. Conventional water-flushed toilets with indoor cisterns use large quantities of water. If the volume of waste water generated exceeds 50 litres per person daily, some sort of sewerage system will be required.

Another important consideration in selecting an excreta-disposal system is the cost to each household. In developing countries, barely 3 per cent of household expenditure is for sanitation. The comparative costs of various systems are given in Table 9.10.

Table 9.10 Comparative monthly costs of various excreta-disposal systems per household (in U.S.$)

Excreta-disposal system	Approximate monthly cost*
Pit latrines	5
Pour-flush toilets	5
Composting toilets	5
Cartage	5
Aquaprivies	15
Septic tanks	45
Conventional sewerage	45

* Includes payments on investment loans at a hypothetical interest rate of 8% over 5 years (for low-cost systems), over 10 years (for medium-cost systems), and over 20 years (for high-cost systems). Source: World Bank (1978)

At some point after an excreta-disposal system has been installed, the people using it may wish to make improvements. In developing countries, it is best to do this in stages. Cairncross and Feachem (1983) advocate starting with a modest improvement, and then progressively upgrading in a 'sanitation sequence'.

9.5 Use of Biomass Fuels

Biomass (or traditional) fuels are the principal source of energy for cooking and heat-

ing for about half of the world's population. These fuels (i.e. wood, charcoal, crop residues/agricultural wastes, and manure) are composed of complex organic matter, vegetable proteins, and carbohydrates incorporating carbon, nitrogen, oxygen, hydrogen, and certain other elements in trace amounts. Their combustion often produces harmful substances (e.g. a range of polycyclic hydrocarbons not found in the fuels themselves). Although biomass fuels supply only approximately 10 per cent of global energy requirements in terms of total energy output, half of the world's households cook with them daily. In developing countries, 30 per cent of urban households and 90 per cent of rural households rely on biomass fuels. The severity and extent of health problems associated with pollution from the combustion of biomass fuels are discussed by de Koning et al. (1985) and Smith (1987).

Cooking and heating serve basic functions in human well-being, but the population growth is causing biomass fuels to become scarce. If the appliances used for biomass-fuel combustion (i.e. cooking stoves and fires) do not satisfy minimal criteria of availability, efficient combustion, and environmental hygiene, public health and well-being will suffer. The social costs of domestic energy requirements – like those of domestic water supply – can be expressed in terms of disease and the time and energy expended by housewives.

Various studies have focused on how much time family members (usually women and children) spend on collecting or harvesting biomass fuels. Results from Latin America, Africa, Asia, and the Pacific indicate that, per household, some 0.7 hours a day (from a range of 0.02 to 1.67 hours) is spent on collecting fuel and that some 2.9 hours a day (from a range of 0.25 to 6.4 hours) is spent on cooking (WHO 1984).

There is growing evidence that emissions from the combustion of biomass fuels are a major factor in the high rates of mortality and morbidity in developing countries. Intoxication or acute and chronic irritation by air pollutants affect the respiratory tract and can give rise to:

- Acute respiratory infection (ARI), which is responsible for about a third of all childhood deaths in developing countries (Pio et al. 1985). Although vaccination and case management are partially effective, long-term solutions will depend on controlling risk factors. Besides indoor air pollution, these factors include malnutrition, crowded living conditions, and low birth weights. Pandey et al. (1987) estimated that, in Nepal, the control of indoor smoke would eliminate as much as 25 per cent of all moderate and severe ARI's in children under 2 years;
- Chronic respiratory disease, which is the result of long-term exposure to indoor air pollution and repeated respiratory infections. It causes permanent damage to the lungs and, eventually, to the heart. Women, especially, fall victim to this disabling and life-shortening condition. There is growing evidence that in certain areas (often at high altitudes) chronic respiratory disease is a serious public health problem;
- Cancer of the respiratory tract, which is linked to the carcinogenic and mutagenic substances contained in the emissions from biomass fuel. These are some of the same substances found in tobacco smoke. The levels of exposure to them are such that, theoretically, a significant incidence of lung cancer can be expected. Reliable statistics to confirm this hypothesis, however, are still lacking;
- Carbon monoxide intoxication, which, in its acute form, can be lethal. In its chronic form, CO intoxication reduces the oxygen-carrying capacity of the blood. In pregnant women, this can retard foetal growth and result in a low birth weight.

The availability of adequate cooking facilities influences the frequency of cooking and the quality of the dishes prepared. By this link, biomass-fuel combustion has an impact on nutrition and the occurrence of food poisoning and diarrhoeal diseases. Generally, there is a close interaction between food hygiene, water supply, excreta disposal, and cooking facilities (WHO 1984a).

In rural areas, cooking stoves are often inefficient in that only 10 to 15 per cent of the fuel's energy potential is used. Stoves can be classified according to their type of combustion chamber. These may be:

- Open chamber (e.g. the three-stone fire found world-wide);
- Enclosed chamber without flue. These stoves are made of clay or metal. Examples are the 'Thai bucket', the clay stoves of Pondicherry (India), and the deep pit stoves of Bangla Desh;
- Enclosed chamber with flue. A chimney on the flue creates a natural draft. Examples are the Magan and Hyderabad stoves of India, the Singer stoves of Indonesia, and the Lorena stoves of Guatemala.

The rate at which fuel is burned greatly determines the composition of the emissions. High burning rates lead to more complete combustion and a reduced release of harmful products into the air. Nevertheless, high burning rates lower the efficiency of cooking stoves, especially with dishes that require slow cooking. Numerous improved designs have decreased the combustion efficiency of stoves by enclosing the combustion chamber and reducing the air flow. While this makes better use of the fuel, it can lead to higher emissions of pollutants (Bussman 1988). Ideally, then, designers should strike a balance between stove efficiency and pollutant emission (Smith 1989).

Indoors, the ambient air quality is a function of the quantity of emissions from combustion and the rate of ventilation. Ventilation depends on housing design and climate. To ascertain the ambient air quality and the extent of indoor air pollution, one commonly measures the levels of carbon monoxide and Suspended Particulate Matter (SPM). Data on the ambient air quality in houses in developing countries are now available from numerous studies. Generally, the results indicate that indoor air pollution is a matter of grave concern. In 15 recent studies, the concentration of SPM in the air ranged from 2000 to 5000 micrograms/m^3 (Boleij et al. 1988). In contrast, in industrialized countries, indoor air pollution from tobacco smoke at levels of 100 micrograms/m^3 is regarded as a risk factor for acute respiratory infections in children.

High concentrations of air pollutants do not necessarily mean high exposure unless people spend time in places where and when these concentrations are found. In rural areas in the tropics, where agriculture is the main occupation, people spend much time outdoors. Cooking and sleeping take up most of the time spent indoors. Cooking implies high levels of emissions from the fire. Accordingly, the exposure of the cook/housewife is high. Small children, who usually stay near their mothers, are also at risk. Women and small children, therefore, generally suffer more from respiratory ailments than men do. As a rule, these findings apply to situations where people cook, live, and sleep in a single room, or where different rooms are not properly closed off. When the kitchen is separate from the living quarters, exposure risks are less.

Engineering solutions to the problems of biomass-fuel combustion are complex and involve the design of low-cost wood stoves and the removal of emissions by flues,

chimneys, and proper ventilation. Programs to introduce improved cooking stoves have had encouraging results (Foundation for Woodstove Dissemination 1987). Some programs choose factory-produced metal stoves requiring a high degree of quality control; others choose locally-made stoves of mud and clay. Whatever the choice, to be successful, these programs have to respect local cultural preferences and ensure the active participation of the community. They also need the support of a strong educational effort to motivate and instruct prospective users.

The body of technical and socio-economic knowledge and expertise on improved cooking stoves is growing. Advice, or information on organizations active in this field in various countries, is available on request from:

Foundation for Woodstove Dissemination
Executive Secretariat
Korte Janstraat 7
3512 GM Utrecht
The Netherlands.

9.6 Housing Design and Construction Materials

People spend a great deal of time inside their houses. They may, however, share this habitat with certain insect vectors. Moreover, the micro-climate in the house may favour the man-to-man transmission of bacterial and viral diseases. Hygienic standards for housing should take into account the local health hazards, and should be concerned with housing density and spatial layout; with floor space and the number of rooms; construction materials for the floor, walls, and roof; and ventilation, insulation, and lighting. Some of the pertinent features to be considered will be discussed below.

Screening and the Use of Bed Nets

Mosquitoes enter and leave houses through eaves, windows, and doors. Hence, screening these openings can help to control malaria. In practice, the effectiveness of screening depends on the bionomics of the local vector and the pattern of transmission. To be effective, screening requires household discipline in its use and maintenance. Because of its cost and the behavioural requirements, screening is not used much in low-cost housing.

Bed nets have been used in the tropics for many years. When used correctly, they are an effective protection against mosquitoes. A simple method of treating bed nets and curtains with pyrethroids was recently described (Rozendaal 1989; Lines et al. 1987; Major et al. 1987; WHO 1987). This method can be implemented by anyone with only a little supervision. Treated bed nets remain effective for 6 to 12 months. The cost of treatment per net is as low as U.S. $0.50. An extra advantage of this method is that protection against mosquitoes continues even if the bed nets are damaged or not let down over the bed; their mere presence in the sleeping area seems to reduce man-vector contact.

Building Materials

In Latin America, the vectors of Chagas' disease are peridomestic triatomine bugs. These bugs find a suitable habitat in the thatched roofs and cracked mud walls of rural houses (Mott et al. 1978; WHO 1987). Vector densities – and consequently disease transmission – can be reduced by the use of more permanent materials for roofs and alternative materials for walls, or, if mud is used, by smoothing wall surfaces properly. Field trials have shown that insecticide added to paints also provides effective long-term protection. The additional costs of more permanent construction are offset by the costs of periodic insecticide spraying.

In southern Sudan and other parts of the Sahel, cracks in mud walls provide suitable breeding spots for sandfly vectors of kala-azar. Measures similar to those taken against Chagas' disease can also help to prevent kala-azar.

Space and Ventilation

The combination of overcrowding and poor ventilation not only increases the risk of direct disease transmission, but also creates a micro-climate particularly favourable to the spread of airborne infections by droplets and dust particles.

Although meningococcal meningitis, which is an airborne infection, is not usually a public health problem in temperate climates, it can break out in devastating epidemics under certain tropical conditions (Greenwood et al. 1984; Cvjetanovic 1976). In the so-called Cerebro-Spinal Meningitis Belt (CSM Belt) of Africa, which lies between the equator and the south of the Sahara and extends to the Indian Ocean, epidemics flare up from time to time. Recently, there have been CSM epidemics in Mongolia, where climatic conditions are cold, but equally dry. In Africa, the disease is associated with certain types of the traditional *banco* houses, which are badly lit and poorly ventilated. In Mongolia, it is associated with a similar type of traditional house: the *yurt*. Studies in Mali and Burkina Faso have shown that better ventilation and lighting in houses can reduce epidemics.

Martin (1977) summarized reports published between 1842 and 1966 on housing, health, and social conditions in England. He found that the high rate of urban morbidity and mortality was associated with overcrowding of houses and land, but that it was twice as likely to be associated with overcrowding inside houses. Estimates were that, between 1928 and 1938, one-third of all infant mortality was attributable to overcrowding.

An American study (Britten 1942) showed that prolonged and intimate household contacts have a striking influence on the transmission of acute, mainly respiratory, infections (e.g. measles, whooping cough, diphtheria, mumps, scarlet fever) and chronic respiratory infections (e.g. pneumonia, tuberculosis, rheumatic fever).

A typical observation from temperate and cold climates is that, when windows are opened again in spring, droplet infections tend to disappear. These lessons from past studies of living conditions in England and America apply equally well to the present situation in developing countries.

9.7 Improvement of Nutrition and the Role of Women

Good nutrition is a vital component of human welfare and the main determinant of good health. Accordingly, the improvement of nutrition should be a major concern in the planning of all agricultural and economic development (Pacey and Payne 1985; FAO 1984; Anten et al. 1986).

Various diseases are brought on by an insufficient or unbalanced intake of nutrients. Too few calories or too little protein, which are usually supplied by staple foods, are the main causes of poor nutrition. In children, malnutrition stunts growth and retards development; in adults, it lowers labour capacity, thereby influencing economic development.

Malnutrition lowers resistance to diseases and increases their severity once they have set in. In a malnourished patient, a relatively harmless illness is more prolonged and the outcome is more often fatal. Estimates are that malnutrition is indirectly responsible for more than half of all childhood deaths in developing countries.

Just as malnutrition can lower resistance to disease, so, too, can disease contribute to malnutrition. In many parasitic infections, the parasites take nutrients away from the already precariously little food consumed by their host. *Ascaris* infections, for instance, can result in the loss of 3 to 25 per cent of ingested calories, depending on the worm load (Latham et al. 1977). In other parasitic infections, protein and other nutrients are lost through blood in faeces (hookworm) and urine (schistosomiasis). In malaria and other febrile infections, growth in children is retarded and anaemia is common. Similarly, growth retardation has been demonstrated in *S. haematobium* infections, especially if the worm loads are high. Iron-deficiency anaemia is caused by hookworm and schistosomiasis infections.

Although the results of research largely pertain to children, their implications are equally valid for adults. A study in Indonesia, for example, revealed that the productivity of non-anaemic labourers was approximately 20 per cent higher than that of anaemic labourers (Karyadi and Basta 1973).

Thus, the relation between nutritional state and infection is reciprocal: malnutrition results in lower food production, and lower food production results in malnutrition. Malnutrition can precipitate an infection and, in its wake, the infection takes a more serious course. Consequently, planning efforts to improve nutrition in the community clearly require a double-pronged, multi-sectoral approach (Figure 9.5). On the one

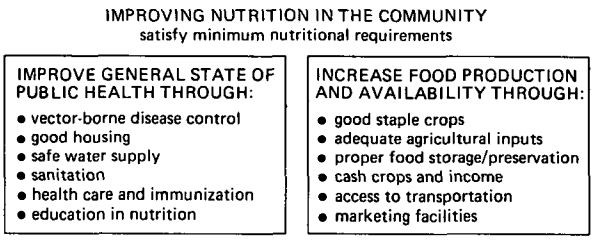

Figure 9.5 Outline of a double-pronged, multi-sectoral strategy to improve nutrition in the community

hand, the incidence of endemic illnesses needs to be reduced to improve the people's general physical condition and enhance their ability to derive the full nutritional benefit from the foodstuffs they consume. On the other hand, the production of food needs to be increased and a sufficient portion of it made available to the population.

The role that women play in nutrition is a special one. Women as a group are considered to be particularly vulnerable to adverse nutritional conditions and to need extra attention in plans for health and nutrition. Women are also social actors who influence other people's nutritional condition, especially that of their children.

Naturally, these views are reflected in nutrition programs, but the role of women should also be viewed in a much wider context. In Africa, women have always been responsible for a major portion of small-scale crop production, both for home consumption and the market (FAO 1979). In 1974, it was estimated that women formed 60 to 80 per cent of the agricultural labour force. In general, women spend more hours on agricultural activities than men do. Women make certain decisions on planting and cultivation, adapt to innovations, and decide on the disposal of foodstuffs not needed for family consumption. In animal husbandry, women are usually responsible for poultry, but they are also responsible for the minor livestock (goats and sheep). As a result of male out-migration and cash-cropping, women are now spending more time tending large livestock, but they are not deriving the benefits.

The socio-economic development policies that have induced the male out-migration have left – to the care of women – the food crops that sustain the family, the cash crops, and animal husbandry. An example of how women have fared in development schemes is presented below.

The Mwea Irrigation Settlement Scheme, Kenya

The Mwea Irrigation Settlement Scheme lies near the foothills of Mount Kenya at an altitude of 1100 m. The Scheme is on a semi-arid plain, which had a low population density before irrigation was begun. The colonial government started the Scheme in 1951 to settle landless families. It has been used almost exclusively for semi-mechanized rice cropping. *Schistosomiasis mansoni* caused serious problems between 1960 and 1970, but was successfully controlled with molluscicides. Malaria is seasonal in the area.

In their final assessment of the Scheme, Hanger and Morris (1973) stated: '... the unsatisfactory recognition of a woman's rights and needs within the Scheme remains one of the greatest weaknesses of the Mwea system'.

From 1966 onwards, various nutritional, health, and general socio-economic surveys were conducted among the Scheme's population (Korte 1969). For comparison, information was also collected from nearby off-Scheme areas (including a coffee-growing area). The survey findings indicated a discrepancy between the socio-economic progress in the Scheme and the improvement of the general health and nutrition of the people, particularly when compared with that of off-Scheme people. The investigators concluded that a higher income does not automatically lead to better health.

In the off-Scheme coffee-growing area, on the average, about half of a woman's agricultural work was done for her husband's cash crops (coffee and maize). Quite distinct was the time a woman spent on her own food-crop garden, which was intended

primarily to feed her family. Viewed against the background of the off-Scheme community, the position of the Mwea women was decidedly less favourable. The most significant difference was the lack of land where women could cultivate their own crops and thus provide for their families. Instead, women in Mwea had to rely on cash contributions from their husbands. The loss of independence was also evident in the supply of fuel. The off-Scheme women usually gathered their own firewood, but firewood in Mwea was scarce and all households had to buy it.

Houses in Mwea were planned without much consideration for the women. There was no separate kitchen. Water was easily available within the Scheme, but was polluted. Prices of commodities were higher than in the off-Scheme areas, presumably because the tenants were so dependent on the market. The Scheme also required the women to help cultivate the rice. During the peak of the agricultural season, the demands on the women increased so much that they created a direct clash of work priorities. At this time, moreover, the larger numbers of people in the household and other difficulties made preparing food very burdensome.

A comparison between the Mwea women and their off-Scheme counterparts showed a distinct deterioration in the general household affairs and farming of the Mwea women. Hangar and Morris (1973) concluded that the welfare of the tenant families could have been greatly influenced by more systematic planning and greater attention to housing, a domestic water supply, a clear recognition of a woman's claim to at least half of the rice income, a system of firewood provision on the Scheme, and a minimum allowance in land use for a subsistence crop other than rice.

9.8 Health Services

The health services are one of the partners in the intersectoral collaboration for Primary Health Care (PHC). The nature and magnitude of health problems that PHC has to tackle differs, of course, from country to country and even from region to region in the same country. These differences are reflected in the priorities that ministries of health give, for instance, to malaria or schistosomiasis control, and in the tasks of health workers.

In the control of vector-borne diseases, the tasks of health workers are generally (WHO 1983; 1984b-c; 1987) the following:

- To conduct mass vaccination and treatment campaigns;
- To diagnose, treat, and follow-up cases by passive or active case-finding;
- To collect epidemiological data for the monitoring and surveillance of the local situation;
- To control disease vectors and household and personal pests (e.g. mites, lice, fleas);
- To provide education in hygiene and to encourage community participation.

Because of their professional knowledge and skills, health workers fulfil a key role in PHC. Equally important, however, are their familiarity with the local health situation and the trust they enjoy from the community they serve.

9.8.1 Vaccination

The global eradication of smallpox in 1979, after an enormous international effort lasting more than ten years, is a shining example of how effective vaccination can be. As vectors and parasites build up resistance to chemotherapeutics and insecticides, vaccines are becoming an ever more vital line of defence against disease. Vaccination is especially important in combatting infections that affect large populations in the tropics and have the potential of flaring up into seasonal epidemics or of spreading into the temperate zones. At present, the most important vaccine available is that for yellow fever, but gradual progress is being made in developing vaccines for malaria and dengue fever.

The 17D yellow fever vaccine is highly effective and safe. Re-vaccination is recommended every ten years, but protection will persist for 40 years in at least 62 per cent of those vaccinated. Experience during epidemics indicates an even higher percentage of persistence.

Effective vaccines are also available for tick-borne encephalitis, Japanese encephalitis, Rift Valley fever, and Venezuelan equine encephalomyelitis, but they are used on a very limited scale only. Usually, the spread of these arboviral epidemics can be controlled by vaccinating the host animals (e.g. horses, pigs, sheep, and cattle).

Vaccination is a major activity of PHC. It has significantly reduced infant and child morbidity and mortality throughout the world. Through national immunization programs, children are being protected against poliomyelitis, measles, whooping cough, tetanus, diphtheria, and tuberculosis.

9.8.2 Chemotherapy in the Control of Vector-Borne Diseases

Bilharzia

Praziquantel is the drug most commonly used nowadays to treat bilharzia; it is effective against all types of the disease. Another drug, metrifonate, is effective only against urinary bilharzia and is quite cheap, about U.S. $0.50 per average dose. The administration of metrifonate, however, is complicated, requiring three separate doses at 15-day intervals, which makes it difficult to get people to complete the full course of treatment. Thus, in most cases, cost estimates for a program of control can be made based on praziquantel, which would not differ markedly from the costs of a program that uses metrifonate.

Praziquantel is used in the Study Zone of the Blue Nile Health Project. The program of administration proceeds in two phases, the 'attack phase' and the 'passive phase'. The attack phase has two parts:

- An intensive mass chemotherapy campaign in the 'core' and 'fringe' strata villages;
- A slower program in the 'road' stratum villages.

(For explanations of 'core', 'fringe', and 'road' strata, see Volume 2, Annex 4.)

The passive phase is one of detection and treatment, and is a permanent feature of the health services system. It continues as long as transmission takes place and, if preventive measures are able to maintain transmission at low levels, should be able to hold community prevalence below 10 per cent.

The attack phase should not need to be repeated, given the integrated nature of the trial strategy, which seeks to lower transmission permanently. Thus the cost is regarded as a single expenditure, covering only a short period. Included in the cost are the mapping of detailed census results, the training of personnel, and preparatory village meetings. For each of the separate strata, the cost is expressed per capita and per village.

The attack phase in the 24 villages of the core and fringe strata cost about U.S. $50,000 in 1982 prices, which is about U.S. $2000 per village, or U.S. $1.53 per capita. In the road stratum, the cost was about U.S. $4900, or U.S. $700 per village and U.S. $0.20 per capita. The attack phase in all 31 villages cost about U.S. $55,000, or U.S. $0.96 per capita in 1982 prices. After adjustments for inflation, this price would be about US $1.00 per capita in 1984 prices.

The passive phase of the praziquantel chemotherapy was conducted by 6 rapid-diagnosis laboratories, which were established as part of the improvements to the basic health services. Each of these laboratories cost U.S. $103 a month to operate, plus additional monthly costs of about U.S. $5 for equipment, U.S. $20 for praziquantel, and U.S. $5 for other drugs.

The annual cost of the 6 laboratories was apportioned to the basic health services (50 per cent), to schistosomiasis control (25 per cent), and to malaria control (25 per cent). The annual praziquantel cost was added to the cost of schistosomiasis control, giving a total annual cost of U.S. $3384 for passive chemotherapy for schistosomiasis control. This amounts to U.S. $0.06 per capita in 1984 prices (Table 9.11).

Malaria

Malaria chemotherapy usually takes the form of preventive mass chemotherapy, in which the drug is the main expense – about U.S. $0.25 per person treated. In a long-term program, however, a passive case-detection system is used to reduce drug wastage. In this type of system, treatment is given only if infection is detected by microscopic examination of a blood slide. The costs of malaria chemotherapy in rapid-diagnosis laboratories are similar to those for bilharzia, except for the lower cost of the drugs. In the Study Zone, the annual per capita cost of passive malaria diagnosis and chemotherapy in all 31 villages was U.S. $0.04 in 1984 prices, for a population of 57,286. Drugs accounted for 20 per cent of all foreign purchases (Table 9.11).

9.9 Education in Hygiene

The provision of even the very best of facilities to control disease in the domestic environment will prove futile unless the people understand why these facilities have been provided and how they should be used. If the farmers and their families are not motivated to use the facilities properly, disease transmission will continue unabated.

It has long been recognized, therefore, that irrigation projects need a component to educate the people in hygiene. This education should aim at changing attitudes and behaviour to break the chain of disease transmission associated with poor hygiene

Table 9.11 Comparative costs of the passive maintenance phase of the bilharzia and malaria chemotherapy programs in the Study Zone (in 1984 U.S.$)

Item		Total amount	Allocation for bilharzia chemotherapy	Allocation for malaria chemotherapy
Monthly local costs (for 1 laboratory)				
– Buildings	$	8.00	2.00	2.00
– Cleaning & maintenance		2.00	.50	.50
– Salaries		80.00	20.00	20.00
– Supplies		5.00	1.25	1.25
– Training (0.1 man-month)		8.00	2.00	2.00
		103.00	25.75	25.75
Monthly foreign costs (for 1 laboratory)				
– Equipment		5.00	1.25	1.25
– Praziquantal		20.00	20.00	0
– Other drugs		5.00	0	5.00
		30.00	21.25	6.25
Totals	$	133.00	47.00	32.00
Annual costs				
– For all 6 laboratories	$	9,572.00	3,384.00	2,304.00
– Per capita		.17	.06	.04

and sanitation. Nevertheless, education in hygiene must be based on the fact that human behaviour is deeply rooted in social and cultural factors. It is no longer viewed as something to be modified to suit technology. Decision-makers must understand the cultural roots of behaviour before they can hope to change it. The success of new ideas, facts, or behavioural patterns introduced from 'outside' will be determined by their compatibility with the indigenous cultural system. Any attempts at rapid socio-cultural change can shake the people's cultural foundations and lay them open to a radical displacement of values and behavioural patterns.

Dunn (1976) visualized a cultural system as a broad-based pyramid. Its foundation is formed by large immovable blocks that he calls 'value orientations'. These have to do with man's relation to nature and the supernatural world. Upon the large blocks rest many smaller blocks that represent values, attitudes, and beliefs. These are linked to the underlying values and value orientations. Because of their size, the smaller blocks can be more easily torn out of the cultural structure and replaced in the process of adapting to a changing environment. Resting lightly upon the structure of beliefs and attitudes are many small blocks at the top of the pyramid. These represent individual and group behaviour in all its variety.

Education in hygiene is part of a wider concept of health education (Burgers et

al. 1988; Boot 1985). In spite of this, only a few projects pay explicit attention to the relationship between development, human behaviour, and disease. Since its start in 1919, the Gezira Irrigation Scheme was beset with health problems. Malaria, bilharzia, diarrhoeal diseases, and cholera were rife, as were smallpox, meningitis, and relapsing fever (Bayoumi 1979). In 1973-74, a severe malaria epidemic once again struck Gezira. When it was shown that this epidemic was responsible for an average loss of 33 working days per tenant, the authorities decided that a different health policy was required. As a result, the Blue Nile Health Project was conceived and has been implemented since 1981.

The neglect of hygiene in development projects reflects the longstanding separation between the various sectors involved in development. Most of the professionals concerned have been trained in a scientific tradition that allows them little time to explore outside their own field, even though successful project implementation requires active cooperation among engineers, epidemiologists, and behavioural scientists. It would be a good thing if the curricula of engineers, social scientists, economists, and health professionals included courses in epidemiology and the use of environmental engineering to control diseases.

9.9.1 Modifying Health-Related Behaviour

In Individuals

Ideally, at an early stage in project planning, the social and cultural dimensions of the project should be highlighted with a careful study of disease-related behaviour. The study should include the relationships between specific types of behaviour and specific diseases. This information can be gathered from interviews or from literature. As part of field research, other information (e.g. on epidemiology) will have to be collected during surveys, so, because this is expensive and trained personnel is scarce, surveys should have a multi-purpose function, incorporating demographics, epidemiology, and behavioural science. During the surveys, many related topics can also be studied to support appropriate project design. We have already discussed many of these topics in this chapter (i.e. water contact, water use, excreta disposal, use of biomass fuel, housing design, and nutrition).

Dunn (1976; 1979) advocates classifying health-related behaviour as one of four types:

- Deliberate health enhancing;
- Non-deliberate health enhancing;
- Deliberate health lowering;
- Non-deliberate health lowering.

Behavioural data classified in this way provides a sound basis for programs of education in hygiene. The key decisions in planning these programs are:

- Which behavioural categories need changing? (These will be the subjects of the program);
- Which groups urgently need to change their behaviour? (These will be the target groups of the program);

- What should the new behavioural categories be? (These will be the objectives of the program);
- Who can best do the educating, or who are the best intermediaries?
- When and where can the program best take place?
- How can the program best be done?

In Organizations

Traditionally, hygiene has been considered the responsibility of the project beneficiaries. The outbreak of epidemics in irrigation projects, however, has taught us that it should be a prominent consideration in policy decisions. In a sense, then, policymakers, planners, and the executive officers of projects are also a target group for education in hygiene, in that they must be made aware of the need for it.

Essential for this purpose are well-designed research projects to assess the effectiveness and efficiency of controlling diseases by environmental modification and management, and by changes in behaviour. If it can be demonstrated that such measures are effective at an acceptable cost, this will help greatly in persuading financing bodies, planners, engineers, and even individual farmers to allocate resources for their application (PEEM 1986a).

Education in hygiene is also important for project staff – both professional and non-professional. This can be provided by in-service training or by short courses (IRC 1987). If such training is given by the more senior staff, it can reinforce the idea that hygienic behaviour is a matter for the entire project organization. A consistent code of conduct within the project organization will help the educational programs for the community at large. Nevertheless, getting the message across to the people will require considerable care, dedication, and persistence.

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Because the sections in Chapter 9 deal with such separate subjects, we have grouped their references section by section, hoping this will be of service to our readers.

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10 The Economics of Health in Irrigation

Because health considerations are such an important part of an irrigation project, it makes sense to include them in the economic appraisal of the project. It also makes sense to start considering health in a very early stage of planning, so that one has time to study and analyze the various options and alternatives.

There are two approaches to the economics of health in an irrigation project. The more straightforward one is to demand that the project not cause any additional disease. In this approach, no time is lost in assessing the economic consequences of disease. There is only a Cost-Effectiveness Analysis (CEA) to find the lowest-cost options that reduce health risks.

The second approach is to conduct a Cost-Benefit Analysis (CBA). In this approach, the economic costs of negative health are compared with the economic benefits of its prevention. As long as financial and economic criteria largely decide whether investments will be made in irrigation, and as long as projects continue to be appraised in the light of a CBA, health aspects stand a better chance of being considered if they are integrated into the framework of a CBA.

This chapter therefore differs from comparable literature such as the valuable contributions initiated or supported by WHO, which stress the CEA. Whilst the theoretical merits of that approach are acknowledged, it needs to find a far wider practical application before it can serve as the main instrument for including health effects in economic appraisals.

In the design and planning of an irrigation project, the economic feasibility of the planned investment has to be estimated and compared with other possible projects or project alternatives. This provides a sound basis for financial decision-making. A much applied procedure is to determine the Internal Rate of Return (IRR). For large irrigation projects, the IRR is usually calculated for various technical alternatives, the necessary data being supplied by a multi-disciplinary team of specialists. For our present purpose, we need data from the health specialist on the possible effects on health and on the efficacy of potential control measures.

To perform an economic analysis of the health effects of irrigation, one has to put a price tag on those effects. This chapter explains how this can be done and how the effects can be quantified and incorporated into an economic appraisal. It should be noted, however, that up to the present not much work has been done on collecting and analyzing health-cost data. The examples we present are therefore somewhat hypothetical.

(A summary of health-cost data is presented in Technical Note 3.)

10.1 Health Effects of Irrigation Projects

Although there is growing evidence that irrigation projects are often accompanied by increased health risks, there is also enough recent and historical evidence to support

the statement that economic development in general has an overall positive impact on health (Carrin 1984; Stewart 1985). Increased incomes lead to better nutrition, sanitation, and hygiene – factors that apparently influence the overall health status more than public expenditure on health care. Therefore, if irrigation contributes to increased incomes, the improved well-being will eventually also be reflected in better health, albeit with a considerable time lag. Moreover, because the positive health effects are related to the overall macro-economic development, they cannot all be attributed to a specific project, unlike the negative ones.

A conventional economic analysis of irrigation will to some extent deal with its positive effects through the resulting increases in income. Such effects can therefore be neglected during the life of the project, although one could argue that, in this way, the indirect and long-term positive health effects are not sufficiently covered. A macro-economic perspective would be better for such a purpose, but this goes beyond the project level which we are dealing with here (Vianen and Waardenburg 1975).

Project planning covers a limited time horizon, which corresponds to the economic lifetime of a project. That will usually be a period of from 10 to 30 years. One should therefore concentrate on the negative health effects that will become visible during that period. Such a focus seems justified when we consider the general neglect of these effects in conventional economic appraisals.

10.1.1 Health risks

Throughout the life of an irrigation project, the prevalence and/or incidence of water-related diseases may increase directly as a result of the project (World Bank/UNDP/Govt.of France 1985) – the four major diseases being malaria, schistosomiasis, onchocerciasis, and trypanosomiasis. In an economic sense, the latter two diseases differ from the former two, because their occurrence can have drastic economic consequences, possibly leading to a serious limitation of many of the economic activities in the area (e.g. livestock keeping). If this is likely to happen, every investment to control onchocerciasis and trypanosomiasis should be considered firmly feasible. If the economic activities will only be modestly affected by those two diseases, they can be treated economically in the same way as outlined for malaria and schistosomiasis.

The increased prevalence and incidence of malaria and schistosomiasis as a result of irrigation have been substantiated by many case studies (Mills and Thomas 1984; Rosenfield 1979; Sharma and Uprety 1982; WHO 1980b; WHO 1983b). Studies have also been made on the ex-ante prediction of incremental health risks (Bruce-Chwatt 1981; Rosenfield and Bower 1978; Cohen 1977; PEEM 1985; Rosenfield 1979).

For the present analysis, all one needs is a broad idea of the incremental health risks that can be expected, in terms of changes in morbidity and mortality. Irrigation projects can then be classified according to the extent of their incremental health risks, qualitatively from low to medium to high (e.g. on a scale of 0 to 5 or more). In some predictable cases, these risks may be negligible, or the prevalence and incidence of a disease may already be so high that an irrigation project will not make any noticeable changes.

Such a broad classification should be possible on the basis of the size of the project, the climate and rainfall pattern of the site, and engineering and project-related data.

This assumes, of course, that reliable data on the presently prevailing diseases are available, and that the step from increased health risks to changes in morbidity and mortality can be made. An economic analysis is very sensitive to the availability of data, the lack of which can often be a problem.

Morrow and his colleagues (Ghana Health Assessment Project Team 1981; Morrow 1980; Morrow 1985) went furthest in trying to quantify the health impact of various diseases in Ghana, assessing them in terms of severity of illness, disability, and death. Morrow's approach is probably still too complicated for planning purposes and for the rapid appraisal that is usually required. All that is needed, however, is a first approximation.

Table 10.1 illustrates a possible way of classifying irrigation projects by their health risks.

Table 10.1 Relative increase in health risks (changes in prevalence) due to malaria and schistosomiasis

Risk classes	1		2		3		4		5	
	<10%		10-20%		20-40%		40-60%		>60%	
Project	M*	S**	M	S	M	S	M	S	M	S
1					x					
2	x							x		
3					x	x				
4	x									

* = Malaria
** = Schistosomiasis

Table 10.1 is based on hypothetical projects, which we shall use as examples throughout this chapter. By remaining close to actual observations, we have taken care to create realistic situations.

After the ex-ante assessment of the health risks, the next question that arises is whether it is worthwhile to continue the economic analysis of health changes. As this exercise in itself involves costs, the order of magnitude of the risks should indicate whether further efforts are justified. They are not justified for Project 4 in Table 10.1, for example, because the expected changes in health status are negligible. Projects 1, 2, and 3, however, qualify for further analysis.

The figures in Table 10.1 have been simplified. Firstly, all types of malaria and schistosomiasis have been lumped together, although there are different types of these diseases with widely varying characteristics. But, as long as the particular type of schistosomiasis and/or malaria are not identified per project area, this simplification seems justified. Secondly, no information is given as to the time profile of the health changes, although time profiles of disease patterns vary from slow increases to sudden jumps, further complicating an indication of average risks. Some indication of the time profile could be added for further calculation (e.g. when the peak will be reached).

10.1.2 Morbidity and Mortality Changes

Taking our hypothetical examples a step further, we now translate the relative changes in health risks into absolute morbidity and mortality changes. Lack of adequate data may limit these to rough averages. Sometimes, however, it is possible to specify the days of healthy life lost throughout the life of a project (Morrow 1980; Morrow 1985; Prost and Presscott 1984; Romeder and McWhinnie 1977). Table 10.2 illustrates this for Projects 1, 2, and 3.

Project 1 is a rice irrigation project of 1000 ha, with a target group of 4000 people (1 ha per household; 4 persons per household) and a population at risk of 10,000 people who live in the project area. The lifetime of the project has been estimated at 10 years. An increase in malaria prevalence of 20% has been predicted, the peak being reached after 3 years (10% after 2 years). For 7 years, therefore, there will be 2000 extra cases of malaria annually, with 40 extra fatal cases each year. Knowing that one attack lasts an average of 8 days, with another 18 days lost to disability in the ensuing year (5%), we can calculate the loss of healthy life. We can thus quantify the negative health effects of Project 1 at around 0.8 million days, or an average of 80,000 days per project year.

Project 2 is a rice irrigation project of 2500 ha, with a target group of 10,000 people (1 ha and 4 people per household) and a population of 20,000 people at risk. Ignoring the increased prevalence of malaria, we find that there will be a slow increase in schistosomiasis cases which will affect up to 50% of the total population, with 1 case in 500 being fatal. The project lifetime is 20 years. The degree of disability is taken as 20%. We can thus quantify the negative health effects of Project 2 at around 12 million days, or an average of 600,000 days per project year.

Project 3 is a rice irrigation project of 5000 ha, a target group of 20,000 people, and a population of 30,000 in the project area. The lifetime of the project is 30 years. The extra cases of malaria will occur during the first 2 years, whereas the extra schistosomiasis is assumed to begin after 5 years, reaching its peak after 10 years. As this is a large project, we can safely assume that sufficient time was available for a fairly sophisticated study, meaning that more details are available on population growth, death rates, degrees of treatment, etc. The negative health effects are quantified at 30 million, or 1 million days per project year.

It will be obvious that such calculations require a number of bold assumptions. Complicated disease patterns have to be broken down into average figures (e.g. extra annual cases, average duration of attack, average number of attacks per person, degree of disability afterwards, death rates). For each particular case, one has to judge to what extent an order of magnitude can be calculated or derived. Nevertheless, in the absence of explicit estimates, decisions will have to be made anyway, but now on the basis of implicit estimates and sometimes vague value judgements. Any intelligent guess is better than none at all because it will at least force the decision-makers to think about the issues involved and their orders of magnitude.

10.2 Economic Consequences of Health Changes

Calculating the possible economic effects of increased health risks makes explicit the relationship between health and economics in general. To safeguard its identity and be able to come up with operational results, economic theory reduces well-being to its material aspects. Whilst acknowledging, in principle, the questionable nature of a separation between material and immaterial well-being, economists work with the fundamental hypothesis that increases in material well-being are (almost always) desirable. The major indicator to express material well-being is per capita income.

10.2.1 Direct Effects

Direct Costs of Health

Starting from the premise that illness is considered an economic 'bad', in contrast to an economic 'good', people are willing to pay for its avoidance, control, or decrease. The costs of restoring, maintaining, or improving upon a certain level of health can be regarded as the direct costs of health. Increased health risks call for above-normal expenditures on health. Although, in general, preventive costs are also part of the direct costs, we need not consider them in this context where we are dealing with extra cases only. Therefore, expressing the direct costs in a useful indicator (i.e. as the extra costs of treatment) will normally be a fairly straightforward exercise.

If an irrigation project leads to 1000 extra cases of malaria, and if the average cost of treating one case is U.S. $4, then the direct economic costs of health attributable to that project will be $4000. In applying this simple method, however, we meet a number of complications.

Variation in Cost of Treatment

The cost of treatment (see Technical Note 3) varies greatly from country to country, and even from case to case, depending on the type of treatment. Indicative figures for the conventional treatment of schistosomiasis vary at present from U.S. $1 to $3 per case (including diagnosis) – a considerable reduction in view of an earlier range of $3.5 to $16 (Mott 1984). For malaria, the cost of treatment may vary between $1 and $20 (WHO 1983a; World Bank/UNDP/Govt.of France 1985).

In poor countries, much of the health costs are private expenditures, approximately 3% of final consumer expenditure being on health. In some African countries, annual private expenditure (per capita) of U.S. $8 on malaria control alone has been observed, whereas the average public expenditure on malaria varies only from $0 to $0.8 (WHO 1980b). The degree of treatment also varies, whilst a great number of cases of malaria and schistosomiasis go untreated.

Table 10.2 Morbidity/mortality changes and days of healthy life lost in Projects 1, 2 and 3

Project 1

Rice irrigation 1000 ha
Population at risk 10,000
Project lifetime 10 years
Change in malaria prevalence 20%
Fatal cases 2%
Duration malaria attack:
first year 8 days
second year 18 days

No. of extra cases		No. of fatals
Year 1	–	–
2	–	–
3	1000	20
4	2000	40
5	2000	40
6	2000	40
7	2000	40
8	2000	40
9	2000	40
10	2000	40

Morbidity/disability

Year 1	–
2	–
3	980 × 8
4	980 × 18 + 1960 × 8
5-10	1960 × 18 + 1960 × 8
	= (980 × 8) + (980 × 18) +
	(1960 × 8) + 6(1960 × 26) =

Project 2

Rice irrigation 2500 ha
Population at risk 20,000
Project lifetime 20 years
Prevalence malaria ignored
Increase of schistosomiasis cases
up to 50% of population
Fatal cases 1 per 500
Degree of disability during
disease 20%

No. of cases		No. of fatals
Year 1	500	1
2	1500	2
3	2500	5
4	3500	7
5	4500	9
6	5500	11
7	6500	13
8	7500	15
9	8500	17
10	9500	19
11-20	10000	20

Morbidity/disability

Year 1	499	
2	1498	
3	2495	
4	3493	
5	4491	
6	5489	} × 365 × 0.2
7	6487	

Project 3

Rice irrigation 5000 ha
Population at risk 30,000
Project lifetime 30 years
Change in malaria prevalence 30%
Fatal cases 1 per 100
Duration malaria attack:
first year 4 days
second year 18 days

Change in schistosomiasis prevalence
30%, with fatal cases 1 per 1000
Duration of schistosomiasis 20 years
Degree of disability during disease 15%

Malaria:

No. of extra cases		No of fatals
Year 1	4500	45
2	9000	90
3-30	9000	90

Schistosomiasis:

No. of cases		No. of fatals
Year 1-5	–	–
6	1000	1
7	2000	2
8	3000	3
9	5000	5
10	7000	7
11	9000	9
12-30	10000	10

Malaria morbidity

Year 1	4455 × 4
2	4455 × 18 + 8910 × 4
3-30	8910 × 18 + 8910 × 4
	= 5,622,210

Malaria mortality

Year 1	29.5 × 45 × 365
2	28.5 × 90 × 365

Mortality (assuming death to occur mid-year)

Year	1	–
	2	–
	3	7.5 × 20 × 365
	4	6.5 × 40 × 365
	5	5.5 × 40 × 365
	6	4.5 × 40 × 365
	7	3.5 × 40 × 365
	8	2.5 × 40 × 365
	9	1.5 × 40 × 365
	10	0.5 × 40 × 365
		= 7.5 × 20 × 365 + 24.5 × 40 × 365 = 412,450

	9	8483
	10	9481
	11-20	9980
	= 10,928,173	

Mortality

Year	1	19.5 × 1 × 365
	2	18.5 × 2 × 365
	3	17.5 × 5 × 365
	4	16.5 × 7 × 365
	5	15.5 × 9 × 365
	6	14.5 × 11 × 365
	7	13.5 × 13 × 365
	8	12.5 × 15 × 365
	9	11.5 × 17 × 365
	10	10.5 × 19 × 365
	11	9.5 × 20 × 365
	12	8.5 × 20 × 365
	↓	↓
	20	0.5 × 20 × 365
		= 845,523

	30	0.5 × 90 × 365
= 29.5 × 45 × 365 + 420.5 × 90 × 365		
= 14,297,963		

Schistosomiasis morbidity

Year	1-5	–
	6	999
	7	1998
	8	2997
	9	4995 } × 365 × 0.15 × 0.8*
	10	6993
	11	8991
	12-30	9990
		= 9,495,095

* 0.8 accounting for duration of disease

Schistosomiasis mortality

Year	1-5	–
	6	24.5 × 1 × 365
	7	23.5 × 2 × 365
	8	22.5 × 3 × 365
	9	21.5 × 5 × 365
	10	20.5 × 7 × 365
	11	19.5 × 9 × 365
	12	18.5 × 10 × 365
	13	17.5 × 10 × 365
	↓	↓
	30	0.5 × 10 × 365
		= 826,908

Days of healthy life lost

Morbidity	346,920
Mortality	412,450
	759,370

or 80,000 days/year (rounded off)

Days of healthy life lost

Morbidity	10,928,173
Mortality	845,523
	11,773,696

or 600,000 days/year (rounded off)

Days of healthy life lost

	Morbidity	Mortality
Malaria	5,622,210	14,297,963
Schisto	9,495,095	826,908
Total	15,117,305	15,124,871
Grand total:	30,242,176	

or 1,000,000 days per year

Of course, actual levels of treatment are hard to trace accurately. Much private expenditure, in particular, remains invisible (e.g. that spent on traditional medicine). Costs of public treatment are often underestimated as well, because, in conventional assessments, many overheads (salaries, buildings, equipment) are ignored (Mach and Abel-Smith 1983; WHO 1983a).

Nevertheless, it is possible to translate the negative health effects of irrigation into the direct annual costs of treatment. Therefore, if the target of 'No increased prevalence of disease due to the project' is accepted, the treatment costs can be calculated on the basis of actual prevalences.

Calculation of Cost of Treatment

The cost of treatment will have to be calculated for each particular situation. It can often be derived from health programs already in operation.

As suggested in literature (Mach and Abel-Smith 1983; Mott 1984), the order of magnitude of the cost on a per-case base ranges from U.S. $2 to $6 per case of schistosomiasis or malaria. Although, to treat a disease effectively, the whole population at risk should normally be dealt with, here we are only considering the direct effects of treatment, so we only need to calculate the costs of treating the extra cases.

Applying this method to our three example projects, we obtain, as a first approximation, the estimates given in Table 10.3.

Table 10.3 Direct costs of treating extra cases (in U.S. $)

Project	Extra cases		Annual cost of treatment per case		Period of treatment (years)		Total cost	Average cost per project year
	M	S	M	S	M	S		
1	2,000	–	4	–	8	–	64,000	6,400
2	–	10,000	–	3.5	–	10	350,000	17,500
3	9,000	10,000	3	2	30	20	1,210,000	40,333

In these examples, it has been assumed that malaria will have to be treated each year throughout the project period, unlike schistosomias, which, for various reasons (limited number of clinical visits, water supply, non-serious cases, etc.), will not require annual treatment. The cost of treatment reflects an annual average, to be calculated on the basis of existing statistics on the number of in- and out-patients, the number of self-treatment cases, transport, drugs, etc.

In the absence of control or preventive measures, Projects 1, 2, and 3 will cause a direct loss to the economy of U.S. $64,000, $350,000, and $1,210,000, respectively. As the benefits of prevention are at least equal to such 'foregone' costs, this gives a first approximation of the amounts that can be spent on achieving the target of 'No additional disease'.

10.2.2 Indirect Effects

The indirect economic effects of health changes are certainly not easy to assess, and are much more controversial, for that matter, than the direct effects. Apart from the usual data and measurement problems, the methods of analysis are somewhat questionable.

Problems in Assessing the Indirect Costs of Health

It is easy to observe that illness reduces the working capacity of people, thereby reducing the quality and quantity of labour. It is a far more difficult matter to estimate by how much, and it is even more difficult to derive an acceptable economic value that represents that reduction. The most straightforward way to deal with this would be to assume that all healthy days of life lost are working days, of which there are at least 250 in a year, and that the indirect economic costs are therefore the loss of production or income. If the average daily wage could be taken as an indicator of productivity, the simple multiplication of number of days lost by that daily wage would represent the indirect economic costs of a disease. This, however, might be considered too simplistic to be fully acceptable. Some points open to question are the following:

1) Average wages are not an adequate indicator of productivity because of differing marginal wages and institutional influences;
2) Not all days lost will be working days. People outside the labour force and those who are unemployed do not lose marketable output or income when they fall ill. Moreover, the seasonal nature of employment and health in many poor countries introduces another qualification;
3) There is no empirical evidence to support the statement that all adult people suffering from malaria or schistosomiasis lose their full working capacity when ill. Studies of the effects of schistosomiasis on work performance have come up with conflicting findings. In some of the cases, patients performed less well than others under otherwise similar circumstances, and thus lost some income or production (Mills and Thomas 1984; Presscott 1979; Audibert 1986). Because a remarkable percentage of schistosomiasis occurs among children, it is very difficult to estimate productivity loss (although children usually do some work);
4) The economic valuation of life, and therefore of death, is a very controversial issue. The practice of estimating the economic loss due to premature death by calculating the loss of the expected income earnings over the remaining lifetime (based on average life expectancy) does not work. It might be easier if we assume that the economic value of life at least equals the cost of its maintenance and reproduction, and then take a minimum subsistence level, reflected in a certain percentage of the average daily wage, as a basis for our calculations.
   If the indirect cost of disease and death is quantified through the amount of time lost, it is tacitly assumed that one day of complete disability equals one day of death. This is the result of the narrow concept of health that economists tend to use, defining it only in terms of production or income gained or foregone, as if people would not prefer a period of full disease rather than death, or as if they did not value leisure and health as such. This practice also means that infant mortal-

ity gets an extremely high price tag because of the greater loss of potential lifetime. This is a value judgement that does not seem to be acceptable in most societies. Some 'weights' may therefore have to be applied, or the morbidity and mortality of children could be ignored in the indirect costs (although not in the direct costs).

5) More complicating factors still have to be introduced. Apart from criticism levelled against the income concept (or value of production) as an indicator of well-being, the whole approach is open to question. Whilst nobody will deny that the concept of time lost is crucial in attributing an economic value to disease, it seems preferable to put this in a household or community perspective rather than in an individual one (Popkin 1982; WHO 1980a). When a person falls ill, the effects of the illness are rarely felt by the victim alone. Usually, a certain amount of compensating activity is undertaken by others, particularly within the household. Some jobs may be done by others in their spare time, children may be kept away from school for a while, urgent matters may get priority at the expense of the more routine household activities, and some jobs may be postponed or cancelled. The loss of income or production will probably be less than that directly related to the days lost by the victim, but other costs of coping with the disease may occur. Health care will take extra time (including visits to hospitals), less remunerative crops may be grown because of their lower labour demands, or some 'home' output may be sacrificed to maintain cash incomes. The resulting time (re-)allocations depend largely on established social and economic patterns of behaviour, and as such are less traceable than is usually suggested.

   These distributional consequences are hard to ignore, and so, too, are other institutional factors that are tacitly assumed through the income/production approach (e.g. differences in labour force participation between classes and sexes, causes of particular levels of unemployment). But it is also clear that such issues cannot easily be included in an operational framework for planning purposes. Much more empirical research seems necessary before diseases can be fully and adequately dealt with in economic analyses, if at all.

The same applies to a great many long-term and external effects of disease in general, such as nutrition losses, consumption dissatisfaction, restricted movements, and intellectual disability (Brown 1983).

Guidelines for Assessing Indirect Costs

The above considerations complicate the straightforward approach of equating the indirect economic effects with the number of healthy days lost, multiplied by the average daily production or wage. On the one hand, that would result in an over-estimate of the economic cost of the disease, because, in an economic sense, only a part of that time is lost. On the other hand, it ignores certain external costs that might lead to a higher estimate.

In the absence of a complete analysis of the effects of disease on the allocation of time, it seems wise to accept a certain part of the time lost, as an expression of the production foregone, multiplied by a price that is a reasonable approximation of the value of that production. This seems fully justified in view of the many other assumptions that enter into conventional economic appraisals.

Malaria (Morbidity and Mortality)

If no specific research can be arranged for a particular project, some crude parameters can be derived from the evidence available elsewhere. Research findings suggest that for each case of malaria an adult loses from 10 to 30 days in one year. If the dates of the majority of adult cases could be identified, a high incidence during the main agricultural (rainy) season would lead to a correction upwards, or downwards in the opposite case. (It should be stressed that irrigation reduces that seasonal fluctuation, contributing to a more average situation throughout the year.) Depending on the incidence, intensity, and time pattern of malaria amongst adults, 5 to 15% of the annual production per person could be taken as the indirect costs of the disease (Conly 1976).

Instead of using the conventional expression for the value of annual production per person – i.e. Gross National Product (GNP) per capita – it might be better to introduce the concept of full income. This not only considers formal production, usually for the market, but includes a value for typical 'home' activities (e.g. food preparation, house construction, and other subsistence activities). These can add as much as 40% to the GNP in some poor countries (Mott 1984). If this cannot be calculated, the daily wage can be used as an approximation. Although the loss of production per day is usually less than the daily wage, using the whole wage means compensating for some extra negative side-effects ('home' output, etc.).

For mortality as a result of the extra malaria (and schistosomiasis), minimum annual subsistence levels multiplied by the remaining number of years of an average person's life (a maximum of 40 years in this case, from 15 to 55) can be used as an approximation. If one adheres to the limited time horizon of the project, this calculation will only cover the remaining project years.

Schistosomiasis (Morbidity)

For the majority of non-fatal cases of schistosomiasis amongst adults, 5 to 10% loss of annual production seems a justified estimate, or 20% for severe cases (Jobin 1984). The question still arises 'For how many years will this percentage have to be applied?' The average duration of chronic schistosomiasis appears to be 10 to 20 years, but with a certain level of treatment, not so much time will be lost. Throughout the project life, a number of infected children will enter the labour force as well – the more so, the longer the life of the project. Some rough guesses need to be made from the available evidence on the particular disease pattern and distribution among age groups. For projects with a long lifetime, 5 to 10% of all cases might be taken as production loss, to compensate for the entry of children into the labour force. This would certainly simplify the calculations, which are no more than approximations anyway.

There may be situations where no realistic estimates can be made because of the lack of data or because of a disease pattern that is far too complicated, diversified, or whimsical. It may then still be possible to include some modest loss of production for health reasons, say 2 to 5%. This is already being done for other matters as well (e.g. loss of production due to inadequate storage facilities), which are equally impossible to trace accurately.

Indirect Costs as a Percentage of the Direct Costs

Usually, the indirect costs of disease are far greater than the direct costs. For an order of magnitude, a lower and an upper limit for the total costs might be set at 3 to 7 times the direct costs, or the indirect costs at 2 to 6 times the direct costs. Once the direct costs have been calculated, the question is, in view of the scarcity of evidence, 'Which factor seems reasonable for the indirect costs?'

Assessing the Indirect Costs for the Example Projects

For the three example projects, we have assessed the indirect economic costs. These are shown in Table 10.4. We stress that these projects are merely illustrative and that we have made certain assumptions and follow fairly straightforward methods of calculation. It should not be forgotten, however, that all one needs is an order of magnitude, which, in the design and appraisal phases, can serve as an important parameter for the choice between project options.

10.3 Cost-Benefit Analysis

A powerful tool in planning is the Cost-Benefit Analysis (CBA). Although it has serious theoretical shortcomings (Bol 1982; Irvin 1978), it allows a useful comparison to be made of the costs and benefits of an investment.

Including the negative health effects in a CBA can produce one of two outcomes:

- The project no longer meets the investment selection criterion (i.e. the IRR is lower than required). If so, this provides a sound economic reason for rejecting a project that would have caused serious health problems;
- The project still meets the investment selection criterion. This means that the benefits from irrigation are large enough to pay for the adverse effects of ill health.

If the second outcome is found, action to prevent the adverse health effects is still recommended, for a number of reasons:

- Prevention is always better than cure;
- The beneficiary group is not necessarily the same as those adversely affected;
- A sum equivalent to the present value of the direct and indirect costs of ill health can be spent on preventive measures without affecting the economic feasibility of the project.

Neglecting complicating factors (e.g. subsidies, price corrections, shadow prices, and shadow wage rates), we have made CBA's for the three example projects. These are presented in Table 10.5. The CBA's are based on the following assumptions:

- Investment cost U.S. $5000 per hectare;
- Operation and maintenance cost U.S. $200 per hectare per year;
- Yield level 3500 kg paddy per hectare per year;
- World market price paddy U.S. $325 per ton;
- Cost of production U.S. $87.5 per hectare per year.

Table 10.4 Indirect costs of health changes in Projects 1, 2, and 3 (in U.S. $)

Project 1	Project 2	Project 3
Assumptions: 1. No of malaria cases is 2000/year (Table 10.2) 2. 60% of cases occur in population under 15 3. Annual adult production value is $300 4. Each adult case leads to losses of between 5 and 15% of annual production value Calculation lower limit: 2000 × 0.4 × 0.05 × $300 = $12,000/year Calculation upper limit: 2000 × 0.4 × 0.15 × $300 = $36,000/year Average value of indirect costs used for further calculation (Table 10.5) $24,000/year	Assumptions: 1. No. of schistosomiasis cases is 10,000/year; average no. of days of healthy life lost is 600,000/year (Table 10.2) 2. As in Project 1 3. Production value is $150 per person per year, or $1.50 per adult per day 4. Lower limit of production loss is taken as 10% of annual production per person, for each case 5. Upper limit is taken as 40% of daily production value per adult, for all days of healthy life lost Calculation lower limit: 10,000 × 0.1 × $150 = $150,000/year Calculation upper limit 600,000 × 0.4 × $1.50 = $360,000/year Average value of indirect costs used for further calculation (Table 10.5) $255,000/year	Assumptions (malaria) 1. No. of cases is 9000/year (Table 10.2) 2. As in Project 1 3. Annual adult production value is $325 4. As in Project 1 Calculation lower limit: 9000 × 0.4 × 0.05 × $325 = $58,500 Calculation upper limit: 9000 × 0.4 × 0.15 × $325 = $175,500 Average indirect costs (malaria) = $117,000/year Assumptions (schistosomiasis): 1. No. of cases is 10,000/year; average no. of days of healthy life lost is 1,000,000 per year (Table 10.2) 2. As in Project 2 3. Production value is $125 per person per year, or $1.25 per adult per day 4. As in Project 2 Calculation lower limit: 10,000 × 0.1 × $125 = $125,000 Calculation upper limit: 1,000,000 × 0.4 × $1.25 = $500,000 Average indirect costs (schistosomiasis) = $312,500/year Total indirect costs (malaria and schistosomiasis) used for further calculation (Table 10.5) = $429,500/year

Table 10.5 Cost-Benefit Analyses for Projects 1, 2, and 3 (in U.S. $)

Project 1	Project 2	Project 3
Investment		
$5,000,000	$12,500,000	$25,000,000
Maintenance		
$200,000	$ 500,000	$ 1,000,000
Benefits		
$1,050,000	$ 2,625,000	$ 5,250,000
Annual cash flow		
$850,000	$ 2,125,000	$ 4,250,000
The IRR is 11.0%	16.1%	16.8%
Including the health costs		
Direct costs		
$6,400	$ 17,500	$ 40,000
Indirect costs		
$20,000	$ 255,000	$ 429,500
brings the annual cash flow down to		
$823,600	$ 1,852,500	$ 3,780,500
The IRR is 10.3%	13.7%	14.9%

The investment selection criterion used in the three example projects is the IRR. Over the last decades, the required IRR in Third World countries has usually been within the range of 8 to 12%. If the IRR for Projects 1, 2, and 3 was 10%, the inclusion of the health effects in the CBA lowers the IRR, but the projects still remain feasible.

10.3.1 Control Measures or Design Alternatives

Any control measure that costs less than the adverse health effects it helps to prevent is economically feasible. For example, the average annual costs of the negative health effects in Projects 1, 2, and 3 are U.S. $26,400, $272,500, and $469,500 respectively. Dividing these amounts by the population at risk (10,000, 20,000, and 30,000 respectively), we find an annual per capita cost of $2.6, $13.6, and $15.7 respectively. Disease prevention measures that cost less on a per capita basis are therefore economically feasible.

Design alternatives for disease prevention represent initial investment costs. To evaluate their economic feasibility, these investment costs must be compared with the present value of the health costs that they prevent throughout the project life. Table 10.6 shows the permissible cost of design alternatives for disease prevention in Projects 1, 2, and 3.

Table 10.6 shows, for example, that, in Project 3, an additional investment of up to U.S. $3.08 million would pay for itself, provided that it was 100% effective in preventing diseases. Usually, however, this will not be the case, and additional measures will be needed, which represent an annual cost. To arrive at the permissible cost of the design alternative, such annual costs have to be deducted from the annual health costs prevented.

Table 10.6 Permissible cost of design alternatives for disease prevention in Projects 1, 2, and 3

Project	Annual health costs prevented*) ($)	Project life*) (years)	IRR**) (%)	Multiplication factor***) (–)	Permissible cost of design alternative ($)
1	26,400	10	10	6.145	162,228
2	272,500	20	14	6.623	1,804,767
3	469,500	30	15	6.566	3,082,737

*) From Table 10.4 (annual health costs)
**) From Table 10.5 (IRR, including the health costs)
***) Multiplication factor that gives the present value of $1 received annually throughout the project life at a discount rate equal to the IRR value shown in Table 10.6

Many engineering measures for the control of diseases are also beneficial for irrigation. Measures such as canal lining, mechanical weed control, or even an adequate number of system operators may become economically justifiable after the health effects have been included in the CBA. Hypothetical though the example projects may be, they demonstrate how powerful it can be to consider the health effects in a CBA. It can lead to the choice of an alternative design for health reasons, and one that is justified in economic terms.

10.4 Cost-Effectiveness Analysis

A CBA that includes health considerations is not always relevant to an irrigation project. Some projects are too large to be appraised in terms of a partial analysis like a CBA; other projects may be too small. There may also be situations where, because of the paucity of data or distributional considerations, it is not really possible to express the economic effects of health changes in monetary terms. In such cases, a Cost-Effectiveness Analysis (CEA) offers an interesting alternative.

The difference between a Cost-Benefit Analysis and a Cost-Effectiveness Analysis is discussed in much of the literature on health economics (Bol 1982; Irvin 1978; Paulini 1979; Prost and Prescott 1984). Whereas a CBA compares a project's monetized benefits and costs to verify its economic feasibility, a CEA investigates the best or cheapest way of achieving a desired objective by comparing the costs and effects of possible interventions.

If the objective is 'No additional disease due to irrigation', the criteria of effectiveness may be (Carrin 1984):

- The number of lives saved;
- The number of days of healthy life gained;
- The extra number of persons protected against malaria and schistosomiasis;
- The reduction in the number of cases or in the prevalence rate of these diseases.

The most pragmatic measure of effectiveness, in view of its limited data requirements, may be the number of case-years of infection prevented, or the number of new cases prevented during the lifetime of the project (Rosenfield 1979). Other meaningful indicators are the cost per death averted or the cost per day of healthy life lost (Walsh

and Warren 1980; Morrow 1985).

If only one criterion for effectiveness is applied, a CEA is always open to the general criticism that this is too narrow a perspective. Multiple objectives can be introduced within the framework of a CEA, but this requires explicit treatment of their mutual trade-offs (Carrin 1984).

Ideally, the cost-effectiveness of a particular measure is the present (discounted) value of the total costs divided by the total number of cases prevented. The average annual cost per case prevented avoids the controversial issue of discounting (i.e. how to value the future in terms of the present) (Prost and Presscott 1984).

10.4.1 Methodology and Examples

A CEA requires the following steps (Rosenfield 1979):
- Predicting the number of cases per year without control measures;
- Substracting the annual number of cases with control;
- Summing the differences over the lifetime of the project;
- Calculating the control costs per year, which may be summed by discounting;
- Calculating the unit cost of each case prevented;
- Doing this for each alternative intervention (or design) and comparing the different outcomes.

Rosenfield (1979) developed a schistosomiasis transmission model and applied it to calculate the ex-ante cost effectiveness of different measures to control that disease. Using data from the St Lucia project in Puerto Rico for the years 1970-77, she arrived at the comparison shown in Table 10.7.

Because chemotherapy alone appears to be almost as effective as when it is combined with domestic water supply, chemotherapy is by far the most cost-effective control measure.

It speaks for itself that certain assumptions are needed to arrive at such a clear-cut comparison. Existing cost figures are often hard to compare, because the same details are not always included. The concept of cost in health often lacks uniformity (Mach and Abel-Smith 1983; Paulini 1979).

Table 10.7 Cost-effectiveness of schistosomiasis control (in U.S. $)

Control measure	Case-years of infection prevented	Cost per case-year prevented
A combination of chemotherapy and domestic water supply	3652	$16.5
Chemotherapy	3517	$ 4.4
Domestic water supply	2732	$20.5
Mollusciciding	1257	$41.2

No control would have given 9430 case-years of infection

Repeating the same exercise for the Lake Volta Project, Rosenfield (1979) estimated the prevalence of schistosomiasis with different control strategies for the first 10 years after project construction. The cost per case-year of infection prevented varied from U.S. $10 to $448 (1972 prices). In this project, a combination of the three possible control measures proved to be the most cost-effective. It is worthwhile mentioning that the best strategy would only cost 2% of the total investment cost of the Lake Volta Project.

In eighteen studies that used the same measure of effectiveness, the annual cost per case-year of schistosomiasis prevented, with various control measures, ranged between U.S. $2.8 and $84.2 (1984 prices) (Creese 1985).

Unfortunately, not much information of this kind is available about malaria, although its control may be even more important than that of schistosomiasis. The only study that calculated the (annual) cost per case-year prevented yielded a somewhat misleading figure (U.S. $1280) because it included all preparatory research. Walsh and Warren (1980) provided average figures for mosquito control in Africa: the cost per death averted varied from U.S. $250 to $600 (see also Barnum et al. 1980; Lee and Mills 1983; Prost and Presscott 1984).

A question that cannot be answered with a CEA is: 'What is the total amount of money that should be spent on health control?' That amount will depend on alternative investments, also those outside the particular field or sector, but it can be found through a CBA. By using a monetary indicator, a CBA can in principle compare any option. Then, once the budget constraint is known, a CEA can indicate which control appears to be most effective economically, within the given limits.

Suppose, for example, that the management of Project 1 were to receive an annual amount of U.S. $9000 for health control. Knowing only the relative increase in malaria (20%), they would then have to choose the most effective way of spending that amount by comparing alternative control strategies. If the technical options open to them are larval control, chemoprophylaxis, or some extra maintenance that would allow better water control or greater flexibility, they would have to estimate the effectiveness of each in preventing new cases of malaria within the given budget. Assuming that the larval control would be able to prevent all new cases from the 5th year onwards, that chemoprophylaxis would reduce all new cases by 60% right from the start (by covering the 2000 children within the target group), and that extra maintenance would reduce the extra risks by 20% per 2 years, they would simply assess the respective cost-effectiveness of each method. Bearing in mind the time profile of the predicted increase in malaria (an extra 10% after 2 years and a peak of 20% after 3 years), they would find the effectiveness of the three control methods to be, respectively, 10,000, 9000, and 7800 (new) cases prevented over the lifetime of the project. Discounting the budget of U.S. $9000 at 10% over 10 years would lead to cost-effectiveness figures of, respectively, U.S. $5.5, $6.1, and $7.8 per case prevented. On the basis of this hypothetical exercise, larval control would be selected.

Similar exercises could be undertaken for the other two projects, but it is evident that, in practice, the problem will be one of estimating the effect of a particular control therapy. Once that is known, the calculations will be simple. If the target is 'No additional disease', one could also work out a CEA starting from that target and find the

least-cost method. An example of this is presented in Chapter 6 (Table 6.8), where the annual costs of alternative designs are compared. That cost analysis comes close to a (simplified) Cost-Effectiveness Analysis.

10.5 Summary

The methodology presented in this chapter shows how the (negative) health effects of irrigation can be included in the economic appraisal of an irrigation project. It may be helpful if we summarize the steps to be taken.

1) Two types of 'technical' inputs will have to be provided by the health expert:
   - A quantification of the health impact of the project (i.e. the increased prevalence of water-borne diseases) in terms of changes in morbidity and mortality;
   - The technical efficacy of potential control measures in preventing extra diseases within the given context.

   Both parameters will have to be presented in ways that are easily accessible (e.g. a time profile of extra disease days throughout the lifetime of the project, and the influence that control options can exert on that profile);
2) These potential health effects will have to be translated into economic effects; these are the implicit costs to the project if no corrective action is taken, and the benefits of alternative design or control measures that would prevent the occurrence of those extra costs.

   The direct economic effects are the extra costs of treatment due to an increased prevalence of disease; they include the real cost of the extra services (personnel, drugs, hospital overhead) and the private expenditure of patients (transport and other travel costs).

   The indirect economic effects are the loss of production or income incurred by the patients as a result of the extra prevalence of disease; these depend on the seasonality of the disease (during peak labour demand or not), the extent to which working members of a household are affected, the scope for coping with the extra disease, and the average daily productivity per person. The number of working days lost multiplied by the average daily wage gives a reasonable approximation of these indirect effects, certainly in an appraisal situation, with limited time and money available for research.

   Often, it pays to express the indirect effects as a percentage of the direct ones, because the latter can be calculated more precisely. In terms of assumptions about working days and production lost, one need not strive for exactitude; only an order of magnitude is required for planning purposes.
3) If the health effects can be quantified and expressed in monetary terms, these can be included in a Cost-Benefit Analysis to compare different options. Design and project choice will be altered by this inclusion, because seemingly more expensive options may now become economically worthwhile if their extra benefits (health costs foregone) exceed the extra investment costs. Comparing the Net Present Value or Internal Rate of Return of the potential alternatives with or without extra health control will lead to an economic choice on the incorporation of health measures into the project.
4) If health effects can be quantified but not monetized, a Cost-Effectiveness Analysis

can serve a similar purpose. By expressing health effects in terms of healthy days lost, extra prevalence or incidence of particular diseases, and extra case-years of infection or new cases, one can compare the cost-effectiveness of different control measures or design options. If, for each alternative, one calculates its average annual cost and the average annual disease cases it will reduce, one can choose the least-cost method. If the objective of 'No additional disease from irrigation' is accepted, one can find the most cost-effective way of achieving that objective.

The above steps can easily be integrated into the '10-Steps Approach' suggested in Chapter 6, because they overlap. The above steps stress the economic aspects of the health effects of irrigation in project planning, and the 10-steps stress the engineering aspects.

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Technical Note 1
The Epidemiology of Mosquito-borne Diseases

Prepared by Dr L. Molineaux

1 Introduction

Epidemiology is the science that describes and explains the distribution of disease in human populations: who has the disease (or the infection), how seriously, and when, where, and why?

This note reviews the principles of the epidemiology of mosquito-borne diseases, and relates them to control, particularly to environmental control. The presentation is intentionally schematic. Any reader wanting to know more about the epidemiological principles is referred to *Epidemiology and Control of Vector-borne Disease*, U.S. Department of Health, Education, and Welfare, The Public Health Service, and Communicable Disease Control.

As this note is mainly concerned with environmental control and is primarily addressed to engineers, the emphasis is on infection rather than on disease. Certain control methods (e.g. the treatment of patients suffering from malaria) can have a major impact on the prevalence and severity of a disease – and on mortality – but will have little effect on the incidence and prevalence of infection.

2 The Factors Involved (Qualitative Epidemiology)

2.1 The Populations Involved

The parasite population is the population of mosquito-borne parasitic organisms responsible for human disease. Included in that population are viruses, protozoa, and helminths. The parasite population circulates in the human population, in one or more mosquito populations, and, in certain cases, also in one or more animal populations.

There are three main types of association. These are illustrated in Figure 1. The species primarily responsible for maintaining the parasitic population is called the reservoir. In Type 1, the reservoir is man; in Types 2 and 3, the reservoir is animal. (The dotted arrows in Type 2 indicate that man is usually not a reservoir for the animal disease.) In Type 3, man may become infected (and ill) but not infective; he is then known as a dead-end host.

In addition to the 'horizontal' transmission routes in Figure 1, certain infections are also transmitted 'vertically': from female parent to offspring, either in man (as with congenital malaria) or in the mosquito (as with certain group viruses).

Implications for Control

The control strategy adopted should take into account the various populations involved and their degree of association. If, for example, an animal reservoir exists and is ignored, control efforts may fail.

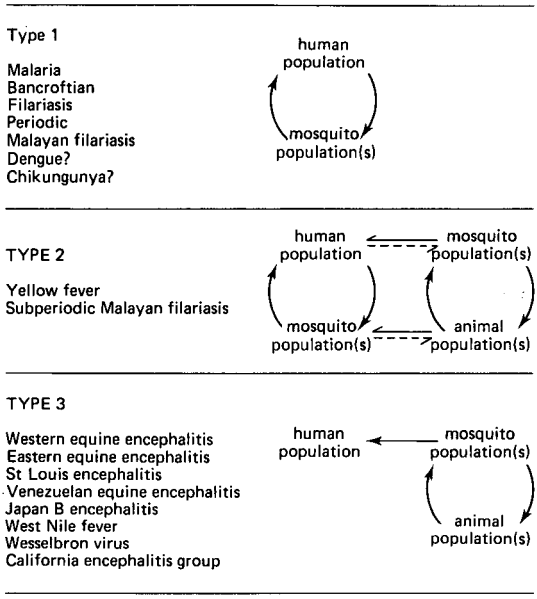

Figure 1 The three main types of associations between populations involved in the transmission of mosquito-borne infections

2.2 The Infection in the Human Host

Multiplication and/or Development

The parasitic agents fall into three groups. They may:
- Multiply only (as in virus diseases);
- Develop only (as in filariasis);
- Multiply and develop (as in malaria).

Immunity and Superinfection

Viruses typically produce rapid, complete, and life-long immunity, with no superinfection (a second infection in the wake of the first). In malaria, immunity develops slowly and progressively as a result of repeated infections (and superinfections), and is always partial and reversible. Less is known about immunity to filariasis, but it is likely that superinfection is common and that, because the worms are long-lived, there is an accumulation of parasites. Immunity may develop even more slowly than with malaria.

Disease

Mosquito-borne parasitic agents may produce acute or chronic illness, or both. If

one's aim is to control disease by controlling its transmission, it may be useful to distinguish between illness (acute or chronic) resulting from the first infection and illness resulting from repeated infections. The latter could result in an accumulation of parasites or in immunopathology (a lowered resistance to disease), or both.

With the possible exception of dengue, mosquito-borne viruses cause infection and disease through the first contact. In dengue, the initial infection may not give rise to any apparent disease, but creates an immunopathological reaction. Upon later re-infections, the immunopathology may give the chronic disease. Dengue is mentioned as a possible exception because some of its manifestations are attributed to immunopathology – a theory that is not universally accepted.

In most non-immunes, the first infection of malaria typically produces acute illness (life-threatening in the case of *P. falciparum*), whereas repeated infections produce relatively mild chronic illness in most persons, and, for reasons not yet well understood, severe chronic illness in a few.

Filariasis produces acute illness, but its most serious consequences (elephantiasis, hydrocoele) result from prolonged exposure, although, again for reasons not yet well understood, only in certain persons.

Implications for control

If disease results mainly from repeated contact, any reduction in transmission can only result in a decrease in disease. If disease results mainly from the first contact, two scenarios are possible:

- If man is not the reservoir (in which case the immunity of the human population is usually low), any reduction in transmission will again result in a decrease in disease;
- If man is the reservoir (in which case the immunity of the human population may be high, as it is in areas of intense malaria transmission), a partial reduction in transmission may displace morbidity (and any resulting mortality) towards older age-groups (from infants to children to adolescents to adults). This may or may not be socially acceptable. With malaria, this very issue has been the subject of much controversy. Really hard data are not available, for understandable reasons, mainly ethical, but one should be aware of the problem and be ready to consider remedial measures (e.g. increasing the effectiveness of the control of transmission and/or of the diagnosis and treatment of cases) or an even more radical change in strategy.

2.3 The Infection in the Mosquito

The reader is reminded that only adult female mosquitoes transmit diseases to man and animals.

Multiplication and/or Development

What has been said about infection in the human host can be repeated here. The para-

sitic agents will multiply only, develop only, or multiply and develop. In all cases, an incubation period is required before the mosquito becomes infective. Mosquitoes are poikilothermic (i.e. they only multiply and/or develop within a certain range of temperature). Within that range, the incubation period varies inversely with temperature.

Mosquito Survival

In the mosquito, the infection's incubation period is typically of the same order of magnitude as its life expectancy. Most infected mosquitoes do not survive long enough to become infective. The infection itself may shorten the life of the mosquito, although this is not known with certainty and, in most cases, is probably of minor epidemiological importance.

2.4 Entomological Factors of Transmission

The rate of transmission depends on the following factors:

a) The number of adult female mosquitoes; this in turn depends on their rate of emergence and their life expectancy;
b) The frequency with which they feed;
c) The proportion of bloodmeals taken from the relevant hosts (e.g. man in the case of malaria). This depends on genetically conditioned preferences and on the relative availability and accessibility of alternative hosts. Accessibility is affected by environmental factors (e.g. types of human and animal shelters) and by behavioural factors, such as:
   - Does the vector bite by day or by night?
   - Does it prefer to bite indoors or out?
   - Where are men and animals when the vector bites them?
d) The length of the infection's incubation period in the mosquito;
e) The life expectancy of the mosquito, which affects both the proportion of mosquitoes surviving the incubation period, and the number of infections they distribute after becoming infective.

Implications for Control

Residual spraying reduces Factors a) and e). Other vector control methods reduce Factor a). Research is currently exploring the possibility of replacing a vector population with a physiologically insusceptible population. Factor c) can be reduced by decreasing the accessibility of man (e.g. with screened houses, bed-nets, repellents, and/or by zooprophylaxis, i.e. increasing the availability and accessibility of alternative sources of blood). Some of these measures are adapted to night-biters, either exclusively (bed-nets) or largely (screened houses).

2.5 Other Environmental Factors

The ways in which the environment and the manipulation of it affect the emergence of mosquitoes are covered elsewhere in this book. Here, a few points only are considered.

Temperature has multiple effects. Within tolerated limits, a rise in temperature:

- Accelerates the development of the aquatic stages;
- Shortens the incubation period in the vector;
- Increases the vector's frequency of feeding;
- Shortens the vector's life expectancy, although probably to a lesser extent than the incubation period is shortened. This means that the fraction surviving the incubation period probably increases. That, at least, was found to be true in the single case in which this matter was explicitly investigated, namely in a study of malaria transmitted by *A. maculipennis* in the U.S.S.R.

The air's saturation deficit may also inversely affect the vector's life expectancy.

The availability of shelters other than houses (e.g. vegetation) may reduce the vector's endophily.

Implications for Control

The effect of temperature on the development of the aquatic stages is relevant when the frequency of larvicide applications is being decided. The other effects of temperature are relevant when one is evaluating the intensity of transmission, which in turn is relevant when control strategies and objectives are being selected.

3 The Dynamics of Transmission (Quantitative Epidemiology)

The environmental control of mosquito-borne disease, alone or in combination with other control methods, may have the following objectives:

- To prevent epidemics;
- To eradicate an endemic disease;
- To reduce an endemic disease to an 'acceptable' level.

When emergency measures are called for to control an on-going epidemic, environmental control will only be of minor importance, but in achieving any of the above objectives, it – and quantitative epidemiology – have definite roles to play.

3.1 The Basic Reproduction Rate (R)

The basic reproduction rate (R) is the number of secondary cases (infections) that result from the introduction of an infective case into a population of susceptibles. R is the maximum reproduction rate that is theoretically possible in a given situation. The actual reproduction rate is reduced below R through the effect of immunity. This

holds true whether immunity is complete, as in viral diseases, or incomplete, as in malaria. In a stable situation, the actual reproduction rate is equal to one.

A formula for the basic reproduction rate of a vector-borne disease in a vertebrate population (e.g. man) is given in Equation 1 (after McDonald 1957, The Epidemiology and Control of Malaria, Oxford University Press)

$$R = \left(\frac{1}{r}\right)(ma)(b')(p^n)\left(\frac{1}{-\log_e p}\right)(a)(b) = \frac{ma^2bb'p^n}{-r\log_e p} \tag{1}$$

where:

r	=	the rate at which a non-immune infective recovers from infectivity;
$\frac{1}{r}$	=	the infective period (days) in man;
m	=	the number of vectors per man;
a	=	the number of bloodmeals taken on man per vector per day;
ma	=	the number of vector bites per man per day;
p	=	the proportion of vectors surviving 1 day (assuming the mortality of vectors to be independent of age and infection);
n	=	the incubation period (days) in the vector;
p^n	=	the proportion of vectors surviving the incubation period;
$-\log_e p$	=	the vector's life expectancy (days), independent of age;
b'	=	the proportion of bites on infective persons which result in infection of the vectors;
b	=	the proportion of bites by infective vectors on non-immune persons which result in infection of the persons.

Remark

MacDonald's formula is identical to the above, except for the factor b', which we have added.

3.2 The Vectorial Capacity

If we remove r from R, we obtain a 'daily basic reproduction rate' or a 'daily (effective) contact rate'. Let us call that quantity 'the vectorial capacity' and denote it by C. We then have

$$C = \frac{ma^2bb'p^n}{-\log_e p} \text{ and } R = \frac{C}{2} \tag{2}$$

Remark

When several vector and vertebrate populations are involved, there will be a distinct contact rate (vectorial capacity) for each pair of vector and vertebrate species.

3.3 Threshold: the Critical Vectorial Capacity and the Critical Mosquito Density

There is a risk of an epidemic only if $R > 1$ (i.e. if $C > r$), and an infection can remain endemic only if $R > 1$ (i.e. if $C > r$). A further condition for the infection to remain endemic is an adequate supply of susceptibles, which depends on population size, birth rate, and type of immunity produced. An infection like malaria, which produces only a slow, progressive, incomplete, and reversible immunity, can maintain itself in a much smaller population than can viral infections, which produce a rapid, complete, and irreversible immunity.

Critical Vectorial Capacity

The critical vectorial capacity (C^*), below which there is no risk of an epidemic, and below which the infection cannot remain endemic, is

$$C^* = r$$

The critical vectorial capacity is a characteristic of the parasite; it is higher for infections with a large r (i.e. a short infectious period).

Critical Vector Density

For given r, a, b, b', p, and n, there is a critical value of m (m^*) (i.e. a critical vector density), namely the value that satisfies

$$\frac{m^* a^2 bb' p^n}{-\log_e p} = r \text{ or } m^* = \frac{-r \log_e p}{a^2 bb' p^n} \tag{3}$$

There is also a critical value of 'ma', the man-biting rate, namely

$$(ma)^* = \frac{-r \log_e p}{abb' p^n} \tag{4}$$

Figure 2, based on Equation 3, shows the critical density for different recovery rates as a function of

$$\frac{a^2 bb' p^n}{-\log_e p}$$

which can be considered an index of vector efficiency.

Environmental control may reduce vector density and/or man-vector contact. The concept of critical vector density, illustrated in Figure 2, is useful when a control program is being planned, even though the estimates of the parameters involve a large measure of uncertainty.

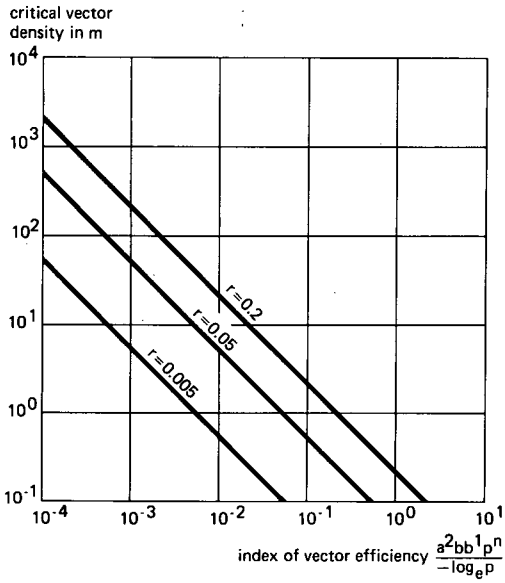

Figure 2 The critical density as a function of an index of vector efficiency for different recovery rates

Relevance for Control

If the objective is to eradicate or prevent epidemics, we want $R < 1$ or $C < r$. Note that in certain mosquito-borne infections, the actual vectorial capacity can be hundreds (perhaps even thousands) of times larger than the critical value. We therefore need estimates of both the natural vectorial capacity and its expected reduction after control measures have been applied. If fully protective immunization is possible and if $X =$ the proportion of the population that is immunized, the interruption of transmission requires

$$(1\text{-}X)R < 1 \text{ or } (1\text{-}X)C < r \tag{5}$$

or

$$(1\text{-}X)\left(\frac{mp^n}{-\log_e p}\right)(a^2)(bb') < r \tag{6}$$

This equation helps in understanding the impact and synergism of broad classes of control methods:

- Immunization reduces (1-X);
- Vector control reduces $\left(\frac{mp^n}{-\log_e p}\right)$; residual spraying reduces m and p; the other methods of vector control only reduce m;
- The reduction of man-vector contact reduces (a^2);
- Drugs increase r.

3.4 The Relationship between Vectorial Capacity and the Endemic Level of Malaria

This section deals specifically with malaria, because it is for malaria that this aspect of quantitative epidemiology has been best developed and is most relevant.

Figure 3 illustrates the central place occupied by the vectorial capacity in the epidemiology of malaria. The endemic level (the amount of malaria in a population) is determined by certain intrinsic (genetic) characteristics of man and parasite – characteristics that are relatively stable in time and space – and by the vectorial capacity – which is unstable and can vary greatly and rapidly in time and space. Variations in vectorial capacity are thus mainly responsible for the differences between different malaria situations, and for seasonal and other temporal changes in a particular malaria situation. The vectorial capacity is determined by certain intrinsic (genetic) characteristics of the vectors, which are relatively stable in a given place, but can vary greatly between places, between different anopheline species, and sometimes also within a single species. The environment, which is unstable in time and space, affects the vectorial capacity. Through natural selection (suggested by the dotted arrows in Figure 3), the environment slowly affects the genetics of man, vectors, and parasites.

The relationship between the vectorial capacity and the endemic level is shown in Figure 4, which has been derived from different mathematical models of the transmission of malaria. The figure shows the natural equilibrium endemic level, which corresponds, in the long run, to a given level of vectorial capacity. The main qualitative features of the relationship are independent of the model used and have been firmly established. They are:

- There is a critical level of vectorial capacity below which malaria cannot maintain itself;
- Above the critical level, the relationship is non-linear:
  - In the lower range, a small difference in vectorial capacity produces a large difference in endemic level;
  - In the higher range, even a large difference in vectorial capacity produces little or no difference in endemic level. (Note that the horizontal scale is logarithmic.) This saturation effect is due to the finite size of the human population and to

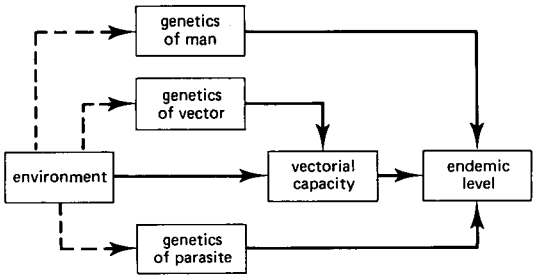

Figure 3 The central place of the vectorial capacity in the epidemiology of malaria

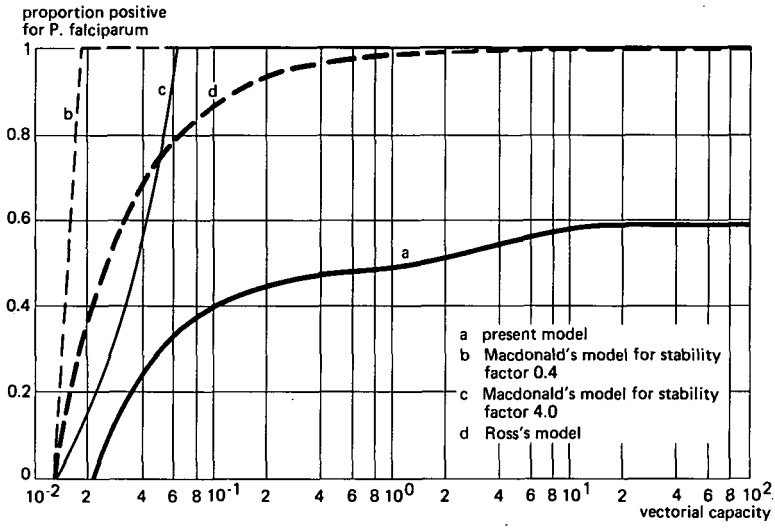

Figure 4 Yearly average crude parasite rate as a function of yearly average vectorial capacity (from Dietz et al. 1974, WHO Bulletin 50: 347-357)

immunity. Immunity has been taken into account in the model of Dietz et al., but not in the other models of Figure 4; they therefore produce endemic levels of up to 100 per cent.

Implications for Control

The implications for control are obvious and important. In the model of Dietz et al., for example, a reduction in vectorial capacity from 20 to 2 would only reduce the prevalence of (patent) *P. falciparum* parasitaemia from 59 to 51 per cent. A decrease in vectorial capacity from 2 to 0.2 would reduce the prevalence of malaria from 51 to 45 per cent. A decrease in vectorial capacity from 0.2 to 0.02 would reduce prevalence from 45 per cent to zero.

Even though the actual figures are questionable (because of assumptions made and measurement errors), there is no doubt about the general relationship. Historically, the existence of a threshold had already been demonstrated by Ross, and the implications of the non-linear relationship for control were explicitly deduced and stressed by Moshkovsky (1967, WHO Bulletin 36: 992-996).

The long-term natural equilibrium between vectorial capacity and endemic level, as considered here, is particularly relevant for environmental management, because environmental management will bring permanent changes that will lead to a permanent reduction in vectorial capacity and a lower endemic level.

3.5 Integrated Control: Synergism between Methods

Figure 5 illustrates the synergism between immunization, reduction of the vectorial

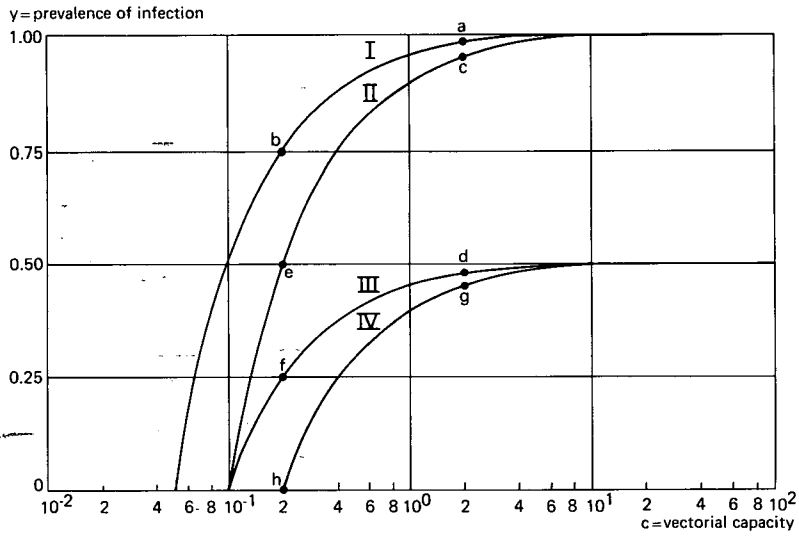

Figure 5 Impact of a reduction in the vectorial capacity, an increase in the recovery rate, and immunization – alone or in combination – on a hypothetical vector-borne infection

capacity, and an increase in the recovery rate. In this hypothetical case, none of the three methods alone (employed with moderate effectiveness) would result in eradication; neither would any of the three combinations of two of the three measures; but the three methods combined would achieve eradication. At the present time, however, there is no mosquito-borne disease on which all three measures could be employed. The figure involves some rather crude assumptions, particularly those about the homogeneity of the human population and its contact with vectors, and about immunization and drug treatment. Even so, the figure illustrates an important general principle: immunity against an infection is produced by immunization (malaria and sporozoite vaccins).

In the simplest malaria model (i.e. the one-step reversible catalytic model, Ross's single-equation model), the equilibrium relationship between the variables is

$$y = (1-X)[1-r/(r-x)C]$$

Curve I represents the original relationship between y and C for r = 0.05 and X = 0. Curves II, III, and IV represent the new relationships that result, respectively, from doubling the recovery rate, protecting half the population by immunization, or both. Point 'a' represents the initial prevalence for C = 2. Points 'b to h' represent the impact of three interventions, alone or in combination, as follows:

	Points							
Interventions	a	b	c	d	e	f	g	h
10-fold reduction of C	–	+	–	–	+	+	–	+
Doubling r	–	–	+	–	+	–	+	+
Protecting 50% by vaccination	–	–	–	+	–	+	+	+

4 Environmental Management in relation to Epidemiological Factors and to Other Control Methods

The purpose of this section is:
- To identify where environmental management interferes with the web of causation of mosquito-borne diseases in comparison with other interventions;
- To indicate the principles used in calculating the expected impact of environmental management on vectorial capacity (and, in the case of malaria, on the endemic level as well), again in comparison with other interventions.

Figure 6 outlines the natural and man-made factors that determine the epidemiological situation of a disease transmitted to the human population through mosquitoes. With a few minor adaptations, the figure can also apply to mosquito-borne infections in other vertebrate hosts. The natural and man-made factors are considered in relation to each other, in relation to control measures (e.g. those that use environmental management), and in relation to methods of evaluating the epidemiological impact. For the purpose of Figure 6, environmental management is broadly defined as:
- Water management for vector control;
- Screening of houses;
- Siting of houses.

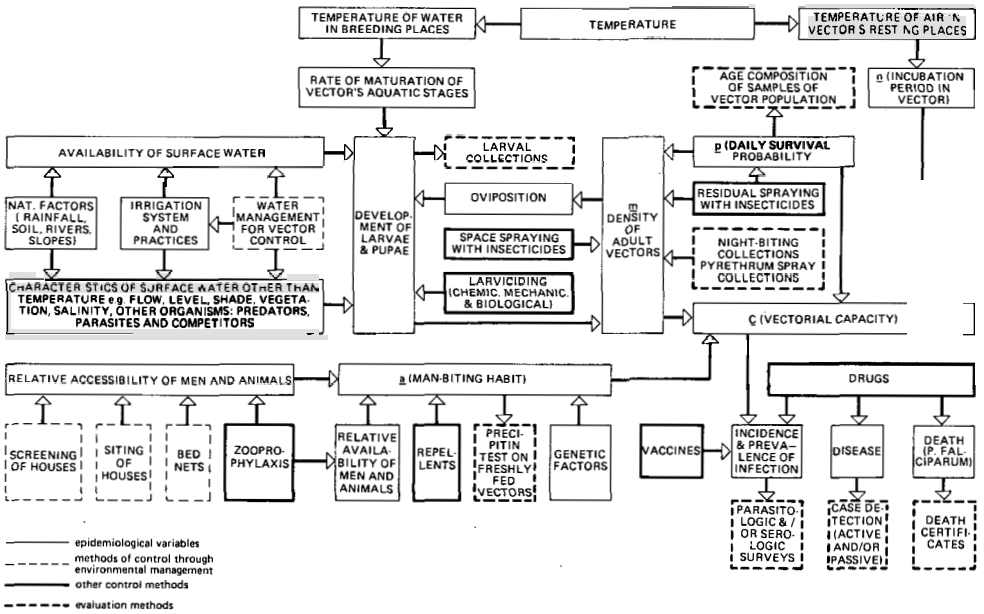

Figure 6 Malaria: natural and man-made factors, control measures, and evaluation methods, with particular reference to environmental management

Water management aims at reducing surface water, or at modifying certain of its characteristics so as to reduce the emergence of adult vectors, hence their density m, hence the vectorial capacity C. The other control methods that reduce m are:

- Direct attacks on the larvae (i.e. larviciding), which can be done:
  - Chemically, with insecticides;
  - Mechanically, with oils or monolayers used to block the larvae's respiratory tracheas;
  - Biologically, with larvivorous fish;
- Direct attacks on the adult with insecticides, either by space spraying or by residual spraying.

When the various methods are being compared, the following considerations are relevant:

- Water management and larviciding require a knowledge of the breeding habits of the local vectors and an up-to-date census of their breeding places. The impact of these measures will vary with their correct application and with the proportion of breeding places covered;
- For space or residual spraying, no knowledge of the local breeding habits nor a census of breeding places is required;
- The use of insecticides (for chemical larviciding, or space or residual spraying) generates the risk of creating resistant genotypes;
- Water management and mechanical larviciding do not involve this risk;
- Nor is there any risk of resistance to larvivorous fish, although these fish may constitute a danger to other biological species;
- Residual spraying acts not only on m but also on p (see below).

The screening and siting of houses aim at reducing man-vector contact, specifically a. The other methods of reducing 'a' are the use of bed-nets and repellents, and the application of zooprophylaxis (i.e. the use of domestic animals in such numbers, locations, and shelters that a significant number of mosquito bites are diverted from man to animals). Zooprophylaxis and siting of houses are interrelated, so that the definition of environmental management could be broadened to include both.

The impact of a given change in m or n on the vectorial capacity C is easy to calculate with the help of Equation 2. C is a linear function of m (i.e. 'a' decrease in m produces an exactly proportional decrease in C). C is a square function of a (i.e. C changes as the square of a reduction of 'a'; if 'a' reduces by a factor of 2, C reduces by a factor of 4). This difference between m and 'a' is not necessarily of great practical importance because, with the currently available methods, it is usually much easier to reduce m by a factor of 4 than to reduce a by a factor of 2. Residual spraying has the apparent advantage of reducing not only m but also p, and it can be seen from Equation 2 that a small change in p can produce a large change in C, a point which was stressed by MacDonald (1957. The Epidemiology and Control of Malaria, Oxford University Press, London). The reduction in C resulting from residual spraying, however, can easily be overestimated by the (unjustified) assumption of uniform behaviour by the mosquitoes (Molineaux et al. 1979. WHO Bulletin 57: 265-274).

The change of vectorial capacity expected from combined changes in two or three of the variables m, a, and p can also be calculated from Equation 2.

The expected impact on malaria of reducing C from a given initial value to a given final value can be read from Figure 4.

5 Epidemiological Diagnosis of the Baseline Situation

Obviously, from what has preceded, it would be desirable to know the baseline vectorial capacity. Unfortunately, an estimate of C is subject to relatively large biases and errors, which cannot be discussed in any detail here. C can be estimated directly by entomological methods, or, in the case of malaria, indirectly by parasitological (or serological) surveys (using Figure 4 'in reverse' i.e. reading C from the endemic level). The direct method requires estimates of m, a, p, and n. The night-biting collection (NBC) is the best estimator of ma; the second 'a' is estimated by submitting the stomach contents of resting, freshly-fed mosquitoes to the precipitin tests; p is estimated by imposing a model of exponential survival on to the age-composition of samples of the mosquito population. (Different methods of age determination are available – the most common, not necessarily the best, being the distinction between nulliparous and parous mosquitoes.) Biases can be fixed and random errors reduced by standardizing the methods and increasing sampling frequency and sample size. The fact that it has been possible to construct a reasonably realistic model of the transmission of malaria, with C as a key factor, shows that a meaningful and useful estimate of C is possible, even if it is biased (Dietz et al. 1974, WHO Bulletin 50: 347-357; Molineaux et al., 1978, WHO Bulletin 56: 565-571).

The entomological inoculation rate (number of bites by sporozoïte-positive mosquitoes/day/person), also a good indicator of the intensity of transmission, is easier to measure than the vectorial capacity.

Recently, the antisporozoïte antibody profiles in the human population have been able to produce a reliable, rapid, and relatively inexpensive estimate of the entomological inoculation rate (Esposito et al. in press).

In the case of malaria, each of the three approaches (entomological, parasitological, serological) has its special advantages. Close to the critical vectorial capacity, if the vector is relatively efficient (i.e. if 'a' and p are relatively large), the density m will be so low that it may be too expensive to be estimated with any precision; at high vectorial capacities, entomological methods will be more discriminating. On the other hand, it is easy to see from Figure 4 that parasitology is more discriminating at low vectorial capacities than at high. At low vectorial capacities, however, the prevalence of parasitaemia is unstable. Serological findings, which detect antibodies against the parasite's blood stages, are more stable. Another advantage of serological surveys as estimators of the intensity of transmission, is that they are less affected by the use of anti-malaria drugs.

6 Evaluation of the Impact of Control Measures

Evaluating the impact of control measures is important for at least two reasons:

– It can measure the impact of control measures in small-scale field trials before deci-

sions are made whether to use the same methods in large-scale control programs;
- It can monitor the large-scale control programs.

Evaluation should cover:
- The performance of the control operations (e.g. 'Is the census of breeding places correct and up to date?');
- The effectiveness of each of the measures being applied (e.g. 'Does a given change in the salinity of the water actually prevent breeding?');
- The impact on the disease and its component factors (e.g. 'To what extent does water management reduce m?').

When evaluation methods are being selected, the following should be kept in mind:
- What changes in strategy are feasible?
- What does one need to know, and with what precision, in order to guide further action?
- Will it be possible to interpret the findings? Imagine possible changes in the evaluation variables and list possible causes of these changes. Will it be possible to separate the impact of the control measures from the impact of these changes, or, if applicable, will it be possible to separate the impact of different control measures?
- Will the program be able to handle the proposed evaluation methods?

Technical Note 2
Schistosomiasis: A Basic Whole-cycle Transmission Model

Prepared by Dr J.A.M. van Druten

1 A Basic Mathematical Model

Described in this technical note is a basic mathematical model that is useful in assessing the impact of irrigation measures, health measures, and control measures on the incidence and prevalence of schistosomiasis. The model can be used to examine the effect of:

- Changes in the size of the common water area for the human and snail populations;
- The amount of water/skin contact per person per day in washing, bathing, swimming, etc.;
- The amount of water contact per person per day in voiding urine and faeces into the common water area;
- And six other parameters that affect the dynamics of the infection in the human and the snail populations.

The model can help in studying the long-term effects of irrigation, health, and control measures under various assumptions about the rate of losing individual infection, the duration of immunity, and the age distribution of the population. The formulae used in the model are straightforward extensions of those by Barbour (1982).

The model does not refer to a particular field situation, but reflects the general relationship between those variables and parameters in the human and snail populations that play a role in the transmission process. The results obtained have a restricted meaning: they are only valid within the framework of the model's assumptions.

The model is elementary from an epidemiological and mathematical point of view. It does not take into account any heterogeneity in the infection risk or in the worm-load distribution in the human host. This clearly limits its practical application. Recent research has begun to consider how density-dependent mechanisms influence the transmission dynamics (see, for example, May et al. 1981; Anderson and May 1985; and Dietz 1988). Until these considerations and the mechanism of partial concomitant immunity are built into the model, all predictions made by it should be regarded as tentative.

1.1 Main Parameters and Epidemiological Classes

The main parameters included in the model are listed in Table 1. The mathematical representation (a set of differential equations) is given in an Appendix at the end of this note to enable the reader to check the derivation of the formulae.

Like Barbour (1982), we consider only three classes of the human host:

- Those that are currently susceptible (x);
- Those that are infected (y);

– Those that are immune (z).
The model assumes that currently-infected persons are immune to further infection.
Snails are divided into two classes:
– Susceptible (x_s);
– Infected (y_s).

To study the relationship between parameter values and variables, we have to add details of the input (increase) and output (decrease) in each epidemiological class (per unit of time). We also have to establish expressions for the force of infection for humans and snails.

Table 1 Main parameters and variables

Water resources
a = Size of the common accessible water area for human and snail populations;
w = Amount of water/skin contact per person per day in washing, bathing, swimming, etc.;
s = Amount of water contact per person per day in voiding urine and faeces into the common water area.

Human population
n = Size of the population;
x = Number of susceptible individuals;
y = Number of infected individuals;
z = Number of individuals who are immune;
σ = Population density (n/a);
δ = Death rate;
λ = Force of infection (per capita yearly inoculation rate with cercariae);
γ = Rate of losing individual infection (yr^{-1});
r = Rate of losing immunity after infection has terminated (yr^{-1});
R = Basic reproduction rate;
p = Prevalence of the infection (proportion);
i = Incidence of the infection (rate with respect to the total population).

Snail population
n_s = Size of the snail population;
x_s = Number of susceptible snails;
y_s = Number of infected snails;
σ_s = Snail density (n /a);
δ_s = Death rate;
λ_s = Force of infection (per snail, inoculation rate with miracidia);
p_s = Proportion of infected snails.

Parameters that control the transfer of individuals between the three epidemiological classes in the human population (Classes x, y, and z) are δ, λ, γ, and r.
Parameters that can be changed by irrigation, health, and control measures are a, w, s, σ, σ_s, δ, δ_s, γ, and r.

1.2 Dynamics

Shown in Figure 1 is a symbolic representation of the dynamics of the transmission process (i.e. the transfer of individuals between the three epidemiological classes in the human population) and its relationship with the dynamics in the snail population.

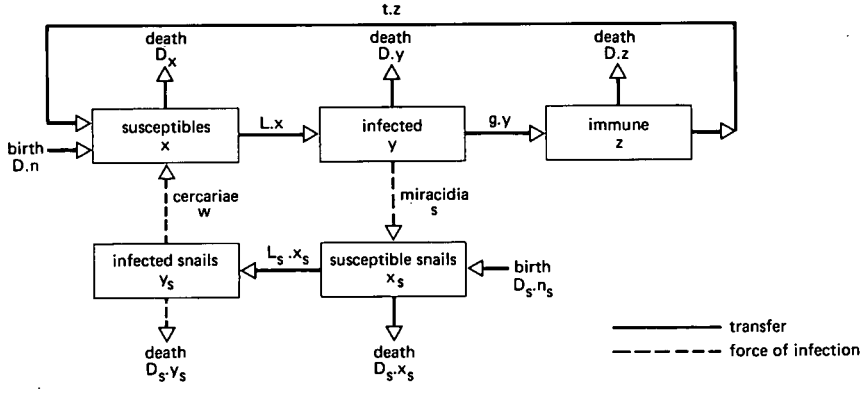

Figure 1 Representation of the flow of infection and its dynamics in the human and snail populations

The force of infection for susceptible individuals is represented by the dotted line running from the class of infected snails to the class of susceptibles in the human population. In the same way, the force of infection for a susceptible snail is represented by the line marked 'miracidia', running from the class of infected persons to the class of susceptible snails. Class differential death rates for humans and snails are not taken into account. If such figures are available from field observations, they can easily be incorporated into an extended model.

1.3 Force of Infection

The force of infection for the human population (λ) is considered proportional to the density of infected snails per unit of common water area (y_s/a) and the amount of water/skin contact per person per day in washing, bathing, swimming, etc. (Parameter w). The human cercariae inoculation rate can therefore be written as

$$\lambda = \beta w y_s/a \tag{1}$$

where β is a constant depending on biological factors (e.g. snail and schistosome species) and environmental factors (e.g. temperature and quality of water).

The force of infection for the snail population (λ_s) (i.e. the number of inoculations with miracidia per snail per unit of time) is considered proportional to the void of urine and faeces into the common water area (Parameter s) and to the ratio of the number of infected human hosts and the size of the snail population (y/n_s). This leads to the following expression for the force of infection in the snail population

$$\lambda_s = \beta_s s y/n_s \tag{2}$$

where β_s is a constant, representing the additional factors that influence the force of infection for snails (e.g. snail species, quality of water, etc.).

2 Incidence and Prevalence

In using the model to study the long-term effects of intervention measures (i.e. irrigation, health, and control measures), we have to foresee to what extent these measures will affect the different parameters. We can then quantify these effects by using intervention coefficients, which describe the relative change in each parameter. Before using such coefficients, however, we have to make estimates of the various baseline parameters. Obviously, these will have different values in different places.

2.1 Irrigation, Health, and Control Measures

Irrigation, health, and control measures are widely different measures, consisting, as they may do, of canal maintenance, drainage, provision of bridges, change in water-flow velocity, and the provision of bathing places and latrines. Obviously, such measures will affect the model's parameters in complex ways. It is clearly beyond the scope of a basic model to describe how all these measures will affect the parameters.

Nevertheless, with the model, we can examine changes in Parameter a (the common water area for the human and the snail populations), Parameter w (the amount of water/skin contact per person per day in washing, bathing, swimming, etc.), Parameter s (the amount of water contact per person per day for sanitation), and six other parameters that affect the dynamics of the infection in the human and snail populations.

To put the relationship between model parameters and intervention measures into perspective, we make a crude link between the parameters and a number of factors that are potentially capable of affecting their values. As illustrated in Figure 2, irrigation measures will affect the size of the common water area and may induce various changes in the ecology of the water system (e.g. by changing the water-flow velocity). As a consequence, the availability of food for snails may change, fecundity and mortality may be affected, and this may ultimately lead to a change in the snail density (σ_s). Further, if molluscicides are applied, they will affect the death rate (δ_s) and thereby the size of the snail population (n_s).

For the human population, irrigation measures will normally enlarge the common water area, as a consequence of which the population density (σ) may decrease. An increase in the accessibility of the water area may substantially increase the values of water/skin contact (w) and sanitation (s). On the other hand, the provision of safe water supplies, bathing places, and bridges, and the improvement of sanitary facilities will reduce those values.

Health measures may be aimed at a general improvement in health, or they may be specific measures against the schistosomes. Chemotherapy will shorten the length of the infected period and may indirectly affect the average length of time that immunity lasts after the infection has terminated. Usually, a single round of chemotherapy will not have any long-lasting effect, and the normal equilibrium will quickly re-establish itself. Regular applications, however, will increase γ and could decrease r.

In the model, the long-term effects of the combined intervention measures have to be based on the expected changes in Parameters a, w, s, σ, σ_s, δ, δ_s, γ, and r. The intervention coefficients, which describe the rate to which each parameter is changed, are denoted by the symbol f. The new parameter values are represented by subscripts

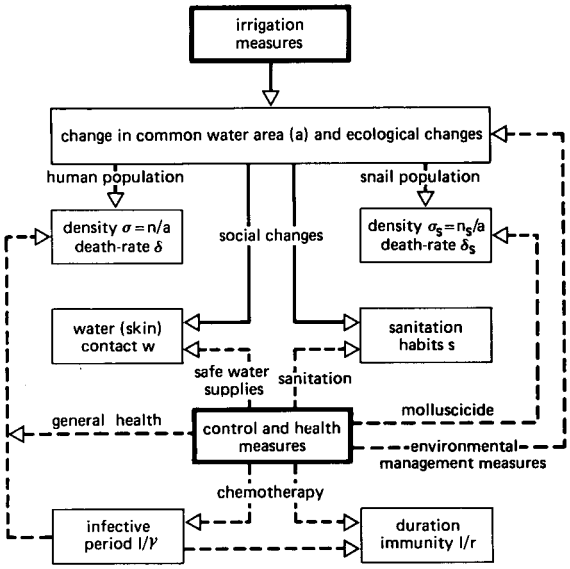

Figure 2 Irrigation, health, and control measures, and the nine parameters in the model that can be changed by these intervention measures

added to the original parameters. For instance, $a' = f_a * a$, where a is the common water area for humans and snails prior to intervention, f_a is the intervention coefficient, and a' is the common water area in the period after intervention. If the size of the common water area is doubled ($f_a = 2$), the immediate effect is that the population density per unit area is halved ($f_\sigma = 1/2$), and $\sigma' = 1/2\,\sigma$.

By adopting a set of intervention coefficients and varying them within a reasonable range, we can study the potential (theoretical) effects of various intervention measures. If the effect of a particular intervention can be neglected, the coefficient is given the value 1.

Of course, representing the effects of intervention measures by nine intervention coefficients is a rather crude and schematic representation. All irrigation projects have their own distinctive characteristics, depending on the type of project and the socio-agricultural practices in the area. As well, in reality, most parameters and intervention coefficients will exhibit considerable heterogeneity, which cannot be incorporated into a basic model.

2.2 Basic Reproduction Rate

The Basic Reproduction Rate (R), which is itself composed of several other parameters, is defined as the number of secondary cases (infected individuals) generated by one infected individual in a population where everyone is susceptible. Any new cases will be produced through the snail population. Under the ideal conditions that

no snails are as yet infected and that one infected person is introduced into the population, R can be written as

$$R = \frac{\beta\beta_s ws\sigma}{\delta_s(\gamma+\delta)} \tag{3}$$

Intervention measures act upon the parameters that comprise R. If the new R attains a value below 1, the disease will be unable to maintain itself in the community. In contrast, infectious diseases with a large R are difficult to control.

An estimate of R based on Equation 3 is virtually impossible because Parameters β and β_s are composed of several other parameters which cannot be observed directly in the field. But, using the set of differential equations from the Appendix, we can derive another equation which expresses R in parameters that can be more readily estimated. In equilibrium, we have

$$R = [(1-p/p_m)(1-p_s)]^{-1} \tag{4}$$

where p is the prevalence (proportion) of infected human hosts, p_s is the prevalence (proportion) of infected snails, and p_m is the maximum prevalence in the human population $(\delta+r)/(\delta+r+\gamma)$

$$p_m = (\delta + r) / (\delta + r + \gamma) \tag{4'}$$

Parameter p_m is attained in situations where R is very large. Questions about acquired immunity and its duration (1/r) have not yet been solved and there is a lack of information about the life span of schistosomes in the human host ($1/\gamma$). To take these matters into account, we use a range of values for the average length of time that individual infection exists ($1/\gamma$: 10 to 20 years) and the duration of time that immunity may persist after infection has terminated (1/r: 0 to 5 years).

Table 2 presents the value of p_m for various values of δ, γ, and r. A stable exponential age distribution is assumed throughout. The theoretical maximum is hardly influenced by the life expectancy of the individuals in the population. In contrast, immunity mechanisms, as far as they are related to Parameters γ and r, may have substantial influence on the level of p_m. Since the value of δ seems of minor importance in determining p_m, the average age of the individuals in the human population is taken to be 30 years. This corresponds to a yearly birth (death) rate of $\delta = 0.033$ per person. Approximately 50% of the individuals is younger then 20 years.

Table 2 Maximum prevalence of the infection in the population for various values of the average length of time that individual infection persists ($1/\gamma$), the duration of immunity after infection (1/r), and the average age of the individuals in the population (exponential age distribution)

	Maximum prevalence p_m*)	
Infected period	10 (years)	20 (years)
Duration of immunity		
0 yrs	1.00 (1.00)	1.00 (1.00)
1 yrs	0.91 (0.91)	0.95 (0.95)
5 yrs	0.70 (0.69)	0.82 (0.81)

*) Average age of the individuals is 30 years; figures between brackets refer to an average age of 50 years

Figure 3 presents the relationship between p and R for various co-factors. In hyper-endemic to holo-endemic areas, where p approaches the maximum prevalence, R assumes large to very large values (10 to 100). There is a clear non-linear relationship between p and R. If p approaches the maximum prevalence (p_m), it is virtually impossible to obtain an accurate estimate of R. As a consequence, it will be difficult to predict the actual effect of intervention measures.

2.3 Baseline Situation

The baseline situation has to be examined carefully. The first step is to verify whether transmission is in equilibrium. Present and future migration can be a problem. Large

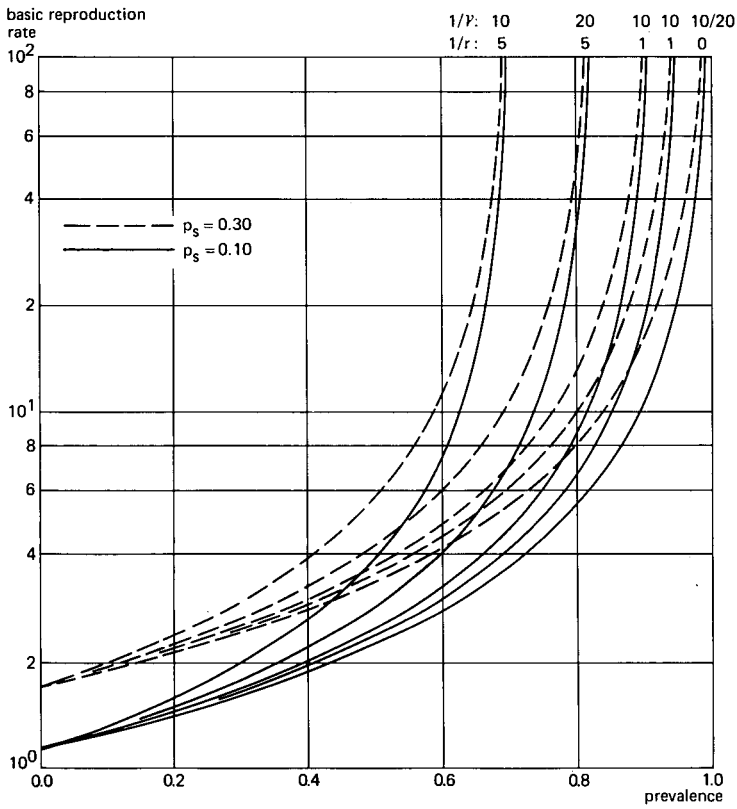

Figure 3 Relationship between the Basic Reproduction Rate (R) and the prevalence of the infection in the community (p). Co-factors are:
- The duration of the infected period ($1/\gamma$);
- The duration of immunity ($1/r$);
- The prevalence of the infection in the snail population (p_s).

In the model, the human life expectancy is taken as 30 years

numbers of susceptibles moving into the study area strongly affect the dynamics of transmission.

Where longitudinal data on the population are available, the force of infection (λ) can be estimated directly by analyzing transfer rates between epidemiological classes in specified periods of time. Longitudinal studies are expensive and time-consuming, however, so such data will not be readily available. In contrast, cross-sectional studies are comparatively cheap and prevalence data are relatively easy to collect. The only problem then is to estimate λ from estimates of the proportion infected in the various age groups. Nevertheless, it is theoretically possible to estimate λ on the basis of the prevalence of the infection in the total population (p), the average age of the human host ($1/\delta$), the rate of losing infection (γ), and the rate of losing immunity (r). The following relationship can be derived

$$\lambda = \frac{\delta + \gamma}{1/p - 1/p_m} \tag{5}$$

To illustrate the implication of this relationship, let us take $p = 60\%$, $\delta = 0.033\ yr^{-1}$ (average age of the human host is 30 years), $\gamma = 0.1\ yr^{-1}$ (in the absence of death, the 'average' infection would last 10 years), and $r = 1\ yr^{-1}$ (immunity persists one year after the infection has terminated). From Table 2, it can be seen that p_m is 0.91 and, from Equation 5, it follows that λ assumes the value of 0.23. This would imply that the average number of inoculations with cercariae per capita per year is 0.23, or in terms of probability of infection, each susceptible has a probability of 21% ($1\text{-}e^{-023}$) of contracting an infection in a period of one year.

The incidence of the infection (i) in the population can be estimated from the prevalence (p) and the average duration of the infected period $\left(\frac{1}{\delta + \gamma}\right)$. It can be derived that $i = p(\delta + \gamma)$. For example, if $p = 0.60$, $\delta = 0.033\ yr^{-1}$, and $\gamma = 0.1\ yr^{-1}$, the equilibrium incidence would be 80 new cases per 1000 population per year. If, however, the average age of the individuals were to be 50 years, and individual infection were to last 20 years, the baseline incidence would be substantially lower: a prevalence of 0.60 would correspond to 42 new cases per 1000 per year.

When applying models to to investigate whether the model can explain the available baseline data. Age-prevalence curves generally peak, then decline slowly with increasing age, or remain more or less constant (Hairston 1965; 1973). The model can generate, at least qualitatively, these types of curves (by simulation, following a cohort through time). This is illustrated in Figure 4. Each curve corresponds to an overall prevalence of 0.60, although co-factors will be different in each situation. The typical patterns between prevalence and age are associated with different assumptions about the rate of losing infection (γ) and the duration of immunity ($1/r$).

It is interesting to note that there is no clear difference between Curves 2 and 3, suggesting that age prevalence curves do not discriminate well between:

- A long period of infection and a long-lasting immunity, and
- A short period of infection and a short period of immunity.

A mathematical treatment of modelling the loss of immunity in age-prevalence studies can be found in Lewis (1975).

In principle, there are two ways of explaining the typical age prevalence curves.

The first, as illustrated, has to do with the duration of infection and the average length of time that immunity persists after infection has terminated. These factors are explicitly reflected in the model's structure – immunity becoming apparent at older ages, thereby partially protecting the adults. The second has to do with a decrease in exposure to infection in the elderly. In fact, in field studies, the age-trend in the prevalence of infection often shows a stronger decline in the adult age classes than depicted in Figure 4. It seems likely that acquired immunity and a decline in water contact with age help to explain the observed age-prevalence curves. Their relative significance, however, is not yet clear.

3 Impact of Intervention Programs

3.1 The Use of Compound Parameters

The model contains 9 baseline parameters that can be influenced by intervention measures (Table 3). By using compound parameters, we can conveniently reduce the 9-dimensional parameter (intervention) space to a more simple 3-dimensional one, i.e. we can regard the prevalence of schistosomiasis in a community (p) as a function of the Basic Reproduction Rate (R), the maximum prevalence of the infection in the

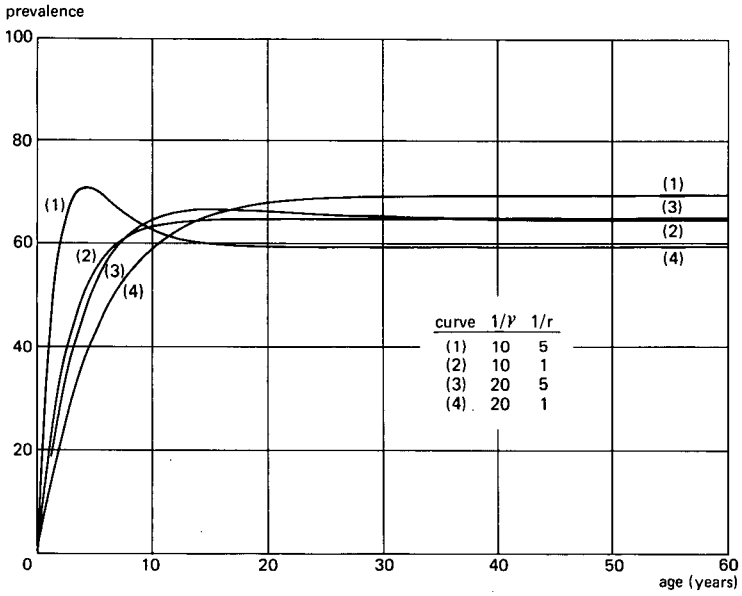

Figure 4 Age prevalence curves in a population where the overall prevalence of the infection is 60% and the average age of the individuals is 30 years. Relationship with the rate of losing individual infection (γ) and the duration of immunity (l/r). Simulation of four situations

community (p_m), and another compound parameter denoted by the symbol c. Expressed as an equation, this reads

$$p = \frac{1 - 1/R}{1/p_m + 1/c} \tag{6}$$

where R and p_m are defined by Equations 3 and 4′, and c is defined as

$$c = \beta w \sigma_s/(\delta + \gamma) \tag{7}$$

Parameter c incorporates information on the amount of water/skin contact (w), snail density (σ_s), and the net average length of time of the individual infection $\left(\frac{1}{(\delta + \gamma)}\right)$. Parameter β is a constant which depends on biological and environmental factors (snail and schistosome species, temperature, water quality, etc.).

The projected new prevalence of the infection depends, among other things, on the changes in the values of R, p_m, and c, which in turn depend on the set of intervention coefficients f_a, f_w, f_s, f_σ, f_{σ_s}, f_δ, f_{δ_s}, f_γ, and f_r.

We shall now examine the tentative impact of various intervention measures by studying the effects of a change in R alone, and a change in R in combination with a change in the compound parameter c.

Table 3 Irrigation, health, and control measures. Schematic representation of parameters that determine the prevalence of the infection in the community

Parameters potentially influenced by intervention		Compound parameters: Basic Reproduction Rate R	Maximum prevalence p_m	Compound Parameter c
Common water area	a	+		
Water/skin contact	w	+		+
Sanitation (faeces, urine)	s	+		
Density human population	σ	+		
Density snail population	σ_s			+
Death rate human population	δ	+	+	+
Death rate snail population	δ_s	+		
Rate of losing infection	γ	+	+	+
Rate of losing immunity	r		+	

Using Equation 3, we can derive R after intervention (R′) as

$$R' = f_R, R, \text{ where } f_R = \frac{f_\sigma f_w f_s (\gamma + \delta)}{f_{\delta_s} (f\gamma \cdot \gamma \cdot f_\delta)} \tag{8}$$

assuming that β and β_s (see Equation 3) remain constant.

The coefficient f_R describes the relative change in R from the baseline situation, and f_σ, f_w, f_s, f_γ, f_δ, and f_{δ_s} are intervention coefficients representing relative changes in the corresponding parameters.

In an intervention program, it is important to estimate the new value of the Basic Reproduction Rate (R'). This can be done by assigning specific values to the intervention coefficients. If, because of irrigation, the common water area for humans and snails is doubled ($f_a = 2$), the human population density per unit water area will be halved ($f_\sigma = 1/2$). Let us further assume that, because of the enlargement of the water area, the probability of water/skin contact is increased by a factor 2 (f_w) and that, as a result of the provision of latrines, the void of urine and faeces into the water area has decreased to 50% of its original level ($f_s = 1/2$). If, furthermore, the rate of losing individual infection and the death rate in the human and snail populations remain the same ($f_\gamma = 1$, $f_\delta = 1$, and $f_{\delta_s} = 1$), it follows that $f_R = f_\sigma \times f_w \times f_s = \frac{1}{2}$. Hence, as a direct consequence of the intervention measures, R would be reduced by 50% ($R' = 1/2\ R$).

It would, of course, be easy to construct a hypothetical example where irrigation causes R to increase rather than to decrease. For instance, suppose that there was no additional provision of latrines and that the enlargement of the water area caused the void of urine and faeces into the water to increase two-fold. Again assuming $f_\sigma' = 1/2$ and $f_w = 2$, it follows that R would be increased by a factor 2. In both situations, the question arises: 'What are the long-term consequences in terms of predicting the incidence and prevalence of the infection?'.

3.2 A Hypothetical Example

To illustrate the use of Equation 6 and make clear the various steps in predicting the new prevalence of infection, we shall work out a numerical example. The example is necessarily simple and hypothetical and contains the following assumptions:

- The average age of the individuals in the population is 30 years (stable exponential age distribution);
- After a susceptible is effectively inoculated, the average length of time that the infection persists is 10 years (i.e. 7.5 years if death by natural cause is taken into account);
- After termination of the infection, the individual is protected for a period of 1 year against re-infection;
- The overall prevalence of the infection in the human population is 60%;
- The prevalence of the infection in the snail population is 30%.

Such high prevalence rates in snails are only occasionally found in field studies. (Barbour, 1982, referring to Bradley and McCullough's data, 1973, incorporates the value of 0.38 for the proportion of infected snails.) We shall use this high prevalence in the example, however, merely for numerical and graphical convenience, and because it enables us to present a 2-dimensional picture of the simultaneous impact of changes in R and in c (Figure 5).

R varies in a continuous way along the x-axis. The middle curve describes the situation $f_c = 1$ (i.e. $c' = c$, no change in c). The lower and upper curves represent effects of intervention programs where $f_c = 1/2$ and $f_c = 2$ respectively. The baseline prevalence (0.60) corresponds with $f_R = 1$ and $f_c = 1$. The shaded area in the figure refers to the effects of programs with intervention coefficients f_R and f_c, adopting their values

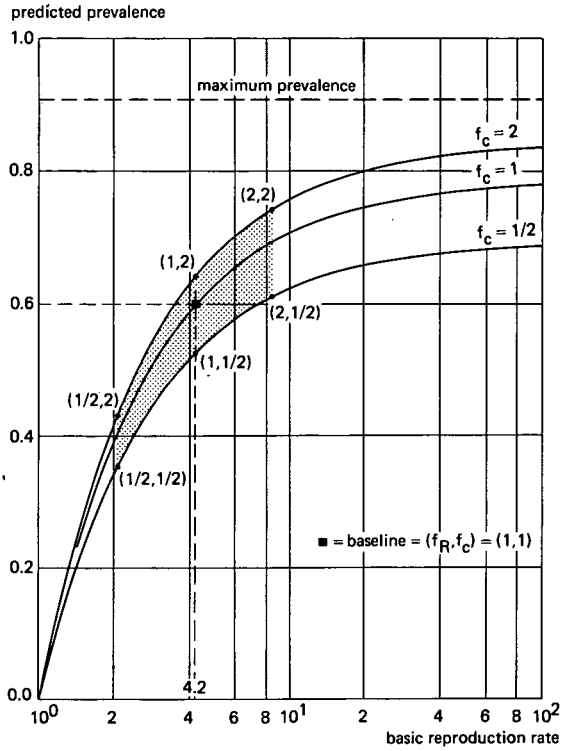

Figure 5 Impact of changes in the basic reproduction rate (R) and the compound parameter c; prediction of long-term prevalence for various intervention coefficients f_R, f_c
The baseline situation is:
- Prevalence in the human and snail populations is 0.60 and 0.30 respectively;
- Average age of the individuals in the community is 30 years;
- Average length of individual infection is 10 years;
- The duration of immunity is 1 year.

in the intervals $1/2 < f_R < 2$ and $1/2 < f_c < 2$. The range of the incidence of the infection which corresponds with these values is presented in Table 4: baseline incidence is 80 cases per year per 1000 population.

A program characterized by $f_R = 1/2$ and $f_c = 1/2$ produces a firm decrease in i and p. The prediction of long-term prevalence is 0.36 and the long-term incidence is 48 cases per year per 1000 population. On the other hand, a program characterized by $f_R = 2$ and $f_c = 2$ would induce a substantial increase in i and p: $i = 99\ yr^{-1}$ per 1000, $p = 0.74$.

Tables 3 and 4 support MacDonald's statement that, in the control of schistosomiasis, safe water supplies are more important than the provision of latrines. The provision of safe water affects the amount of water/skin contact per person per day (Parameter w). From Table 4, it follows that a decrease in w changes the value of R as well as that of c. A decrease in the void of urine and faeces into the common water area, however, due to the use of latrines, only affects R. Therefore, a reduction in w by

Table 4 Prediction of prevalence and incidence. Impact of various intervention programs. The baseline situation*) before intervention is as described in the text

Compound Parameter c Intervention coefficient f_c	Prediction of prevalence and incidence**) Basic Reproduction Rate R Intervention coefficient f_R 1/2	1	2
1/2	0.36 (48)	0.53 (71)	0.61 (81)
1	0.41 (55)	0.60 (80)	0.69 (92)
2	0.44 (59)	0.64 (85)	0.74 (99)

*) $f_R = 1$ and $f_c = 1$ corresponds with the baseline situation
**) Incidence rates are between brackets (cases per year per 1000 population)

a factor f_w is more effective in reducing the long-term incidence and prevalence of the infection than a reduction in s by the same ratio ($f_s = f_w$).

Although the example is hypothetical and the snail infection rate at baseline is high, Figure 5 illustrates the non-linear relation between R and the prevalence of the infection in the population. (The model can be made more realistic by incorporating the incubation period for the molluscan host.) The figure indicates that an intervention program which reduces R from 100 to 10 (i.e. a very strong reduction) may have little effect on the prevalence of the infection. If R could be reduced from 10 to a value lower than 1, the infection would not be able to maintain itself at an endemic level. This somewhat ideal situation is not easily attained. Generally, R will adopt some value above 1, pushing the system to a new endemic equilibrium.

3.3 Sensitivity Analysis

The length of time of individual infection and the duration of immunity are important factors in a study of the dynamics of the transmission process. Table 5 presents the results of a sensitivity analysis of the influence of these factors on the prediction of the long-term incidence and prevalence of the infection in the community. The figures in the column labeled with the baseline values $1/\gamma = 10$ years and $1/r = 1$ year correspond to the data in Table 4 and the shaded area in Figure 5. The first two rows in Table 5, rows with the intervention coefficients $f_R = 1/2$, $f_c = 1/2$, and $f_R = 1/2$, $f = 1$, further support MacDonald's statement that safe water supplies are more important than latrines. Table 5 also suggests that the actual predictions of the new incidence and prevalence strongly depend on the baseline assumptions. Given a baseline prevalence of 0.60, the theoretical baseline incidence assumes a value between 50 and 80 cases per year per 1000 population (dependent on the value range of $1/\gamma$). Therefore, predicting the new incidence is particularly difficult if the actual duration of individual infection is not known. Table 5 suggests that, in field situations where the duration of infection is relatively short and immunity is long-lasting, i and p are relatively insensitive to moderate changes in R and c.

Table 5 Prediction of prevalence and incidence. A sensitivity analysis. Effects of changing the baseline assumptions of the length of time of individual infection and the duration of immunity

		Prediction of prevalence and incidence					
		Duration of individual infection ($1/\gamma$)					
		10 (yrs)			20 (yrs)		
Intervention coefficients*)		Duration of immunity ($1/r$)					
f_R	f_c	5(yrs)	1(yr)	0(yr)	5(yrs)	1(yr)	0(yr)
		Prediction of prevalence**)					
1/2	1/2	0.51	0.36	0.31	0.42	0.34	0.31
1/2	1	0.53	0.41	0.37	0.46	0.39	0.37
1/2	2	0.55	0.44	0.40	0.48	0.42	0.40
1	1	0.60	0.60	0.60	0.60	0.60	0.60
2	1/2	0.60	0.61	0.61	0.61	0.61	0.61
2	1	0.63	0.69	0.72	0.67	0.71	0.72
2	2	0.65	0.74	0.78	0.71	0.76	0.78
		Prediction of incidence***)					
1/2	1/2	68	48	41	35	28	26
1/2	1	71	55	49	38	32	31
1/2	2	73	59	53	40	35	33
1	1	80	80	80	50	50	50
2	1/2	80	81	81	51	51	51
2	1	84	92	96	56	59	60
2	2	87	99	104	59	63	65

*) $f_R = 1$ and $f_c = 1$ corresponds with the baseline situation
**) Effects of intervention in the situation $1/\gamma = 10$ yrs and $1/r = 1$ yr are shown graphically in Figure 5
***) Cases per year per 1000 population

In contrast, where immunity does not play any role in protecting the individual after the infection has terminated ($1/r = 0$ yr), a firm reduction in incidence and prevalence could be obtained by an intervention program with the characteristics $f_R = 1/2$ and $f_c = 1/2$ (new prevalence 31%, new incidence 26-41 cases per year per 1000 population). On the other hand, measures that would double the values of R and c would, in this situation, increase the prevalence of the infection to a population level of 78%, and could raise the incidence of the infection to 65-104 cases per year per 1000 population.

3.4 Concluding remarks

In infectious disease epidemiology, model building can be a valuable tool in detecting gaps in our knowledge and in our methods of data collection. If the model does not fit the data, then either the model's assumptions are wrong or the data have been badly collected. This can be fed back to 'epidemiology' to decide which epidemiological factors and data-collection methods we need to predict the effect of control measures. For that to happen, there must be close collaboration between epidemiologists who

have access to data, and specialists who can construct, test, and manipulate mathematical models. In this, interactive computer programs may offer exciting prospects for future research.

Appendix
Mathematical Formulation

The model is represented by the following differential equations

Human population

$$\frac{dx}{dt} = \delta n + rz - (\lambda + \delta)x$$

$$\frac{dy}{dt} = \lambda x - (\gamma + \delta)y$$

$$\frac{dz}{dt} = \gamma y - (r + \delta)z$$

Snail population

$$\frac{dx_s}{dt} = \delta_s n_s - (\lambda_s + \delta_s)x_s$$

$$\frac{dy_s}{dt} = \lambda_s x_s - \delta_s y_s$$

The force of infection for the human and the snail population is, respectively

$$\lambda = \beta w y_s / a \qquad \text{and} \qquad \lambda_s = \beta_s s y / n_s$$

where β and β_s are constants depending on biological and environmental factors. (Social factors are included in the parameters w and s.)

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Technical Note 3
Cost of Control Measures: An Overview

1 Introduction

This note summarizes estimates of the costs of post-construction operational programs for disease control, component by component. It thus provides planners with information that will enable them to estimate the probable costs of such programs in the project they are considering.

To be useful, cost figures for disease control must be current and also broadly based so that they can be applied anywhere in the world. Given the fluctuating nature of currencies and the differential costs for local labour and hard currency expenditures on machinery, drugs, and pesticides, assembling cost experience from different countries and reporting it in a useful manner is somewhat complex. Nevertheless, to maximize the usefulness of this information, the various prices, exchange rates, inflation rates, and hard currency/soft currency components are detailed in Tables 1 and 2. The data are based on figures as these were valid for project conditions in the Sudan during the period 1982 to 1984.

Table 1 Prices of components used in disease-control programs in the Sudan from 1982 to 1984

Item	Units	Jul-Dec 1982	Jan-Dec 1983	Jan-Jun 1984	Jul-Dec 1984
Sudanese pounds (&)	Official	$ 1.11	0.77	0.77	0.50
	Free market	$ 0.80	0.50	0.48	0.45
Electricity	&/kwhr	0.055		0.150	
Diesel fuel	&/imp. gal	1.32		2.30	
Petrol	&/imp gal			4.70	
Bayluscide					
25% ec	DM/litre	27.40	27.40	27.40	
70% wp	DM/kg	45.40	45.40	45.50	
Praziquantel	DM/600 mg tablet	2.00	2.00	(1.50 if million purchased)	
Latrines	&/4 pc slab	26	32	38	
Abate					
50% ec	$/US gal	30			
Oralyte	$/1000 packs	150			
Cement	Metric tonne	500			

Table 2 Currency exchange rates for Sudanese pound and inflation rates for U.S. $, 1979-1987

Year	U.S. $ value in Sudanese pounds	Annual inflation of U.S. $ (%)	1987 $ inflation index
1979	0.70	7.9	1.62
1980	0.80	13.5	1.50
1981	0.90	10.4	1.32
1982	1.25	4.6	1.20
1983	2.00	3.0	1.14
1984	2.20	4.0	1.11
1985	3.00	4.0	1.07
1986	4.00	2.6	1.03
1987	4.50	5.0	1.00

2 Control of Bilharzia (Snails)

2.1 Chemical Control: Data from Older Projects in the Caribbean, Brazil, Egypt, Iran, Tanzania

The cost figures for the chemical control of snails (mollusciciding) are plotted against the geographical parameter of the volume of snail habitat (see Chapter 8, Figure 8.5). For example: Factor A = 10,000 m^3/km^2, Factor B = 0.2 m, and A/B = 50,000. The costs of mollusciciding are in the order of U.S. (1985) $7 per 100 m^3 treated or 10,000/100 × 7 = U.S. $700/$km^2$.

The mollusciciding is in principle based on a 'blanket application', in contrast to its 'focal application' at points of major water contact as is the practice in more recent projects.

2.2 Chemical Control: Data from Recent Studies in the Sudan and Zimbabwe

The Blue Nile Health Project/BNHP Study Zone

A detailed report has been released on an integrated control program in the Blue Nile Health Project/BNHP Study Zone in the Sudan. The initial method used for snail control was a monthly application of bayluscide at points of major water contact if snails were present there (focal mollusciciding). This was started in June 1982, one month before a mass chemotherapy campaign. In September 1982, the chemical control of snails was supplemented by increased dredging and weed control in the canals. Pilot studies on competitor snails and predator fish were started in 1983, in the hope that supplemental biological control methods could be developed and integrated with the other methods by 1986.

Cost records for focal mollusciciding were submitted monthly by the Public Health Inspector in charge of vector control. While his crews were doing the monthly round of mollusciciding, they also sprayed larvicides for the control of anopheline mosquito larvae. The annual costs of snail control ranged from U.S. $0.14 – 0.31 per capita protected (Table 3). The area involved is 265 km^2 (39 major water-contact sites), so,

taking the conservative estimate (from Table 3), we find the costs per km^2 to be U.S. \$67.

Of the total costs, 80 per cent was for bayluscide in 1983, a foreign currency requirement of U.S. \$0.23/capita annually. The rest of the costs were primarily for personnel. The costs of dredging and weeding the canals have to be added. These amount to U.S. \$1000 per km^2. As the main purpose of the dredging and weeding was agricultural, only 10 per cent of these costs should be apportioned to the snail-control program. Adding this 10 per cent brings the costs of the snail-control program to U.S. \$67 + 100 = 167/km^2 annually or U.S. \$0.31 + 0.46 = 0.77 per capita per year.

Table 3 Summary costs for snail control and mosquito larvae control in the Study Zone, period 1982 and 1983

	1982		1983	
Personnel	3912	Sd £	8257	SD £
Market value	1.25	US \$	2.00	US \$
of personnel	3130	US \$	4128	US \$
Transport	259	US \$	296	US \$
Equipment	60	US \$	60	US \$
	3449	US \$	4484	
For snail control	1724	US \$	4484	US \$
For mosquito control	1724	US \$	–	
Cost of bayluscide for snail control 5821 × \$10.54 =	6134	US \$	13154	US \$
Cost of abate for mosquito control 26 US gallons × \$30 =	780	US \$	–	
For snail control	1724 + 6134 = 7858 US \$ = 7858/57286 = US \$0.14 per capita = 7858/265 = US \$30 per km^2		4484 + 13154 = 17638 US \$ = 17638/57286 = US \$0.31 per capita = 17638/265 = US \$67 per km^2	
For mosquito control	1724 + 780 = 2504 US \$ = 2504/57286 = US \$0.04 per capita			

After the field trials of biological methods of snail control have been completed in 1986, the competitor snails can perhaps be introduced into the entire canal system, allowing an eventual reduction in the required number of molluscicide applications. If the competitors displace the planorbids, or outnumber them by 3 to 1, there will be no need to spray chemicals.

The presence of competitors in all the upstream portions of the canal system of the BNHP Study Zone might also reduce the numbers and re-population rates of the planorbid snails. If the biological methods are sufficiently successful to reduce chemi-

cal requirements to 25 per cent of the 1983 levels, the cost of snail control could be reduced to about U.S. $0.10 per capita because the biological control measures could be done by the spray crews at no additional costs. In this case, about half of the cost of the program would be for local labour, with the other half for vehicles, fuel, and bayluscide. The foreign currency requirements for the Ministry of Health might thus be reduced to U.S. $0.05 per capita annually.

Hippo Scheme (Zimbabwe) and Rahad Scheme (Sudan)

In the 1970's and 1980's, several reports were released on newer, larger schemes where a chemical was used as a major component in the control strategy. Two of these schemes were the Hippo Scheme in Zimbabwe and the Rahad Scheme in the Sudan.

The cost of chemical control of snails in Zimbabwe was reasonable, being about U.S. $250 per km^2 or U.S. $1 per capita in 1983 U.S. dollars. This was about the same as the U.S. $114 per km^2 or U.S. $1.40 per capita spent in the Rahad Scheme on chemical control alone, 35 per cent of the total control cost (Table 4).

The advantages of an integrated strategy that uses safe water supplies and chemotherapy are shown in the significantly lower prevalence of bilharzia attained in the Rahad Scheme than in the Hippo Scheme. The per capita cost comparison is not so reliable because of very approximate population estimates.

Because of the similar cost figures for the Sudanese and the Zimbabwean examples, they can be used with some confidence in planning control programs for new irrigation schemes in Africa, especially for similar schemes with intensive cultivation of several crops, or for schemes with crops such as sugar and rice, which have high water requirements.

The annual mollusciciding costs (focal) in the BNHP Study Zone (i.e. U.S. $66/km^2) can be compared with the U.S. $114/km^2 in the Rahad Scheme (1983 level). In the BNHP, the costs were kept low, partly because smaller vehicles were used. Another important factor is the higher population density in the BNHP (216/km^2), compared with 79/km^2 in Rahad, which reduces the time of travel for the BNHP spray crews.

When the cost figures for chemical control of snails in the more recent projects are plotted against the geographical parameter of volume of snail habitats, there are clear indications of decreased program costs in recent years, even though the chemicals themselves became more expensive. The lower costs are primarily due to the recent emphasis on the strategy of focal control, preceded by careful epidemiological studies to define the patterns and localities of transmission. The move toward focal control was, in fact, a direct response to the fast-rising price of the toxic chemical.

3 Treatment with the Drugs Praziquantel and Metrifonate

Recent experience with praziquantel and metrifonate, two recently developed drugs for the treatment of bilharzia infections, has shown that they are fairly good drugs with markedly lower costs and milder side-effects than the drugs previously available.

Table 4 Comparison of cost of schistosomiasis control in Rahad and Hippo Schemes, in 1983 U.S. dollars

Country	Control methods	Evaluation of control results	Area protected in km^2	Population protected	Annual cost of control	Year of cost record	Inflation index to 1983*	Adjusted 1983 Annual cost		
								Total	Cost/ capita	Cost/ km^2
Sudan (Rahad)	Integrated	Initially successful	1,260	100,000	400,000 *143,640	1983	1.00	400,000	4 *1.40	300 *114
Zimbabwe (Hippo)	Niclosamide	Moderately successful	380	75,000 100,000	80,000	1980	1.19	95,000	1	250

* Chemical control only

Considerable experience was gained with praziquantel in the Blue Nile Health Project in the Sudan (see Chapter 9 of this volume, Section 9.8.2). It was used in mass chemotherapy in the Study Zone, which had quite a high prevalence of intestinal bilharzia. Treatment costs came to U.S. $1/capita in the first year of mass treatment and, for a maintenance program in each following year, to U.S. $0.06/capita (in 1984 U.S. dollars).

4 Costs of Community Water-Supply Systems

A major component in programs to control bilharzia is the provision of safe water, usually by the construction of village systems that supply a large number of people from a single source. Such village systems are not only helpful in controlling bilharzia; they also help to reduce diarrhoeal diseases.

Again, the experience in the BHNP Study Zone has provided recent data on the cost of constructing typical community water-supply systems. In 1982, existing systems delivered 40 l/cap/day of safe water at a total annual cost of U.S. $3.39 per capita. In 1984, the systems were improved to deliver a safe supply of 73 l/cap/day at a total cost of U.S. $4.03. Benefits can be apportioned equally to the prevention of bilharzia, to the prevention of diarrhoeal diseases, and to labour savings and convenience.

5 Latrines, Health Education

Latrines are items that are not usually monitored for costs, but recent experience in the Sudan indicates that attractive household latrines can be provided for a total cost of U.S. $100 per unit, or less than U.S. $1 per capita per year, of which about U.S. $0.50 could be apportioned to bilharzia control.

Nor is health education usually monitored for costs, even though it should be an integral part of programs of water supply and sanitation. As to its cost, if we assume that one educator serves 10 villages of 1000 persons each, the total cost should be less than U.S. $0.27 per capita per year. In the Blue Nile Health Project, one-third, or U.S. $0.09, could be apportioned to each of the three major diseases.

6 Control of Malaria

6.1 Screening

If people sleep indoors, window screens in proper housing can provide reasonable protection against malaria. Costs vary markedly with the type of housing and should best be estimated for each separate situation. Nevertheless, the cost of screening the doors and windows of a three-roomed house containing 6 people should average U.S. $1 to 2 per capita per year for good screens. Half of this cost should be charged to fly control against diarrhoeal diseases, and half to malaria. Thus the malaria cost would be U.S. $0.50 to $1 per capita per year.

6.2 Spraying

For the control of malaria mosquitoes in 1981, a single annual spraying of houses with fenitrothion cost Sudanese Pounds 0.52 per capita protected. In Maharashtra, India, a single spray round with malathion cost Rs 4.52 per capita, while the annual cost of a complementary larviciding program with abate was Rs 16.4 per capita.

In the Sudan, larviciding with abate cost U.S. $0.04 per capita per year in 1982 U.S. dollars. In 1984, however, larviciding was replaced with a biological method that used *Gambusia* fish; its annual cost was U.S. $0.07 per capita protected. Its advantage over chemical larviciding is that all its costs are for local labour and materials. In addition, 10 per cent of the canal dredging costs could be charged against larval control, or U.S. $0.46 per capita per year. The major malaria mosquitoes, however, did not breed primarily in the canals cleaned under this program, so it is doubtful whether it had much effect in reducing malaria transmission;

6.3 Chemotherapy

The treatment of cases of malaria fever with chloroquine in mass chemotherapy in the Sudan cost U.S. $0.25 per person treated, mostly for the drug, but a passive case-detection system with treatment lowered the annual cost to U.S. $0.04 per capita protected, in 1984 prices.

7 Drainage

Large drainage systems are usually needed in intensively irrigated agricultural schemes subject to irregular rainfall. The costs depend very much on local topography, rainfall, and populations, and should be estimated individually for large schemes. Nevertheless, a recently designed drainage and water-control system in the Gezira Scheme cost 1.4 million Sudanese pounds in 1982 for an irrigated area of 20,000 ha and a population of 57,000 people. With an estimated 25 years of life, the system would entail annual costs of U.S. $44,800 for depreciation, U.S. $112,000 for investment, and U.S. $10,000 for maintenance, a total of U.S. $166,800 annually, or U.S. $2.91 per capita. The system was designed primarily for agricultural purposes, so only 10 per cent should be apportioned to larval control for malaria protection, or U.S. $0.29 per capita per year, or roughly U.S. $0.8 per hectare per year.

8 Summary Table of Costs

Table 5 Summary of annual per capita costs of disease control components, in 1987 U.S. dollars

	Original			Summary
Control method	Currency	Year	Cost	Cost-1987 Dollars * see Table 2
Bilharzia control				
Chemical control of snails				
– Study Zone** – Sudan	Dollars	1983	0.77	0.88
– Rahad Project – Sudan	Dollars	1983	4.00	4.62
– Hippo Scheme – Zimbabwe	Dollars	1983	1.00	1.15
Chemotherapy				
– Mass program – Sudan	Dollars	1984	1.00	1.11
– Maintenance – Sudan	Dollars	1984	0.06	0.07
Malaria Control				
Control of adult mosquitoes				
– Annual spraying – Sudan	Pounds	1981	0.52	0.72
– Annual spraying – India	Rupees	1980	4.52	0.39
Larval control				
– Chemical – Sudan	Dollars	1982	0.04	0.04
– Biological – Sudan	Dollars	1982	0.07	0.08
– Dredging (10%) – Sudan	Dollars	1983	0.46	0.58
– Chemical – India	Rupees	1980	16.4	1.42
Drugs				
– Mass treatment – Sudan	Dollars	1984	0.25***	0.28
– Passive system – Sudan	Dollars	1984	0.04	0.04
House screens				
– Total cost – Sudan	Dollars	1984	1.50	1.66
– Malaria cost – Sudan	Dollars	1984	0.75	0.83
Drainage				
– Total cost – Sudan	Dollars	1982	2.91	3.45
– Malaria cost – Sudan	Dollars	1982	0.29	0.34
River-blindness control				
– Chemical – West Africa				1.78
Sanitation				
Water supply				
– 40 l/cap/day – Sudan	Dollars	1982	3.39	4.03
– 73 l/cap/day – Sudan	Dollars	1984	4.03	4.47
Latrines and health education				
– Study zone – Sudan	Dollars	1984	1.27	1.41

* For currency conversion and inflation rates
** Including 10% of total cost for dredging and weeding
*** Cost per person treated

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