Critical review of the proposed irrigation and effluent standards for Bonaire

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ABSTRACT

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The quality of Bonaire's coral reef is declining which is caused by the high loads of nutrients that reach the sea. A waste water treatment plant is planned to treat the waste water of all hotels and other premises of Kralendijk's coastal zone. The effluent is to be used for irrigation. The soils in this zone have been studied and erosion and run-off modelled. Nutrient budgets for N and P were calculated and the irrigation requirements of different types of hotel gardens estimated. The proposed effluent norms comply with international standards and reduce the N load to the sea. P is not a problem as this is fixed by the calcareous rock. Despite the high nutrient losses from hotel gardens when using the treated water in hotel gardens, the nutrient loads from the sensitive zone to the sea will be reduced to the 1970 levels when the coral reef was still in good quality. To avoid unnecessary losses, however, it is recommended either to add a denitrification step to the wastewater treatment plant, or use the treated water in horticulture.

Key words: water re-use; nutrient budgets; Bonaire; effluent norms; coral reef

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List of abbreviations

Al	Aluminium
ALIANSA	Nature Alliance Bonaire
BHG	Bonaire Hospitality Group
BOD	Biological Oxygen Demand
BONHATA	Bonaire Hotel Association
C	Carbon
CEC	Cation Exchange Capacity
COD	Chemical Oxygen Demand
DEM	Digital Elevation Model
DOS	Dienst Ontwikkelings Samenwerking
DevCo	Department for Development Cooperation
DROB	Dienst Ruimtelijke Ordening en Beheer
DTD	Detailed Technical Design
FAO	Food and Agriculture Organization
Fe	Iron
GIS	Geographical Information System
ICP	Inductively Coupled Plasma
K	Potassium
Kc	FAO crop coefficient
LBS	Land Based Sources
LVV	Dienst Landbouw, Veeteelt en Visserij
MPN	Most Probable Number
N	Nitrogen
NASA	National Aeronautics and Space Administration
NGO	Non Governmental Organization
p	Probability
P	Phosphorus
pH	Acidity: $-\text{Log}([H^+])$
RUSLE	Revised Universal Soil Loss Equation
SBR	Sequential Batch Reactor
SFA	Segmented Flow Analysis
SRK	Stuurgroep Riolering Kralendijk
SSSB	Sewerage and Sanitation System Bonaire
STINAPA	Foundation National Parks Bonaire
TAO	Territorial Authorizing Officer
TSS	Total Suspended Solids
UV	Ultra Violet
VSO	Ministry of Public Health and Social Development
WEB	Water and Electricity Company
WHO	World Health Organization
WWTP	Waste Water Treatment Plant

Preface

The present report reflects the results of an additional study to TA/DTD-SSSB project no. 9 PTN NEA 003/2 (Sewerage and sanitation system Bonaire). This study is a "Critical review of the proposed irrigation and effluent standards". The contracting authority is the Territorial Authorizing Officer of the Department for Development Cooperation of the Government of the Netherlands Antilles. The project is financed by the 9^{th} European Development Fund.

Several studies on the design and environmental effects of a sewerage and sanitation system for Bonaire preceded this additional study. Dorsch (2004) has prepared the final design for the sewerage system of Bonaire, including the proposal to use the treated effluent in hotel gardens and agriculture. Borst and De Haas (2005) studied the hydrology of Bonaire and drafted N-balances for the complete island. IHE (2004) placed a number of critical remarks on the design of the sewerage system for Bonaire. None of these studies concentrated on the irrigation requirements of the hotel gardens and agricultural land and studied the nutrient budgets of the irrigated lands in detail. This is particularly important as it is proposed that the effluent of the future wastewater treatment plant is proposed to be re-used for irrigation purposes. Without proper nutrient budgets, it is not clear what the fate of these nutrients is. Above all, one does not want these to end up in the ocean as this may finally endanger the quality of the coral reef.

Alterra, after a tender procedure, was awarded a contract by the Territorial Authorizing Officer (TAO) to carry out the additional study on the critical review of the proposed irrigation and effluent standards. Field work at Bonaire was carried out in the period November – December 2005 and soil and water samples were analyzed thereafter in the laboratories of Wageningen University and Research Centre, The Netherlands. Alterra has carried out this study with due care and according to the best professional practices and scientific information known to us. The recommendations and conclusions given by Alterra are meant to support the Government of the Netherlands Antilles in their decision on the SSSB / policy decisions.

Alterra wants to acknowledge the good cooperation with the TAO, the SRK, DROB, the Coordination Workgroup and the Hotel Managers.

Summary

The proposed waste water sewerage and treatment plant for Bonaire, including the reuse of treated effluent water in hotel gardens reduces the present nitrogen load to the sea in the sensitive zone from about 15 ton/yr till about 7 ton/yr. After implementation of the proposed sewerage and sanitation system of Bonaire the nitrogen loads to the sea are restored to the historical situation of the seventies when the coral reef was still in a good condition.

Despite this positive result of the SSSB, the nitrogen leaching from hotel garden will still be excessive (about 365 kg/ha/yr) because the assumed effluent standard for nitrogen of 28 mg/l should be replaced by 5 mg/l for hotel gardens. For agricultural applications 28 mg/l is acceptable on the condition that no other nitrogen fertilizers are used. Phosphorus leaching to the sea is not to be expected in Bonaire due to the large amount of calcium in the sub soil.

Recent studies concluded that the quality of Bonaire's coral reef is declining. One of the main reasons for this decline is the inflow of nutrients with surface and subsurface water. The main source of nutrients is the untreated sewage water. Another source is storm water run-off. Therefore, plans have been made to construct a waste water treatment plant and use the effluent for irrigation of hotel gardens and agricultural land. The norm for irrigation of hotel gardens has been set at 40 kg/ha/yr N. The effluent norm proposed for nutrients is set at 28 mg/l N and 5 mg/l P. A critical review of these norms is needed to arrive at conclusions on nutrient leaching when using this water for irrigation. Compliance to the LBS protocol is also important in this respect and needs to be taken into consideration.

As in the middle of the seventies the coral reefs were still in a healthy state (Bak et al. 2005), we assume that the nutrient load to the sea during that period was not affecting the coral reef. All loads higher than that level will pose a possible danger. We compared the present (2005) nutrient loads with those of the mid-seventies and with those after the installation of the waste water treatment plant.

The sensitive zone, where most of the hotels are situated including the centre of Kralendijk, runs from Hato to Punt Vierkant and is a 200 m wide strip parallel to the coast. In Kralendijk this zone is 500 m wide. The drainage basin, discharging through the sensitive zone into the sea was determined with the aid of a simple digital elevation model (pixel size 90 x 90 m) and by using the topographic map.

Soils of the area have been characterized to learn about their nutrient status, water holding capacity, infiltration rate and surface characteristics. Most soils are shallow, stony and rocky with low organic matter levels. The soils of the saliña's are shallow to deep and very saline. The areas with deep, non saline soils are limited to the LVV premises and an area southeast of Kralendijk.

The soils in the hotel gardens are manmade. Most hotels are situated close to, or at the seafront and were built on limestone rock. Soils here were virtually absent or very shallow. As most hotels wanted to make gardens to grow some plants and trees (a.o. for shadow), soil material was brought up. This material came from weathering diabase and consists mainly of gravely clay loam. Hotel garden soils are usually around 40 cm deep. Most top soils have low organic matter contents. High organic matter levels, however, are found in soils under a permanent grass cover (lawn areas).

The overall soil texture is clay loam and ranges from loam to clay. Soil pH is somewhat high at 7 to 8. The plant available water is estimated at 15% for the deep, non stony soils and 10% for the gravely and shallow soils. Infiltration rates at saturation are generally slow at 10 – 20 cm per day, but sufficient to allow infiltration of 10 – 20 mm of water per hour when soils are not yet saturated with water.

Based on soil, topography, vegetation characteristics and land use, the study area has been subdivided into 8 land units. These land units, together with rainfall data, formed the basis for the run-off calculations

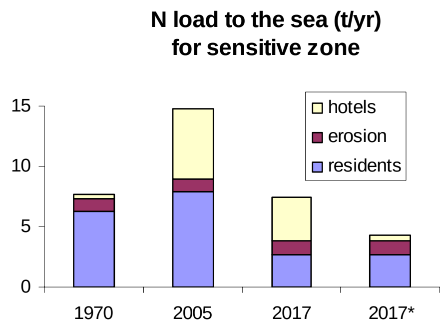
The amount of run-off water has been calculated with the RUSLE model. The average yearly discharge to the sea from the watershed is 16,700 m3. With this water 2480 kg N and 1080 kg P are discharged into the sea. If we take into account the buffering effect of the saliñas this figure becomes lower. When we assume a maximum average water level of 50 cm the discharges become 5540 m3 water and 1090 kg N and 480 kg P. This clearly illustrates the importance of the saliñas!

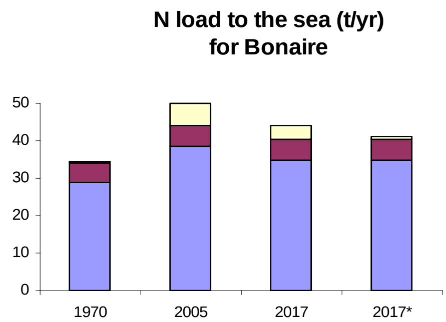
Soil nitrogen levels (total N) are similar throughout the area with average levels of 0.7 to 0.8 g nitrogen / kg in the top soils. The soil nitrogen status is related to the organic matter levels which are generally low to moderate (less than 2% organic C). Exceptions are soils of permanent lawns, here organic matter levels are higher (2 to 4% organic C). Soil phosphorus levels in hotel gardens are higher than more inland. The phosphorus levels in the hotel gardens range from 0.3 to 0.6 g/kg and inland between 0.3 and 0.4 g/kg in the top soils. Harbour village has the highest P content of 1.2 g/kg. This is probably due to frequent application of fertilizers.

In the seventies when the coral reef was still in a healthy state the nitrogen load from the sensitive area to the sea was approximately 7.5 ton N/yr. This was mainly due to discharge of untreated sewage from residents. A small part (13 %) of the N load was caused by erosion. The contribution of tourists/hotels was almost negligible in these years (< 5 %). For the whole island the total nitrogen load to the sea is much higher then the load from the sensitive zone (34 ton/yr) due to the larger area.

Nitrogen loads to the sea from the sensitive zone have been doubled since the seventies and are now almost 15 t/yr. The increased N load is mainly due to the sharp rise in the number of visiting tourists since the mid '70s. Also the increase in the number of residents has lead to a 30% increase in nitrogen load. Our field investigations in the hotel gardens resulted in an estimated nitrogen use of about 635 kg/ha/yr. Garden plants use about 60 kg/ha/yr of the applied nitrogen. Most of the remaining nitrogen is lost by leaching and reaches the sea. Phosphorus is also leached from the hotel gardens but does not reach the sea as phosphorus is strongly bound to the underlying coral rock

Compared to 2005, the total N production by tourists and residents inside the sensitive zone increases with 25% from 16 to 20 t/yr in 2017. Implementation of the present plans for wastewater treatment plant leads to a reduction of the nitrogen load from the sensitive zone to the sea from about 14.5 t/yr in 2005 to 7 t/yr in 2017. This reduction is due to several factors. By better irrigation about 15% less water will be used in the hotel gardens; this also reduces the N input accordingly. Secondly, the N-concentration of the irrigation water reduces with about 50% from 54 to 28 mg/l. Finally, in the sensitive zone, the N discharge by residential septic tanks reduces with about 70% from about 9.5 ton/yr to 3 ton/yr.





For the island as a whole the total human produced N increases from 50 ton/yr in 2005 till 56 ton/yr in 2017. About 9 ton/yr of this increased N-production is removed by the new wastewater treatment plant and about 4 ton/yr is additionally removed by horticulture. The net effect for the whole island will be a reduction in N-load to the sea with about 12% from 50 t/yr in 2005 till 44 t/yr in 2017.

Nitrogen discharge to the sea can be further reduced by using only grey water in the hotel gardens and applying all the effluent for agricultural purposes. In this situation an area of 50 ha can be used for agricultural crops in winter and up to 20 ha in summer. This alternative use of the effluent will lead to a reduction of the nitrogen load in 2017 till 4 t/yr in the sensitive zone and to 41 t/yr for the whole island.

The proposed effluent norms by Dorsch (2005) for BOD, COD, bacteria and phosphorus are acceptable for Bonaire conditions and comply with the internationally accepted standards for irrigation. The proposed standard for nitrogen of 28 mg/l N is acceptable for horticultural crops if these are provided with drip irrigation and careful water management. For hotel garden irrigation the nitrogen standard is a factor of about 5 too high.

1 Introduction

1.1 General

Bonaire's economic development relies heavily on the tourist sector. A majority of the tourists enjoys the beauty of Bonaire's coral reef, either by snorkelling or as the major part does, by diving. Recent studies (Meesters, 1995; Steneck et al, 2005) concluded that the quality of the coral reef is declining and that one of the reasons is the inflow of surface and subsurface water, partly coming from untreated sewage. The inflow of nutrients, of which N and P are the most important, with these waters causes eutrophication of the sea water which in turn gives rise to the unwanted growth of algae and macro-algae. This process increases the vulnerability of the coral reef for diseases and endangers the stability of the coral reef ecosystem.

Sewage water in Bonaire is presently not collected and treated properly. Households and hotels generally have septic tanks and cesspits to temporally store the sewage water. The effluent of septic tanks is leaking through the groundwater to the sea. In the tourist sector the problem of sea pollution by sewage water is recognized and much of the septic tank effluent is used in the hotel gardens in an attempt to reduce the nutrient discharge to the sea. A few hotels even have installed small wastewater treatment plants on their premises to purify the produced wastewater.

Storm water, polluted with sediments and nutrients, flows directly into the saliñas and from there to the sea. Due to the decreasing size of the saliñas sedimentation and retention is less than in the past. The sediments originate from the erosion processes on the island. The nutrients are generated by human activities (deposition of rubble and waste, infiltration of wastewater, etc.) as well as from the large number of free-living animals (goats, donkeys, sheep). In case of heavy rainfalls the accumulated substances in riverbeds and paved areas are washed into the saliñas and to the sea.

Therefore plans have been made to build a waste water treatment plant. The effluent of this plant will be used for irrigation purposes at hotel premises and for growing crops at the Island Service of Agriculture, Cattle Breeding and Fisheries (LVV). Effluent standards of 28 mg N/l and 5 mg P/l are proposed by Dorsch Consult in their feasibility study and in the master plan (Dorsch Consult, 2003). They also propose a nitrogen load norm for irrigation of hotel gardens of 40 kg/ha/yr N for the sensitive zone.

This study gives a critical review of the effluent and irrigation norms and the norm of 40 kg N/ha/yr in the sensitive zone (see also the complete Terms of Reference in Appendix 1).

1.2 Approach and methodology

It is reported by Bak et al. (2005) that the coral reefs of Bonaire were still in a healthy state during the mid-seventies. This can also be concluded from the study of Duyl (1985). At present the coral reefs are declining in quality which presumably is caused by an increased inflow of nutrients into the sea. We will therefore compare the actual N and P loads to the sea with the estimated N and P loads of the mid-seventies. In addition, we will calculate the N and P loads after the proposed wastewater treatment plant has been constructed and arrive at recommendations for the effluent norms. For more details of our study approach and method see Appendix 2.

In this report we consider wastewater and run-off water as the main sources of nutrients, the first of which is the most important one as many hotels use the only partly treated wastewater (after passage through a septic tank or an on-site small treatment plant) for irrigation of the hotel gardens. The soils of the hotels will thus be characterized and sampled. Irrigated amounts of water (including the source) will be estimated and compared with the water requirements of the gardens. In this way a water balance can be made and shortage or excess of water calculated. In case of excess of water, leaching can be determined. Nutrient budgets for the hotel gardens will be calculated and the fate of N and P determined. This will be done for the actual situation, and also with the proposed effluent standards. We will carry this out in relation to the N and P requirements of the hotel garden vegetation.

For agricultural use, in the future situation, also water balance calculations and nutrient budgets will be made. In this case we will concentrate on horticultural crops.

To estimate the amount of nutrients that reach the sea with run-off water, we will use an existing erosion model and apply that for the watershed of "larger Kralendijk". For this model study we will also need soil and land use data of the watershed area. Field work will thus include a reconnaissance study of the soils and land use of the watershed. Soil and water samples will be taken and analyzed.

1.3 Built-up of the report

In Chapter 2 we give a summary of the proposed sewerage and sanitation plan for Bonaire. Chapter 3 reports on our investigations. In section 3.1 we present population and tourist figures of the mid-seventies and of 2005. In 3.2 we give a description of the physical environment (geography, soils, and ecophysiographic units) of the "larger Kralendijk" watershed. The nutrient status of the soils is reported in section 3.3.

In chapter 4 we analyze our findings and provide a critical analysis of the effects of the proposed wastewater treatment plant on nutrient leaching. Finally, conclusions and recommendations are given in Chapter 5.

2 Bonaire Sewerage plan

Within the sensitive area defined as a buffer zone of 500 m wide along the coastline from Punt Vierkant in the south of Kralendijk to Hato in the north a wastewater collection system will be installed. A vacuum system has been selected to reduce the excavation needs. Sewage water will be collected by vacuum stations and subsequently delivered to a central pumping station. From there it is to be conveyed to a new WWTP which will be built at the LVV area. After installation of the new sewage systems and the connection of residents, hotels and commercial premises, the existing facilities (septic tanks) will be taken out of operation. Large hotels with more than one building have usually several house connection pipes from these different building. The septic tanks will be disconnected and pipes will be laid from the common collection pipe to the vacuum house collection chambers. There, the wastewater will be sucked into the vacuum system.

A design period of 20 years has been considered for the sewage collection system resulting in a design horizon of 2027. A population of around 3,000 people (including shops and restaurants) together with approximately 2,700 tourists during the peak period has been assumed to be served by the vacuum network in the year 2027 by Dorsch Consult. Also the hospital and several commercial establishments such as bars, restaurants and shops will be connected to the new sewerage system. Individual households and real estates owner will be responsible for the connection of their own sanitation facilities to the sewerage system. Dorsch expects the government to set up legal restrictions for reuse of untreated wastewater by laws or by-laws. Administrative controls and start-up problems are considered by Dorsch to cause a wastewater generation rate of 50% initially for the residential connections (just after system start-up) to 70% in the year 2017. For the hotels, restaurants and shops a 100% recovery rate is assumed. The Water and Electricity Company (WEB) estimates a water consumption of 500 l/c/d for hotel tourists including a portion used for swimming pools, beach showers and irrigation. Dorsch assumes that the individual water consumption of each hotel guest is about 290 l/c/d, which is relevant for the design of the sewer system. For inhabitants WEB estimates a water consumption of 133 l/cap/d. The demand forecasts for water supply for the future (2017 and 2027) is considered unchanged at 290 l/cap/d for tourists and 133 l/cap/d for inhabitants.

For the design of the sewage collection system and the wastewater treatment plant, special attention has been paid to the tourist industry. The average occupancy rate of tourist establishments was 60% during the year 2002. Since the amount of tourists varies over the year, the monthly tourist arrivals were used to determine a peak factor of 1.32. Application of this peak factor leads then to a design occupancy rate of about 80% (average occupancy is about 60%). Only accommodations with more than 10 beds were included in the estimates of Dorsch. Subsequently, the tourist accommodations outside the sensitive zone (226 beds) were subtracted.

Total number of existing beds in tourist resorts	2985
Number of beds outside the sensitive zone	226
Planned new facilities (Harbour Village, Sunset Beach, Hato Resort)	830
Number of tourist beds considered for the design	3369

In addition to the household and hotel connections, wastewater collection facilities are also planned in the harbour and at Kralendijk's piers where ships can dispose off their wastewater. For boats and smaller yachts special sucking stations will be installed along the coast at certain piers. For cruise ships only faecal sludge will be received. This faecal sludge will be conveyed by trucks to the new wastewater treatment plant for its treatment.

In the design of the wastewater treatment plant provisions have been made to receive also the faecal sludge from septic tanks in the areas not connected to the sewerage system. Also this faecal sludge is assumed to be transported to the wastewater treatment plant by trucks.

For the city Kralendijk also the storm water system will be rehabilitated. The new storm water system will use the two already existing outfalls to the sea. Upstream of each of these outfalls, a first flush chamber with a storage of 110 m^3 will be constructed in order to catch the first flush of polluted storm water runoff at the beginning of each rainfall event. The dirty storm water collected in the tanks will be pumped by a submersible pump to the wastewater treatment plant to be cleaned there and subsequently used for irrigation. The storage volume of 110 m^3 for each of the two outfalls accounts for about 2 mm of rainfall turned into run-off. One third of the total annual rainfall is supposed to be retained in the tanks.

The new central wastewater treatment plant (WWTP) will be constructed on wasteland near the LVV premises, approximately 2 km east of Kralendijk. This distance, combined with the general and consistent wind-direction, is assumed to prevent noise and odour emissions for the residential and tourist areas. Some of the odour producing facilities such as the screen chamber and sludge thickener will be covered. The construction site is publicly owned.

Due to the expected life time of wastewater treatment plants of about 10 years, the design horizon selected is 2017 (for the sewage collection system 2027 has been used). Since tourism is assumed not to increase between 2017 and 2027, the same numbers of 2,700 tourists during peak periods have been assumed for the design. For the population a growth rate of 0.7% has been assumed, resulting in a served population of about 2,800 (including shops and restaurants). For the design of the daily operation procedure, an hourly discharge variation has been assumed, resulting in a peak factor of 4.5. This resulted in a design discharge per hour for the WWTP of 178 m^3/h and a maximum pollution load per day of 346 kg/d BOD5. The expected daily maximum flow is determined at 1255 m^3/d and the average flow expected is 785 m^3/d. The design of the WWPT allegedly allows future extensions. The process calculations of the wastewater treatment units are based on this maximum flow of 178 m^3/h and maximum pollution load of 346 kg/d BOD5.

The WWTP will include the following units for wastewater treatment:

- The inlet structure and screen, with an aerated grit and grease removal unit will remove coarse material, sand, mineral material and floating matter from the wastewater.
- The faecal sludge acceptance station is intended to receive septic sludge from ships and from unconnected septic tanks and cesspits. Septic sludge will be transported by septic tankers with a daily load of about 6-7 m^3/d.
- In the Sequential Batch Reactor (SBR) of activated sludge tanks the dissolved organic material is degraded by bacteria. The biological stage uses surface aerators. Since final purification will take place in the same tank as the aeration, no return sludge (bacteria) needs to be pumped back. By increasing or decreasing the oxygen input, the effluent concentrations of BOD and COD can be managed.
- The purified water is passed through a filter to prevent sludge to be discharged.
- In the UV (Ultra Violet) treatment unit the pathogens and bacteria load will be reduced until less than 0.01% (log 4) of the influent.
- Finally, the cleaned water is transferred to a storage tank at an elevation of 23 m. The size of the storage tank is 785 m^3, sufficient to store the effluent produced during one day.

The WWTP has two outputs: the purified effluent and the sludge. For the further treatment of produced sludge the following facilities will be constructed:

- The sludge will be concentrated in sludge thickener. The daily amount of thickened activated sludge at the outlet is expected to be 12 m^3/d with a dry solids concentration of about 6%.
- Next, further drying of the sludge is proposed on sludge drying beds, using the energy of the sun. This will increase the dry solids concentration until approximately 18%. The dried sludge will be delivered to LVV where it will be mixed with chopped organic material (plant leaves and branches). The mixed material will be stored on the ground in piles. After a 3 – 6 months fermentation process a compost batch should be ready for use in agriculture or landscaping.

The WWTP design is targeted at the removal of organic material from the influent and not on the removal of the nutrients nitrogen and phosphorus. Through the selected activated sludge process a considerable amount of nutrients will be attached to sludge and suspended solids and removed through sedimentation and filtration. The mechanical and biological treatment plant together is expected to give a reduction of BOD of more than 82%, a reduction of COD of more than 77% and a removal of TSS of about 98% (Dorsch Consult, 2005). Approximately 70% of the nutrient contained in the raw wastewater is expected to be eliminated by the process applied in the new wastewater treatment plant. The nutrient load of recycled water will therefore be only about 1/3 of the raw wastewater. The effluent thus produced is therefore expected to fulfil the following standards:

BOD	50 mg/l
COD	125 mg/l
Suspended Solids	5 mg/l
Bacteria	1,000 MPN/100ml
Total Nitrogen	28 mg/l
Phosphorus	5 mg/l

The purified effluent of the WWTP is planned to be reused in hotel gardens for landscaping and for agriculture. Customers of recycled water will be connected to the source of recycled water through a network for pressure pipes starting at the effluent storage tank and extending to the hotel properties. For use in agricultural irrigation, recycled water will be delivered to the depressions and dams already available onsite at the LVV area. The capacity of the available storage dams is estimated by Dorsch at 50,000 m^3 with a surface area of about 35 hectare.

In the existing plans proposed by Dorsch a separate irrigation supply system will return the treated water to the hotel premises. It is proposed to deliver the treated irrigation water through connection pipes to the existing septic tanks. These septic tanks can store the recycled water until it will be used for irrigation.

The total budget required amounts to 14,771 million €. The cost calculations include the house connection manholes and the corresponding collection chambers. Physical internal house connections to the collection chambers are considered to be financed by the real estates owners. The budget breakdown is as follows:

- General construction costs 0.335 million €
- Vacuum system and force mains 6.421 million €
- Irrigation system 0.994 million €
- Storm water system 1.462 million €
- Wastewater treatment plant 1.524 million €
- Mechanical and electrical works 3.115 million €

3 Investigations

For the nitrogen and phosphorus discussions in this and following chapters the loads will be based on the production of nitrogen and phosphorus of human beings. This will be based on the projected population figures as well as on the average number of tourists present on the island c.q. the sensitive zone of the island.

3.1 Situation at Bonaire in 1975 and 2005

Population density and tourism

The population of Bonaire appears to be quite stable due to migration. The data for 1970 have been obtained from statistics as reported by Dorsch Consult (2005). Tourism started to take off in the eighties and has been quite stable since that period. The prices for tourists are generally high and tourists visit the island mainly for its magnificent marine biology. The projections for the average number of tourists visiting the island (Table 1) have been taken from the final design report by Dorsch (2005).

Table 1 Average number of tourists and population in the period 1970-2027

	1970	2005	2017	2027
Number of tourists Bonaire	74	1,457	2,157	2,157
Number of tourists in sensitive zone	74	1,321	2,021[1]	2,021
Population	8,000	10,740	11,454	12,295
Population in sensitive zone	1,757	2,359	2,497	2,659

1 3369 beds in the sensitive zone with occupancy rate of 60%

Dorsch (2005) also lists the main tourist resorts in the sensitive zone. Most of these resorts are located directly on the ocean front and to provide guests with the required shade, tree gardens have been planted. The size of these gardens has been estimated by Dorsch Consult (2005). Harbour Village is not (yet) included in the list given by Dorsch. As this hotel is already completed and operational it has been added under the present (2005) situation. Sunset Beach Hotel, on the other hand, is included in the Dorsch report as an existing hotel, but has been demolished and will be rebuilt in the future. This hotel has therefore been classified under the new resorts. The total area of present hotel gardens comes to 7.19 ha (Table 2). Two additional new establishments are in the progress of construction or in the planning. After construction of these (Sunset Beach Resort and Hato Hotel Resort) the total area of hotel gardens is expected to be 9.43 ha. The Government buildings with gardens, as well as some of the smaller gardens have been neglected in this table (the total neglected garden is about 0.47 ha.

Table 2 Hotels gardens inside the sensitive zone used for analysis

Name of Property	Number of beds	Estimated Property Area (ha)	Estimated Irrigated Area (ha)
Plaza Resort	478	8.11	2.43
Divi Flamingo	258	1.80	0.54
Sand Dollar Con. Resort	256	4.30	1.29
Captain Don's	208	1.90	0.57
Harbour village	180		0.46
Buddy Dive	148	1.40	0.42
Sunset Oceanfront Aptmnts	108	0.15	0.04
Eden Beach	96	0.35	0.11
Hotel Rocheline	88	0.18	0.05
Lions Dive	76	0.80	0.24
Caribbean Court Bonaire	74	1.00	0.30
Yacht Haven Apartments	32	0.50	0.15
Hamlet Oasis	28	1.65	0.49
Aqua Viva Apartments,	28	0.25	0.07
Carib Inn	26	0.10	0.03
TOTAL 2005	2084	22.49	7.19
New establishments			
Sunset Beach Resort	400	4.60	1.38
Hato Hotel Resort	250	2.86	0.86
TOTAL 2017	2734	29.95	9.43

Land use

In former times, agricultural activities were widespread distributed over the island notwithstanding the unreliable rainfall (Westerman and Zonneveld, 1956). Sorghum (*Sorghum vulgare*), locally named 'maishi chikitu' was the main cereal and fodder crop. It was grown mainly on soils derived from volcanic rocks and on non-saline alluvial soils. In the early fifties, sorghum fields occupied 300 to 600 ha. *Aloe vera*, the other main crop, occupied about 1400 ha. This means that less than 10% of the total surface area of Bonaire (26500 ha) was used for agriculture. Since the sixties, agricultural activities decreased steadily. At present, sorghum is grown only very locally and hardly any aloe plantations are left.

Grazing by goats (and sheep and donkeys) is an ongoing activity on the island. At many places and especially in dry years there is a tendency to overgrazing. The major change in land cover between the mid-seventies and 2005 is the increase in residential areas (including hotels).

We therefore assume that in the mid-seventies and at present, the land used for cultivation is comparable in extent and for the calculation of run-off this can be neglected.

3.2 The physical environment and land cover

3.2.1 Geography

The geology of Bonaire was studied and reported by Buisonjé (1974). Originally Bonaire is of volcanic origin. Volcanic rocks of the Washikemba formation (of Cretaceous age) form the base and the core of the island. After the Eocene age these volcanic rocks came to the surface due to tectonic uplifting. During the young tertiary submergence only a small part of present north-western Bonaire remained above sea level. Around this small island, coral growth started. With further uplifts the island increased in size as the coral continued to grow. Several (coral) limestone terraces where formed during the course of time up to the present. While the island was stepwise uplifted, the central part eroded and thus the volcanic rocks were exposed again and eroded as well. Locally, wind blown sands were deposited on top of the volcanic rocks. These calcareous sands have been cemented together and form the so-called eolianites.

In our study area, the "larger Kralendijk watershed", the highest parts are formed by Seru Largu (137 m high, consisting of eolianites) in the North and Seru Grandi (116 m high, consisting of porphyrites) in the Northeast. In the eastern part of the area the Washikemba formation is exposed. The more resistant hills are composed of porphyric rocks; the largest part is composed of diabase and locally tuffs.

Towards the west in our study area, we find two terrace levels: the middle terrace and the lower terrace. North of Hato, the higher terrace is exposed as well. These terraces consist of hard coral limestone and are of depositional nature (Buisonjé, 1974). The lower terrace occurs at a level between 0 and 10 m above sea level; the middle terrace generally up to 20 m, locally higher.

3.2.2 The watershed of the sensitive zone

The field survey started with the delineation of the watershed draining to the sensitive zone of Kralendijk (between Hato and Punt Vierkant). This watershed drains to the west and the major part of the run-off water reaches the sea via the two saliña's (North Saliña and the saliña north of the airport which we call South Saliña). In addition, three main culverts at the seafront of Kralendijk enable storm water discharge from the town (and part of the hinterland) to the sea. The water divide runs north of the Seru Largu and from there to the southeast, east of the Seru Grandi towards Santa Catarina. From there the divide goes to the southwest to the Flamingo Airport. The total surface area of this watershed is about 3085 ha.

3.2.3 Ecophysiographic units

This watershed has been subdivided into 8 ecophysiographic units on the basis of topography, soils and land cover. This subdivision was based on our own observations and with the help of the report of Grontmij/Sogreah (1968). These units form the basis for run-off calculations and sediment loads reaching the saliña's and the sea. The ecophysiographic units are (see figure 1):

- H - Rolling and rocky hills

Slopes go over 20% and soils are very shallow (generally less than 20/30 cm deep) and stony with frequent rock outcrops. Bedrock consists of volcanic rocks of the Washikemba formation (mainly porphyrites but also eolianites). These hills are covered with thorny shrubs and bush.

- O- Rolling, non rocky, plateau

Slopes are over 8 but generally less than 20%. Soils are shallow (less than 20/30 cm deep). Unit O is covered with thorny bush.

- P - Gently undulating to locally rolling terrace and plateau land

Slopes are generally less than 8%. Soils are shallow to moderately deep (20 to 50 cm) and developed on mainly volcanic rock (diabase) of the Washikemba formation. Vegetation is thorny bush.

- D - Nearly level to gently undulating lands with deep soils

Soils are over 50 cm deep and not or only slightly saline. Soils are derived from limestone or from alluvial materials. The Amboine area is used by LVV for agriculture: mainly grassland (Buffalo grass) for grazing and hay making for goats. Other parts are covered with thorny bush.

- R - Nearly level to sloping rock land

Shallow soils (less than 20 cm deep) with frequent rock outcrops. Bedrock consists of coral limestone. **Rf** is the flat to gently sloping part with slopes generally less than 8%; **Rs** is the sloping part with slopes over 8%. The land is covered with thorny bush.

- Z - Nearly level to gently undulating land with saline soils

Soils are shallow to moderately deep and are saline. Shrubs and thorny bush cover the land.

- S - Flat Saliña's

Soils are shallow to deep, highly saline, over coral limestone. The central part of the saliña is bare. After heavy rains the land is flooded; in the dry season salt crusts are at the surface. Around the edges, salt tolerant herbs and shrubs are present.

- U - Flat to gently undulating urban areas

Soils are shallow to moderately deep, over coral limestone. In many places the soil is man made and consists of brought up gravely clay loam (from diabase). Roads and stone wall fences block free movement of surface water causing flooding after heavy rains.

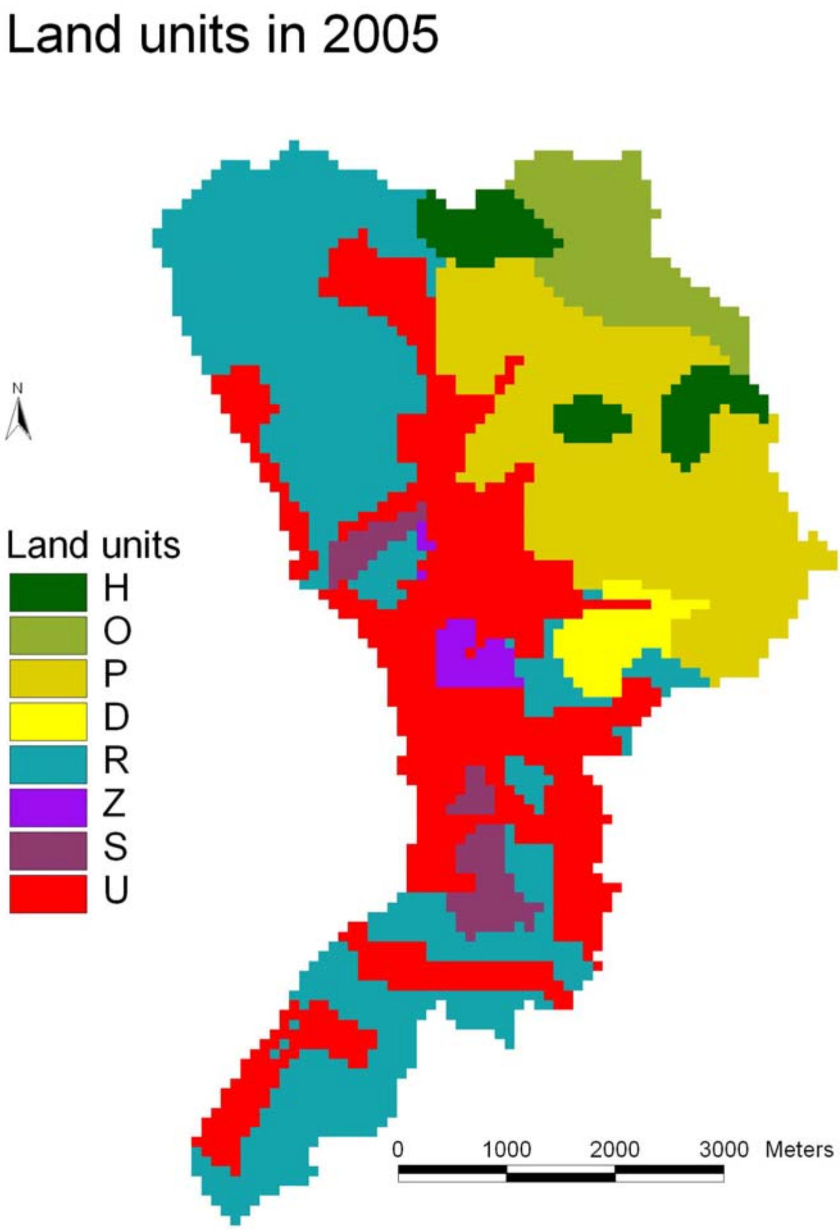


Figure 1 Land units in 2005

3.2.4 Soils

The soils in our study area are chiefly derived from diabase and from limestone. Most soils are shallow, stony and rocky with low organic matter levels. The soils of the saliña's are shallow to deep and very saline. The areas with deep, non saline soils are limited to the LVV grounds and an area southeast of Kralendijk.

The soils in the hotel gardens are, almost without exception, manmade. Most hotels are situated close to, or at the seafront and built on limestone rock. By nature, soils are virtually absent or very shallow here. As most hotels wanted to create gardens for shadow and beautification to grow some plants, soil material was brought up. This material originates from weathering diabase and consists mainly of gravely clay loam. Hotel garden soils are usually around 40 cm deep. Most top soils have low organic matter contents (0.5 – 2% organic matter; although the organic matter content is low, soil structure is moderate to good). High organic matter levels (2 – 4% organic matter is favourable for soil structure and slightly improves water holding capacity and nutrient storage and recycling), however, are found in soils under a permanent grass cover (lawn areas). These higher organic matter levels are caused by a constant addition of organic matter to the soil, coming from grass roots and leaves. These are turned into more stable humus type or organic matter.

At saturation, the soils of our study area with a texture of loam to clay hold about 50% water. The available water holding capacity of the hotel soils is estimated at 15 to 20%. After a soil has been saturated with water and rain or irrigation stops, it rather quickly looses water to the subsoil or underlying rock until it reaches an equilibrium. This is called the water content at field capacity which is about 40%. After that the soil looses water through evaporation and transpiration by plants. The drier the soil becomes, the more difficult it is to remove the soil water. At the point where plant roots are no longer able to suck out the water the soils here hold still about 20 to 25% water. This point is called wilting point. Plant available water is the amount between field capacity and wilting point). This means that 40 cm soil has 60 to 80 mm of plant available water. After a reduction of 30% for the gravel content, this becomes 40 to 55 mm. In summary:

	Water content of 40 cm hotel soil (mm)	
	Original soil	With gravel
Saturation	200	140
Field capacity	160	112
Wilting point	80	56

The soils of the hotels with a texture of clay loam have a low saturated hydraulic conductivity of around 20 to 30 cm/day. Initial infiltration rates, before saturation, however, are higher. Thus irrigation gifts of 10 mm/hr can easily be absorbed.

The soil descriptions, including the results of the physical analysis, are given in Appendix 4. The sampling points and hotel sites are presented in figure 2.

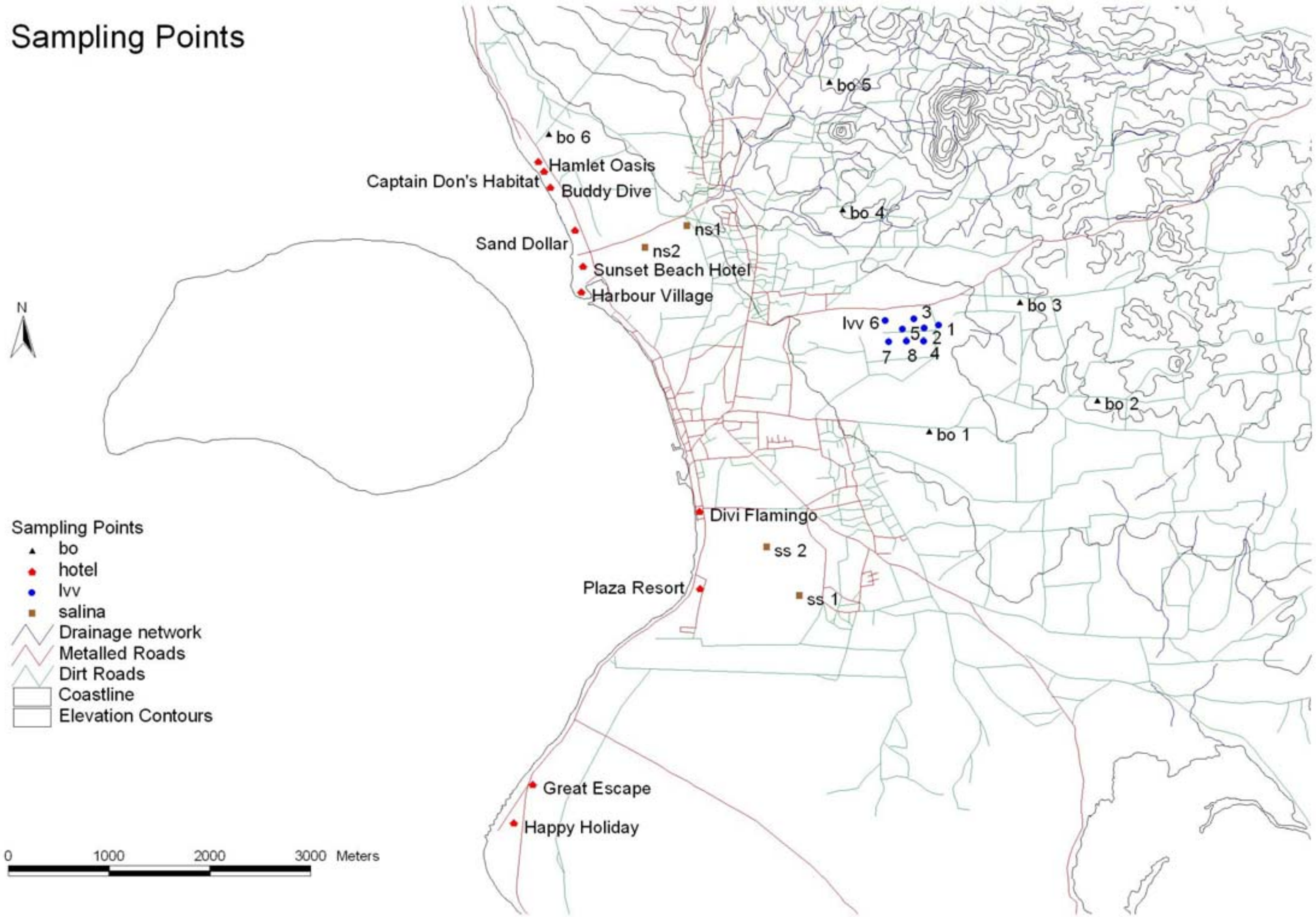


Figure 2 Sampling points

3.3 Nutrient status

Sampling and analysis

To obtain information on the potential sources of nutrients for the pollution of the coastal waters at Bonaire, soil and water samples were collected in the sensitive zone, the inland and the saliñas. Soil samples have been collected at 14 locations in hotel gardens (10), saliñas (2), in the inland (1) and at the agricultural fields (1) of LVV (table 3). In total 60 soil samples and 14 water samples were collected. Relatively little subsoil samples were collected as the soil was often quite shallow (less than 40 cm thick). The presence of bedrock close to the soil surface also inhibited the collection of groundwater. Groundwater was only present at the deep soils at the LVV ranch and in the saliñas.

Soil samples were air dried and passed through a 2 mm sieve to remove stones. The samples were analyzed for total-N and total-P. Total-N and total –P were determined by destruction with H_2SO_4, H_2O_2 and selenium. Oxalate extractable Al, Fe and P were determined to obtain information on the phosphate storage capacity and the degree of phosphate saturation of the soils. To obtain information on the composition of the soil solution, soil extracts were prepared using a 1:2 ratio of soil and water. The soil extracts were analyzed for NH_4, NO_3, total-N and PO_4 using SFA reactor. Total –P was analyzed using an ICP.

Table 3 Overview of the sampling location and the number of collected soil and water samples

Location	Land use	Number of samples				
		Soil		Water		
		Topsoil	Subsoil	Ground water	Surface water	Sea water
Inland	Grazing	6	-	-	-	-
LVV	Agriculture	7	3	1	1	-
Buddy Dive	Hotel garden	3	-	-	-	-
C.D. Habitat	Hotel garden	5	-	-	-	1
Divi Flamingo	Hotel garden	5	-	-	-	1
Great escape	Hotel garden	1	-	-	-	-
Hamlet Oasis	Hotel garden	2	-	-	-	-
Happy Holiday	Hotel garden	1	-	-	-	-
Harbour Village	Hotel garden	5	-	-	-	-
Plaza resort	Hotel garden	10	1	-	-	1
Sand Dollar	Hotel garden	5	-	-	-	-
Sunset	Hotel garden	3	-	-	-	-
Salina Norte	Saliña	2	-	2	2	-
Salina South	Saliña	1	-	-	2	-
East coast	Sea					3

Nutrient contents in the soil solid phase
Total nitrogen content in the 60 soil samples varied between 0.1 and 1.9 g/kg in the topsoil samples. Somewhat lower contents were found in the subsoil samples where contents varied between 0.2 and 0.9 g/kg. Average total-N contents for the inland, agricultural area, hotel gardens and saliñas varied between 0.7 and 0.8 g/kg in the topsoil (Table 4) and there was no significant ($p < 0.05$) difference in contents between the topsoil samples of these four land use types. Subsoil samples showed lower values (0.2-0.5 g/kg). Nitrogen contents in both the topsoil and the subsoil samples are relatively low compared to values generally found in agricultural areas in temperate regions.

Total phosphate content varied between 0.3 and 1.9 g/kg in the topsoil and between 0.2 and 0.9 g/kg in the subsoil. P contents of the inland area were significantly lower compared to the other areas. The highest P contents were found in the hotel gardens, although these contents were not significantly higher than the contents in the agricultural areas and the saliñas.

Phosphate in the soils can be adsorbed to Al- and Fe hydroxides and clay minerals or may form precipitates with calcareous material (apatite, calcium hydroxides). The amount of Al and Fe hydroxides in the soils is relatively low (35-115 mmol/kg) with an average value of 45 mmol/kg. Considering the high pH and the presence of free calcium in most of the soils at Bonaire most of the phosphate will be present in the form of precipitates. Despite this dominant role of calcareous material in the binding of phosphate in the soil, the analysis showed significant differences in phosphate saturation of the Al and Fe binding sites. The lowest phosphate saturation was found in the inland soils (0.04) and the subsoil samples. Somewhat higher values were found in the agricultural area. The highest values were found in the hotel gardens although variation was high.

Table 4 Average nitrogen and phosphate contents, Al- and Fe oxalate content and the degree of phosphate saturation in the soil solid phase of the different land use types. Standard deviation between brackets.

Land use	Soil layer	Total-N	Total-P	$Al+Fe_{ox}$	$P_{ox}/(Al+Fe)_{ox}$
		g/kg	g/kg	mmol/kg	(-)
Inland	Topsoil	0.7 (0.2)	0.31 (0.08)	50 (18)	0.04 (0.02)
Agriculture	Topsoil	0.8 (0.1)	0.44 (0.20)	48 (12)	0.14 (0.14)
	Subsoil	0.5 (0.5)	0.33 (0.16)	47 (3)	0.09 (0.04)
Hotel gardens	Topsoil	0.7 (0.4)	0.59 (0.35)	43 (10)	0.26 (0.23)
	Subsoil	0.2 (-)	0.48 (-)	44	0.11 (-)
Saliñas	Topsoil	0.8 (0.7)	0.52 (0.09)	61 (47)	0.20 (0.10)

The variation in nutrient contents and degree of phosphate saturation in the hotel gardens is much larger compared to the other land use units (Table 4). The highest average nitrogen contents in the hotel gardens were found at Divi Flamingo (1.2 g/kg). These contents were significantly higher than in the other hotel gardens (Figure 3). Divi Flamingo is the only hotel garden with turf grass. For a good appearance of the grass fertilizers are used, which explains the higher N contents (and organic matter contents) in this garden compared to the other hotel gardens.

Low values were found in Hamlet oasis, Happy Holiday and Sand Dollar where average N contents were around 0.2 g/kg. The gardens of these hotels are generally rather young and consist of bare soil or gravel with a low to medium vegetation cover. The variation in P content in the hotel gardens was much less. Most of the hotel gardens had at P content in the topsoil between 0.3 and 0.6 g/kg. The only exception is Harbour Village where average P contents were significantly higher (1.3 g/kg). These high values are most probably due to the use of N-, P-, K- fertilizer at Harbour village which is not common in the other hotel gardens, except at Divi Flamingo. The effect of fertilizer use could not be quantified because no quantitative data on fertilizer use could be provided.

The high P contents in the soil at Harbour Village are also reflected in the phosphate saturation fraction for this side, which is significantly higher (0.7) compared to the other sites. Relatively low values are found at Plaza resort, Happy Holiday and Great Escape (0.1-0.16).

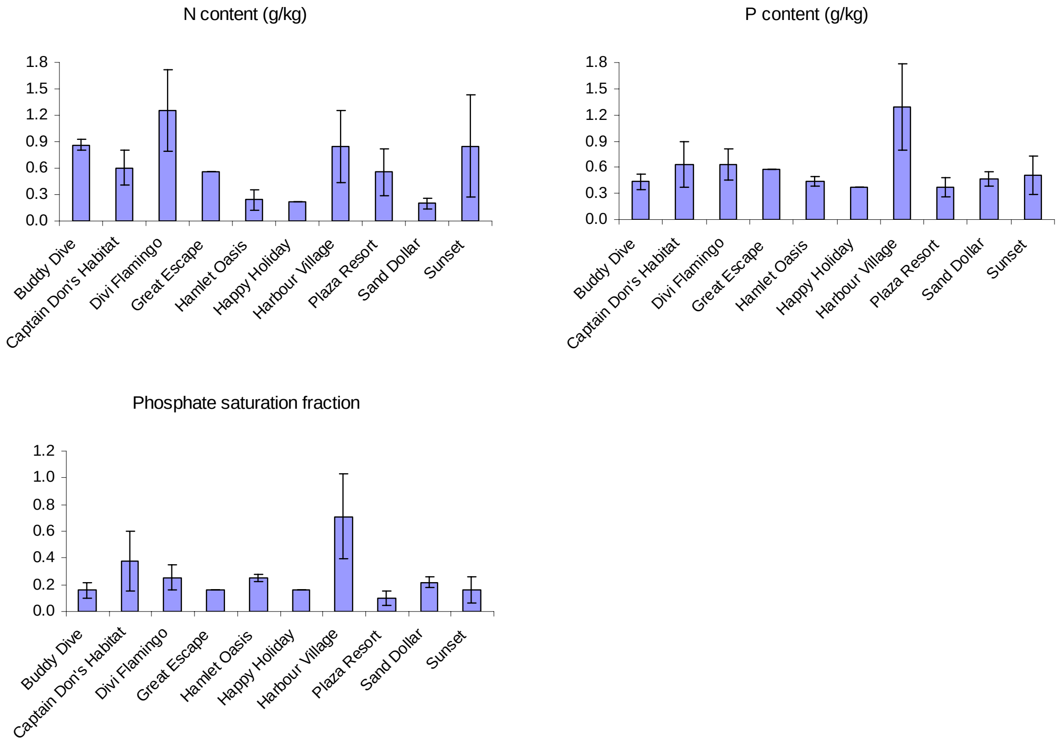


Figure 3 Average nitrogen and phosphate content and phosphate saturation fraction in the hotel gardens.

It may be concluded that the nitrogen contents in the hotel gardens are on average comparable with nitrogen contents in top soils found at other parts of the island. This is quite surprising considering the estimated high nitrogen input (635 kg N/ha/yr, see Table 19) to the hotel gardens due to the use of wastewater from septic tanks. This phenomenon could indicate that the nitrogen which is not taken up by the plants is quickly denitrified or leached (cf. chapter 4.2.2). On the other hand at the time of construction (5-15 year ago) nitrogen contents in the garden soils may have been lower compared to the average nitrogen contents in the top soils at the island. For example subsoil material found in the agricultural area has an N content of 0.5 g/kg which is 0.2 g/kg higher than the average content in the hotel gardens.

Phosphorus contents and the degree of phosphate saturation in the topsoil were higher in the hotel gardens compared to the other sites at the island. In other words the phosphorus status reflects the much higher application of phosphate to the hotel gardens compared to the other areas of the island. The contrasting results compared to nitrogen are not surprising as phosphate is less easily leached than nitrogen. This is because phosphate is strongly adsorbed to the Al- and Fe hydroxides and to calcareous particles in the soil.

Nutrient concentrations in the soil solution

Nitrogen in the 1:2 extracts was present in the form of NO_3, NH_4 and organic nitrogen (Total-N – NO_3-NH_4). NO_3 and organic N were the dominant forms of nitrogen in the 1:2 extracts at most of the locations. Nitrate-N concentrations varied from 0 to 28 mg/l with an average value of 0.7 mg/l in the subsoil samples to 4.3 mg/l in the hotel gardens. Org-N concentrations ranged from 0.2 to 15 mg/l with an average between 0.7 mg/l and 5.7 mg/l in the subsoil in the agricultural area. Phosphorus is dominated by the presence of ortho-P (PO_4). Ortho-P concentrations ranged from 0 to 11 mg/l with an average of 0.08 mg/l in the inland top soils to 1.3 mg/l in the topsoil in the agricultural area. Organic P concentrations are generally low or absent (0-0.2 mg/l).

The differences found in nitrogen and phosphorus concentrations between the different land use types are not statistically significant. This is mainly due to the large variability of the concentrations in the 1: 2 extracts from site to site, leading to high standard deviations (Table 5). Although differences were not significant, the highest average nutrient concentrations were found in the agricultural areas and hotel gardens. Average NO_3, NH_4 and total-N concentrations in the saliñas were somewhat lower, whereas the lowest values were found in the inland top soils. Phosphate and total phosphorus concentrations in both the saliñas and the inland top soils were low compared to values in the agricultural area and the hotel gardens.

Table 5 Average concentrations and standard deviation (between brackets) in a 1:2 soil:water extract

Land use	Soil layer	Concentrations (mg/l)				
		NO_3-N[1]	NH_4-N	N-total[1]	PO_4-P	P-total
Inland	Topsoil	1.4 (1.1)	0.3 (0.2)	2.8 (1.0)	0.08 (0.15)	0.10 (0.11)
Agriculture	Topsoil	3.3 (2.8)	0.9 (1.6)	7.8 (2.7)	1.32 (1.54)	0.68 (0.85)
	Subsoil	0.7 (0.9)	0.4 (0.4)	6.4 (8.3)	0.82 (0.77)	0.23 (0.50)
Hotel gardens	Topsoil	4.3 (5.2)	0.4 (0.9)	6.4 (5.8)	1.07 (1.91)	0.78 (1.20)
	Subsoil	0.8	<0.04	1.5	0.08	0.04
Saliñas	Topsoil	3.4 (2.5)	0.3 (0.3)	5.6 (3.0)	0.12 (0.16)	0.18 (0.15)

[1] concentrations of NO_3 in the soil solution are approximately 15 times higher due to dilution; this will also lead to higher total-N concentration which equals the sum of NO_3, NH_4 and organic N.

The actual concentrations in the soil solution will be in the same order of magnitude as concentrations found in the extracts because the composition of the solution is buffered by the soil solid phase. An exception is NO_3 which is not in equilibrium with the soil solid phase and has been diluted by preparing the extracts. Actual NO_3 concentrations in the soil solution under field conditions are approximately 15 times higher than measured in the extract. This leads to average soil water nitrogen concentrations of about 65 mg/l in the hotel gardens, 55 mg/l in the agricultural area, 50 mg/l in the saliñas and 20 mg/l in the inland soils.

The average total-N concentrations in the 1: 2 extracts of the topsoil of hotel gardens ranged from 1 to 20 mg/l (Figure 4). The highest concentrations were observed at Hamlet Oasis which is remarkable as total-N contents in the solid phase were among the lowest values observed. At the other hotels total-N concentrations ranged between 1.4 mg/l (Happy Holiday) to 8.7 mg/l at Buddy Dive. Nitrate concentrations show a similar picture: high values at Hamlet Oasis and considerably lower values at the other sites. NH_4 in the 1: 2 extracts is only found in significant amounts at Divi Flamingo. Total-N concentrations in the 1: 2 extracts are quite well related (r^2 = 0.59) to the total-N content in the soil solid phase. Exceptions are two sites with extremely high N concentrations (Hamlet Oasis and LVV subsoil at 20-40 cm depth) in the 1: 2 extracts.

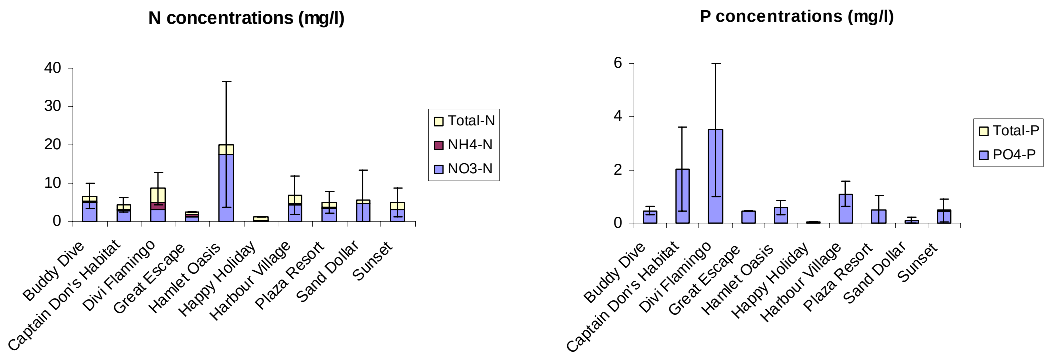


Figure 4 Nitrogen and phosphorus concentrations in the 1: 2 extracts of the hotel gardens.

Average ortho-P concentrations in the hotel gardens ranged from 0.4 to 3.5 mg/l. Average total-P concentrations were almost the same. The highest concentrations were found at Divi Flamingo (3.5 mg/l) and Captain Don's Habitat (2.0 mg/l). In the other gardens the total-P concentrations ranged between 0.1 and 1.1 mg/l. The differences in ortho-P en total-P concentrations between the different hotels were only significant at a p=0.1. The ortho-P and total-P concentrations are only weakly related to the total-P content or the phosphate saturation fraction of the soil solid phase (Figure 5). In some cases ortho-P concentrations exceed the total-P concentrations due to the presence of colloidal clay particles. These particles interfered with the measurements and may have lead to an overestimation of both the soluble and total-P concentrations.

It may be concluded that no significant differences in N and P concentrations could be found between the hotel gardens and other areas due to the high site to site variability in measured concentrations. Despite this the highest N contents were found in hotel gardens. Phosphate concentrations were only weakly related to the total P-content of the soil and phosphate concentrations in the hotel gardens were comparable with those in the agricultural area.

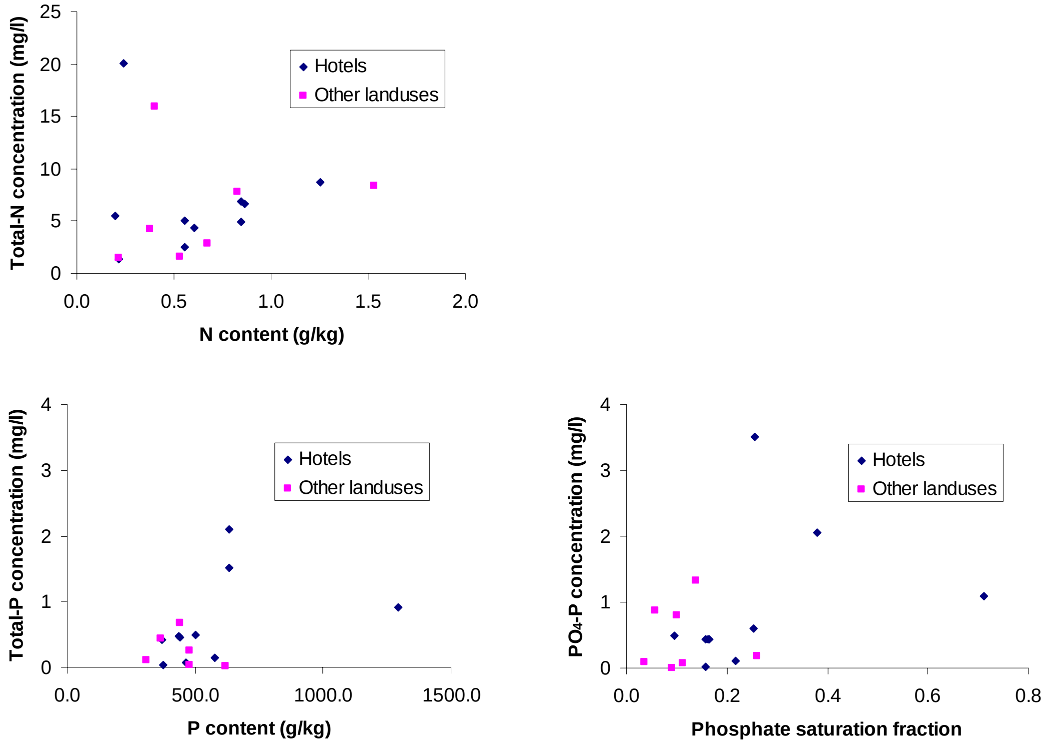


Figure 5 Relation between the N and P content of the soil solid phase and the total N and P concentrations in the 1: 2 extracts and between the phosphate saturation faction and the ortho-P concentration in the 1: 2 extracts.

Nutrient concentrations in groundwater, surface water and seawater

Groundwater was found in the agricultural fields of LVV and in the saliñas only. NO_3 and total-N concentrations in the saliñas were found lower than under the agricultural field. Average NH_4 and phosphorus concentrations were higher in the saliñas (Table 6). The groundwater concentrations in both the agricultural area and the saliñas were low compared to the concentrations in the topsoil in the sensitive area. The nitrate concentrations in the groundwater are in the same order as the concentrations in the subsoil in the agricultural area. Total nitrogen concentrations are much lower in the groundwater (1.8 mg/l) compared to the average values found in the subsoil (6.4). However, the standard deviation in the subsoil samples is high (8.3 mg/l) due to the fact that one out of tree samples has an extremely high N concentrations (16 mg/l) whereas the other values are low. The phosphorus concentrations in the groundwater of the agricultural area are lower compared to the soil water samples from the subsoil.

Surface water samples in the saliñas and the surface water storage reservoir near LVV had low NO_3 and NH_4 concentrations. Organic N concentrations were quite comparable to the groundwater samples and much lower than the concentrations in topsoil samples in the area. Phosphate concentrations in the agricultural area (storage reservoir) are higher than the concentrations in the groundwater but considerably lower than the average concentrations found in the topsoil of the agricultural area. Topsoil P-concentrations in the field close to the reservoir were in the same order of magnitude (0.45 mg/l), however.

Concentrations of nitrogen in sea water at the west coast in front of the hotels are higher compared to concentrations at the uninhabited east coast of Bonaire. At the east coast both the nitrogen and phosphorus concentrations were below the detection limit. At the west coast all three samples showed detectable amounts of NH_4, total-N and PO_4 whereas NO_3 concentrations were below the detection limit in two out of the three samples taken. Due to the variation in concentrations in the west coast samples, only the NH_4 and PO_4 concentrations were significantly higher than the concentrations at the east coast.

Table 6 Average nitrate and phosphate concentrations in groundwater, surface water and seawater. Standard deviation between brackets

Water-type	Land use	Concentrations (mg/l)				
		NO_3-N	NH_4-N	N-total	PO_4-P	P-total
Ground	Agriculture	1.3	0.02	1.8	<0.02	<0.02
Water	Saliña	0.04 (0.1)	0.35 (0.3)	0.8 (0.6)	0.17 (0.11)	0.11 (0.09)
Surface	Agriculture	0.09	0.14	1.0	0.26	0.26
Water	Saliña	<0.03	<0.04	0.7 (0.2)	<0.02	<0.02
Sea	West coast	0.3 (0.5)	0.06 (0.02)	0.6 (0.6)	0.06 (0.03)	<0.02
	East coast	<0.03	<0.04	<0.3	<0.02	<0.02

It may be concluded that some nitrogen is present in the groundwater and surface water in the agricultural area and in the saliñas. Concentrations are low compared to concentrations measured in the soil solution of the topsoil samples in the agricultural area and the hotel gardens.

4 Critical analysis of the effects of the wastewater treatment plant on nutrient leaching

4.1 Nutrient sources

On island level the nutrient sources can be defined on the basis of imports of nutrients. To estimate the sources the import of different substances and the nutrients contained in them must be analyzed. Import of nutrients to the island may take place in the following forms (Gijzen and Van der Steen, 2004):

- Fertilizers used in the hotel gardens and agriculture;
- Food imported to the island (including fish catches) to feed the population and tourists;
- Feed imported to feed the island animals;
- Sewage and sewage sludge imported from visiting boats (and airplanes);
- Nutrients contained in the precipitation falling on the island.

We will not follow the approach of IHE to draft a complete balance of Bonaire, but base our analysis on the land based sources of nutrients only. The food and feed imported to the island is transformed by the residents and tourists on the island into human waste and than disposed off. There are standards for the amount of nutrients (N and P) produced by humans. Mulder (2003) has collected a number of human produced daily nitrogen excretion data (Table 7). They appear to vary between 9.3 g/c/d to as high as 18.2 g/c/d. Dorsch (2005) uses two different design data: 10 and 14.33 g/c/d.

Table 7 Daily human excretion of nitrogen found in the literature and assumed by Dorsch Consult

Description/source	N (g/cap/d)
Gootaas (1965) - lower (Mulder 2003)	9.3
Gootaas (1965) - higher (Mulder 2003)	18.2
Popel (1993) (Mulder 2003)	13.7
RIVM (1991) Netherlands (Mulder 2003)	13
Median	13.35
Dorsch Loading/cap/day (chapter 3.2)	14.33
Dorsch Loading/cap/day (chapter 8.4.5)	10

Data collected in many different countries by Wageningen University indicates a range of 4 to 5 kg of nitrogen produced per capita per year and 0.75 kg of total phosphorus per capita per year (2.05 g/cap/d). We assumed the higher value of 5 kg (13.70 g/cap/d) applicable for tourists because they can be expected to live luxuriously with many proteins in the diet. For residents we assumed the lower value of 4 kg (11.00 g/c/d). Combined with the reported water use for tourists of 290 l/cap/d, this results in raw sewage water concentrations for tourist resorts of 47 mg/l nitrogen and 8 mg/l phosphorus. For residential areas the water consumption has been assumed at 133 l/cap/d and the concentrations would be 83 mg/l nitrogen and 14 mg/l phosphorus. These data, combined with the population and tourist data results in the total production of nitrogen and phosphorus given in Table 8.

Table 8 Development of the number of tourists, residents, water- and nutrient production

	Total Bonaire			Sensitive zone		
	1970	2005	2017	1970	2005	2017
Tourists	74	1,457	2,157	74	1,321	2,021
Residents	8,000	10,740	11,454	1,757	2,359	2,497
N production (kg/y)	32,490	50,407	56,774	7,424	16,077	20,131
P production (kg/y)	5,318	8,279	9,336	1,216	2,659	3,337
Water production[1] (1000 m3/y)	396	676	784	93	254	335
N concentration (mg/l)	82	75	72	80	63	60
P concentration (mg/l)	13	12	12	13	10	10

[1] Assuming a water consumption of 290 l/cap/d for tourists and 133 l/cap/d for residents

In this approach, the nutrient discharges from commercial establishments and the hospital to be connected to the sewerage system have not been taken explicitly into account. We assume that these loads are included in the estimation of the total population as given in Table 8.

4.2 The use of wastewater

4.2.1 Irrigation

Irrigation water requirements

Irrigation water requirements depend on climatic conditions, on effective precipitation, on vegetation characteristics and on the irrigation method used. Long term average climatic conditions for Bonaire have been derived from the FAO database (FAO, Climate database) available on internet (Table 9). Except for rainfall, climatic conditions are fairly constant throughout the year.

The FAO Penman Monteith equation for water use of a short, actively growing, green (grass) crop (FAO, 1998) has been used as the basis for crop water use computations. Reference crop water requirements are computed by:

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} u2(es - ea)}{\Delta + \gamma(1 + 0.43u2)}$$

with:
- ETo reference crop evapotranspiration (mm/d)
- Δ slope of the vapour pressure curve (kPa/°C)
- Rn net incoming radiation at the crop surface ($MJ/m^2/d$)
- G soil heat flux ($MJ/m^2/d$)
- γ psygrometric constant (kPa/°C)
- T mean daily air temperature at 2 m height (°C)
- u2 mean daily wind speed at 2 m height (m/s)

es mean daily saturated vapour pressure (kPa)
ea mean daily actual vapour pressure (kPa)

Table 9 Meteorological data for Flamingo international Airport, Bonaire (Source FAO database)

Month	Tmax (°C)	Tmin (°C)	Humidity (%)	Wind spd (km/d)	Sunshine (hours)	Solar Rad. ($MJ/m^2/d$)	Rain (mm/d)
January	29.1	24.6	77	380	8.1	18.7	1.6
February	29.5	24.6	74	415	8.5	20.7	0.9
March	29.8	25.2	72	432	8.5	22.2	0.5
April	29.9	25.5	74	432	7.9	21.7	0.5
May	30.3	26.1	77	432	7.5	20.9	0.5
June	30.5	26.2	76	475	8.3	21.6	0.5
July	30.5	25.9	77	467	9.0	22.8	0.8
August	30.8	26.2	76	415	9.2	23.4	1.0
September	30.9	26.3	75	389	8.6	22.3	1.1
October	31.2	26.5	75	372	8.0	20.3	2.3
November	30.7	26.1	76	337	7.5	18.2	3.7
December	29.7	25.2	77	346	7.3	17.2	2.8
Average	30.2	25.7	76	408	8.2	20.8	1.3

The change of the saturated vapour pressure with the change of the temperature can be approximated with the empirical relationship:

$$\Delta = 4098 \frac{0.6108 \exp\left(\frac{17.27T}{T+237.3}\right)}{(T+237.3)^2}$$

The net incoming radiation is the difference between the net shortwave radiation absorbed at the crop surface and the emitted long wave radiation:

$$Rn = Rns - Rnl$$

with: Rns net shortwave radiation absorbed by the crop ($MJ/m^2/d$)
Rnl net emitted long wave radiation by the crop ($MJ/m^2/d$)

The net shortwave radiation absorbed is the fraction of the solar radiation not reflected by the crop canopy:

$$Rns = (1-\alpha)Rs$$

with: α albedo, the fraction of reflected shortwave radiation (-)
Rs solar shortwave radiation reaching the earth surface ($MJ/m^2/d$)

In the FAO methodology, the albedo has been settled at a value of 0.23. The incoming shortwave solar radiation is preferably measured in meteorological stations. In the absence of measurements the quantity can be estimated if the relative duration of sunshine hours is known:

$$Rs = \left(a + b\frac{n}{N}\right)Ra$$

with a fraction of solar radiation reaching the earth under cloud conditions

b	the additional fraction under clear sky conditions (-)
n	actual duration of sunshine (hours)
N	day length (hours)
Ra	extra terrestrial solar shortwave radiation ($MJ/m^2/d$)

The fractions a and b in this equation are preferably established by correlation with measured incoming shortwave radiation. In the absence of such measurement data, FAO settled the values as 0.25 for the fraction a and 0.50 for the fraction b, indicating that the incoming radiation under cloudy conditions is one third of that under clear sky conditions. One fourth of the extraterrestrial solar radiation is assumed to be absorbed in the atmosphere.

These equations are included in the Cropwat model (FAO, Cropwat) that has been used in the present study to estimate crop water requirements. Reference crop transpiration is multiplied with the appropriate crop coefficients to obtain net crop water requirement, sometimes also referred to as crop water use. For estimation of the crop coefficients four crop growth periods are distinguished (Fig. 6):

1. The initial stage runs from planting date till about 10% ground cover. The length of the initial stage is dependent on crop, crop variety, planting date and climate. During this stage evapotranspiration is predominantly in the form of soil evaporation. The crop coefficient Kc therefore depends on the frequency of irrigation which determines the moisture content of the top soil. Also the method of irrigation is important for the Kc factor. Using drip irrigation for instance keeps the soil drier resulting in low values for Kc.
2. The crop development stage runs from about 10% soil cover to full soil cover. At the end of this stage soil evaporation approaches zero and the Kc value reaches its maximum value (Fig. 6).
3. The mid-season stage runs from full soil cover until the time of maturity when the leaves start to yellow or fall down, indicating reduction in crop transpiration. During this stage the crop coefficient Kc is assumed at maximum value.
4. The late season stage, finally, runs from the start of maturity till harvest or full senescence.

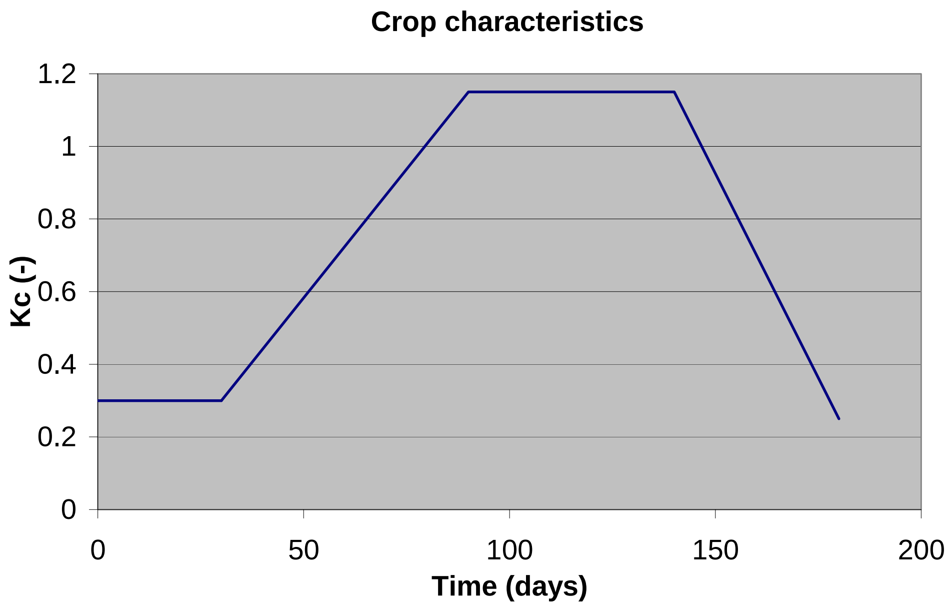


Figure 6 Crop growth stages

For perennial crops such as (evergreen) trees the crop coefficient can be assumed constant during the complete year. FAO (1998) also includes an extensive database of experimentally determined growth stages (duration) and crop coefficients. The soil cover of the shade trees that we have seen in the hotel gardens is about 70%. Therefore, soil cover and degree of wetness will be of importance for crop water requirements. Palm trees with full soil cover are reported to have a crop factor of 0.90. Citrus trees with a soil cover of 70% have a crop factor of 0.70 when surface-irrigated and 0.60 when drip irrigated. The difference between both is due to a wetter soil conditions under surface irrigation. Turf grass has a reported Kc value of 0.95. Vegetable crops have growing periods varying from 100 to 150 days. Due to the constant climate conditions, the start of the growing period can be any time during the year. Vegetable crop data from FAO (1998) for tropical conditions for wet soils for sprinkling and surface irrigation and dry soils for drip irrigation have been used to derive average crop coefficients (Table 10). The underlying assumption is that different vegetable crops at different growth stages are simultaneously present in the field. The average crop coefficients of 0.70 for drip irrigation and 0.90 for surface irrigation derived in this way should therefore never be used for irrigation scheduling of individual field plots. The same procedure has been followed to derive the Kc values for field crops such as maize, sorghum and elephant grass (Table 10).

Table 10 Average crop coefficients (Kc) used in this study (based on FAO, 1998)

Irrigation method	Vegetation					Irrigation efficiency (%)
	Trees/ pebbles	Trees/ bare soil	Trees/ Grass	Vegetable	Field crops	
Drip	0.70	0.90		0.70		90
Sprinkler			1.05		1.00	75
Furrow				0.90	1.00	60

Irrigation crop water requirements need to be corrected for unavoidable irrigation water losses. Irrigation water losses depend on the irrigation method used to apply the water. Drip irrigation is considered the most efficient irrigation method and an efficiency of 90% can be reached under proper management conditions. Drip irrigation is the most commonly used method in hotel gardens, except when turf grass is used as soil cover below trees. With sprinkler irrigation efficiencies of 75% can be realized under the prevailing wind conditions at Bonaire. Sprinkler methods are not recommended for vegetable crops due to the risk of leaf burning and the high relative humidity in Bonaire, because it would promote the occurrence of all type of fungus diseases. Furrow irrigation could be applied for vegetables and field crops, but is not recommended due to the lower efficiencies associated with surface irrigation methods (60% estimated for the present study). Higher efficiencies are possible with surface irrigation, but requires extremely accurate field levelling and accurate timing of irrigations flows. This is considered unrealistic for Bonaire conditions and surface irrigation is therefore not recommended (40% leaching).

Table 11 Net crop water requirements (mm/day)

Month	ETo mm/d	Crop water use Etc (mm/day)					
		Trees/ Gravel	Trees/ bare soil	Trees/ grass	Vegs drip	Vegs furrow	Field crops
Jan	4.65	3.25	4.18	4.88	3.25	4.18	4.65
Feb	5.29	3.70	4.76	5.55	3.70	4.76	5.29
Mar	5.73	4.01	5.16	6.02	4.01	5.16	5.73
Apr	5.65	3.96	5.09	5.94	3.96	5.09	5.65
May	5.43	3.80	4.88	5.70	3.80	4.88	5.43
Jun	5.65	3.96	5.09	5.93	3.96	5.09	5.65
Jul	5.71	4.00	5.14	6.00	4.00	5.14	5.71
Aug	5.81	4.06	5.23	6.10	4.06	5.23	5.81
Sep	5.68	3.98	5.11	5.96	3.98	5.11	5.68
Oct	5.34	3.74	4.81	5.61	3.74	4.81	5.34
Nov	4.75	3.33	4.28	4.99	3.33	4.28	4.75
Dec	4.44	3.10	3.99	4.66	3.10	3.99	4.44
Average	5.34	3.74	4.81	5.61	3.74	4.81	5.34

Using the Kc values in Table 10, the net crop water requirements for the different combinations of crops and irrigation method can be assessed (Table 11). Average crop water requirements range from 37 m^3/ha/d for tree gardens with pebbles as soil cover and for vegetables to 60 m^3/ha/d for tree gardens with turf grass as soil cover.

To estimate the irrigation water requirements, first the net or effective rainfall needs to be subtracted and the unavoidable irrigation water losses must be added:

$$I = \frac{ETo.Kc - Peff}{ef}$$

with:

I irrigation water requirement (mm/d)

Peff	effective rainfall (mm/d)
Ef	irrigation efficiency factor (-).

The average rainfall on Bonaire during the period 1971 – 2004 was 467 mm with a maximum of almost 1,200 mm in 1988 and a minimum of 185 mm in 1998. The distribution during the year is uneven, with a maximum in November (almost 3 mm/d average), followed by October, December and January with more than 1 mm/d on average (Fig. 7).

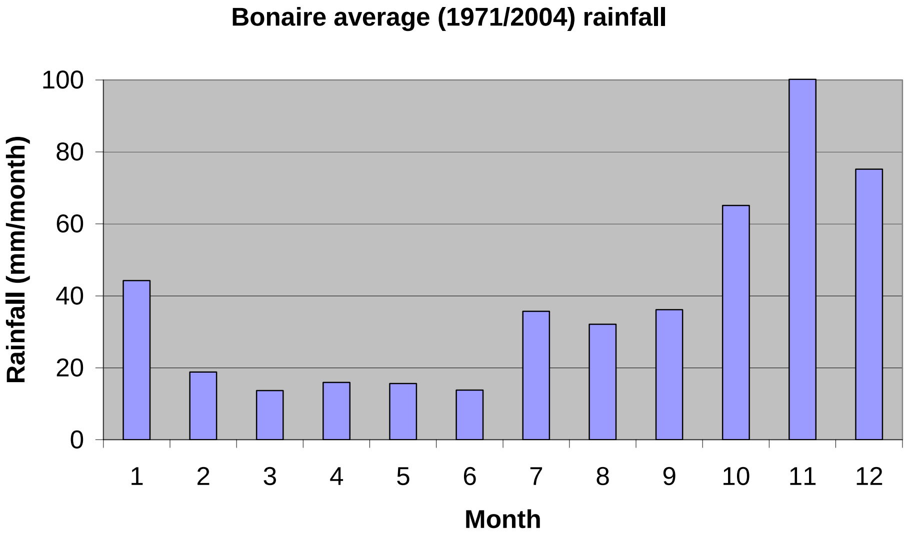


Figure 7 Average rainfall during 1971/2004 reported for Bonaire airport.

For a proper evaluation of water requirements the daily rainfall distribution needs to be known. The first rainfall amount of 2 mm/d can be considered as interception and should be neglected for crop water requirements. In general this quantity accounts for about 20% of the total rainfall. For most of the hotel gardens rainfall quantities above 2 mm/d need to be multiplied with a factor to account for the paved surfaces inside the gardens. This factor depends on the fraction of paved surfaces inside the gardens. Grass gardens generally have quite large garden parcels. Tree gardens we observed as very patchy with small plots of e few m^2, separated by paved surfaces. Rain will not infiltrate on the paved pathways for the guests, but in the soil adjacent to them. We estimate the fraction of pavement in the gardens between 20 and 40%, resulting in a multiplication factor for rainfall over 2 mm/d between 1.25 to 1.50. In the absence of daily rainfall data, in the present computations of irrigation water requirements, these factors have not been taken into account. In the Cropwat (FAO) model it has been used assumed that rainfall is for 80% effective and that monthly rainfall is distributed evenly over all days during the month. Maximum net crop water requirement varies between 3.5 mm/d to 0.5 mm/d for the gardens with pebbles on the soil surface to almost 6 mm/d during March to 2.5 mm/d in November for the tree garden with grass cover (Fig. 8).

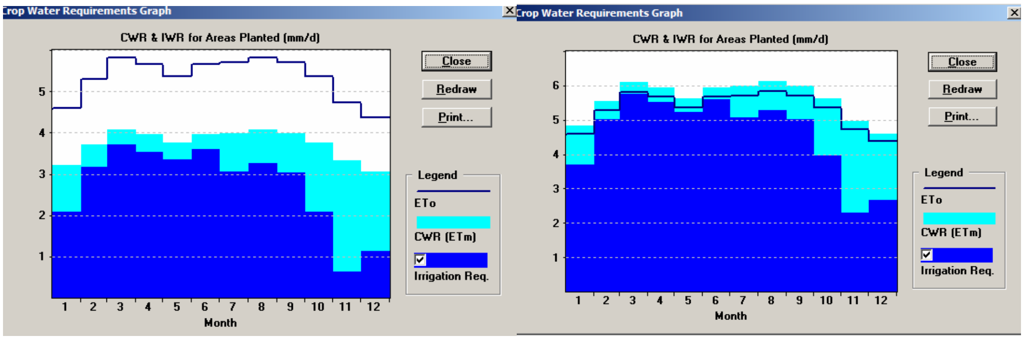


Figure 8 Net crop water requirements (mm/d) two hotel gardens (trees with pebbles left and trees with turf grass right).

Correction for the irrigation method used, results in the irrigation water requirements for the hotel gardens (Table 12). Based on the gardens visited during soil sampling it is estimated that 10% of the garden soils have a soil cover with pebbles, 82% a bare soil or sparse vegetation only and about 8% a turf grass cover.

Table 12 Estimation of irrigation water requirements (mm/d) for the hotel gardens in the sensitive zone for 2005 (7.19 ha).

Month	Peff	Pebbles/drip		Baresoil/drip		Grass/sprinkler		Average
		Etc	Wreq	Etc	Wreq	Etc	Wreq	Wreq
Jan	1.14	3.25	2.35	4.18	3.38	4.88	4.98	3.40
Feb	0.54	3.70	3.51	4.76	4.69	5.55	6.69	4.73
Mar	0.35	4.01	4.07	5.16	5.34	6.02	7.55	5.39
Apr	0.43	3.96	3.92	5.09	5.18	5.94	7.35	5.23
May	0.40	3.80	3.77	4.88	4.98	5.70	7.06	5.03
Jun	0.37	3.96	3.99	5.09	5.24	5.93	7.42	5.29
Jul	0.92	4.00	3.42	5.14	4.69	6.00	6.77	4.73
Aug	0.83	4.06	3.60	5.23	4.89	6.10	7.02	4.93
Sep	0.96	3.98	3.35	5.11	4.61	5.96	6.67	4.65
Oct	1.68	3.74	2.29	4.81	3.47	5.61	5.23	3.49
Nov	2.67	3.33	0.73	4.28	1.79	4.99	3.09	1.78
Dec	1.94	3.10	1.29	3.99	2.28	4.66	3.62	2.29
Average	1.02	3.74	3.02	4.81	4.21	5.61	6.12	4.24

Water availability

For the situation of 1970 no irrigation of hotel gardens has been considered for the present study. Water availability for irrigation of the hotel gardens can be based on the number of hotel guests, the occupancy rates and the wastewater production rate. The average room occupancy rate for Bonaire is about 60% (Appendix 6) with a limited variation over the months (Fig. 9).

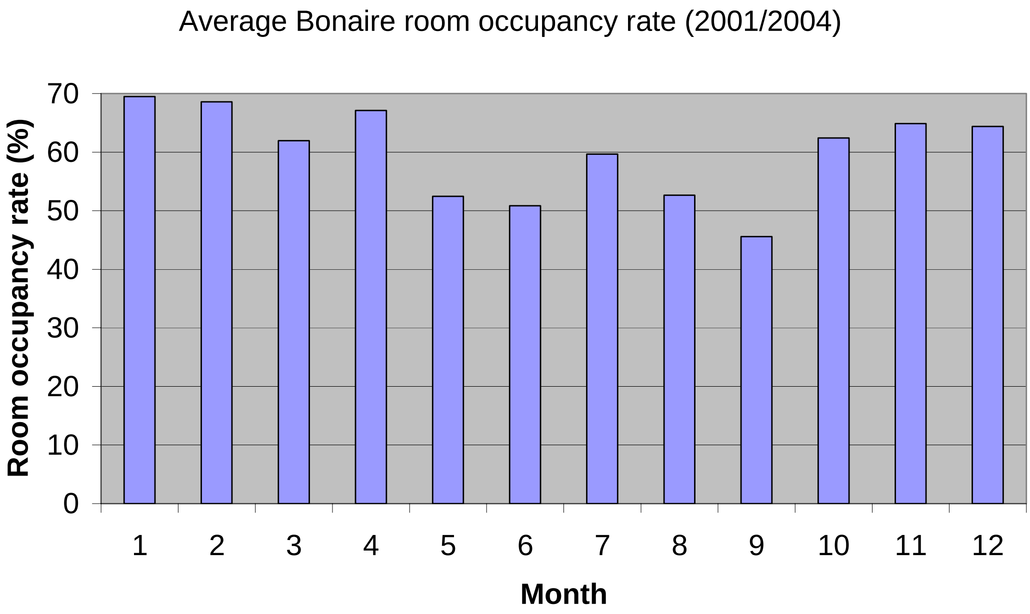


Figure 9 Average (2001/2004) room rate occupancy Bonaire (data Tourism office).

Using the number of beds in the sensitive zone of 2084 (Table 2) for the year 2005 and 290 l/c/d as the specific wastewater discharge, the available water can be computed and compared to the required amount for a garden area of 7.19 ha (Table 13). Except for the period of April through July, produced wastewater exceeds the demand. On average 20% more water is available than required. This means that 20% leaching is being applied on average for the present hotel garden irrigation system.

For the future situation in 2017, the total area of hotel gardens will increase until 9.43 ha (Table 2). The population and tourist accommodations connected to the WWTP are given in Table 1. The recovery rate for residential house connections is 70% only and the wastewater production by residents 133 l/c/d. Using these numbers and the variation in room rate occupancy given above the water availability and requirement for 2017 can be estimated (Table 14). For the water requirement of the extended area of hotel gardens the same distribution of vegetation types has been assumed.

Table 13 Available wastewater and required irrigation water for the hotel gardens in the sensitive zone for the year 2005.

Month	Available water (m^3/d)	Needed water (m^3/d)	Excess water (m^3/d)
Jan	420	245	175
Feb	415	340	74
Mar	374	388	-13
Apr	406	376	30
May	317	361	-44
Jun	307	380	-73
Jul	361	340	21
Aug	318	354	-36

Sep	276	334	-59
Oct	377	251	126
Nov	392	128	254
Dec	389	164	225
Average	363	305	57

Table 14 Future (2017) hotel garden water requirements and excess purified sewage water available for agriculture.

Month	Available water (m^3/d)	Needed water (m^3/d)	Excess water (m^3/d)
Jan	911	321	590
Feb	902	446	456
Mar	838	508	329
Apr	888	493	395
May	745	474	271
Jun	729	499	230
Jul	815	446	370
Aug	747	465	282
Sep	678	438	239
Oct	842	329	512
Nov	866	168	698
Dec	861	216	646
Average	819	400	418

Use of water in agriculture

In order to use the treated sewage water in agriculture, the water can be stored in the surface reservoirs available at the LVV area. The reservoirs are indicated on the maps that we have seen at LVV. There are five reservoirs indicated with a total capacity of about 20,000 m^3:

Surface water reservoir	Capacity (m^3)
1	1,250
2	2,450
3	3,150
4	4,530
5	7,875
Total	19,255

In the analysis we calculated therefore with the 5 reservoirs with an average capacity of 4,000 m^3. Assuming further that the width B of the dam is 46 m, the height H 3.7 m and the longitudinal slope S 2%, the volume of 5 such reservoirs can be calculated with:

$$V = \frac{5B}{8SH} h^3$$

For the losses from the reservoir to the atmosphere (evaporation) and to the groundwater (seepage losses) the wetted area in the five reservoirs needs to be known. This can be derived from the volume as follows (Fig 10):

$$As = \frac{2V}{(\frac{8SHV}{5B})^{\frac{1}{3}}}$$

with:

h water level in the storage reservoir (m)

As wetted surface area of the 5 reservoirs (m^2)

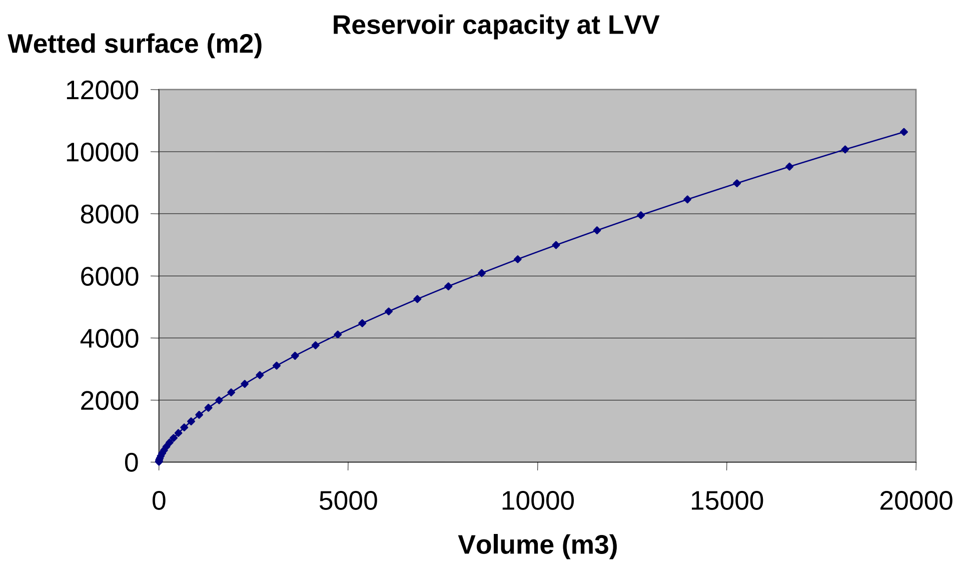


Figure 10 Relation between wetted surface of the storage reservoirs at LVV with the stored volume.

Reservoir losses by evaporation can be calculated by using the same formulas as used for crop evapotranspiration by taking the crop coefficient at 1.05. Leaching losses to the groundwater have been estimated at 10 mm/day. The magnitude of these losses needs to be verified. Using these numbers and assuming further that only vegetable crops will be grown using drip irrigation with a field irrigation efficiency of 90% the area that can be grown with vegetables using the excess water has been established. This is 11.25 ha. Checking the amounts of stored water, however reveals that about 40,000 m^3 of water needs to be stored for a constant vegetable area (Fig 11). This is clearly impossible, because so much storage space is not available.

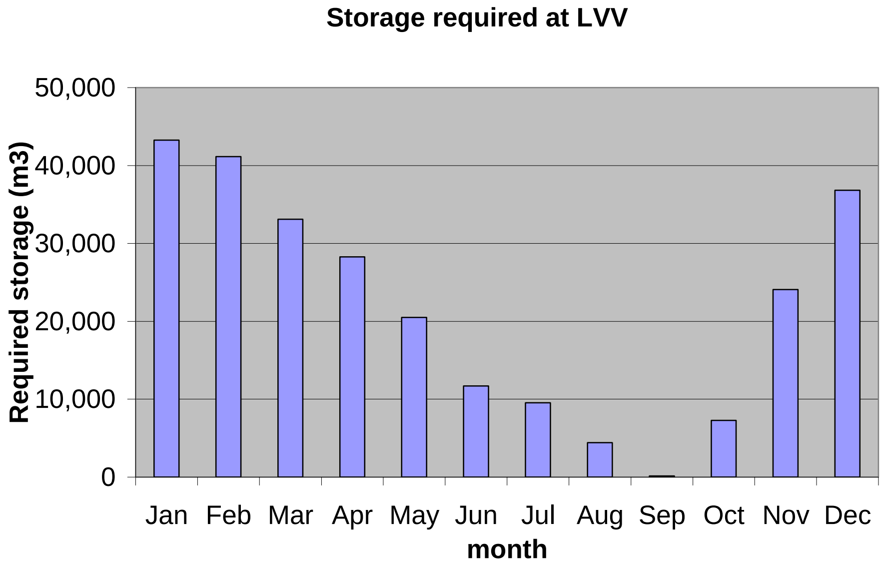


Figure 11 Storage required for agriculture if the vegetable area is kept constant at 11.25 ha

In order to design a cropping pattern that fits the limited storage capacity at the LVV site, a number of iterations have been done. First of all it was assumed that the vegetable crops have a growing period length of four months. Any plot sown must be guaranteed the water supply for the ensuing 4 months. In the first few rounds of iterations a cropping pattern was established that depends fully on the produced excess treated sewage water, without using the storage. This resulted in a vegetable grown area of 25 ha during the rainy period (October/January) till 5.75 ha during June/September. Next it was tried first to increase the winter area further using the storage reservoirs in such a way that the maximum storage of 20,000 m^3 was not exceeded. Then, the summer area was increased as much as possible in order to utilize all water as much as possible. This resulted in 30 ha of crops in the winter and about 9 ha crops during the summer (Table 15). The reservoir volume reaches its maximum in December and falls dry in September and October.

Table 15 Vegetable area at LVV, using the maximum storage capacity, and using this storage capacity to the maximum for summer growth of crops.

	Agriculture		Reservoir				
Month	Area (ha)	Water use (m3)	Inflow (m3/m)	Volume (m3)	Surface (ha)	Evaporation (m3)	Seepage (m3)
Jan	30.00	21,820	-3,521	15,295	0.57	-606	-1,756
Feb	16.50	16,238	-3,463	10,829	0.45	-632	-1,260
Mar	9.00	11,344	-1,132	8,688	0.39	-672	-1,204
Apr	9.00	10,597	1,248	8,953	0.40	-643	-1,189
May	9.00	10,529	-2,133	6,042	0.30	-491	-945
Jun	9.00	10,762	-3,856	1,826	0.14	-226	-412
Jul	9.00	9,534	1,924	3,240	0.20	-302	-624
Aug	9.00	10,030	-1,291	1,614	0.13	-198	-392
Sep	9.00	9,038	-1,855	0	0.00	0	-1
Oct	22.50	15,938	-51	0	0.00	0	0
Nov	30.00	6,564	14,366	13,416	0.52	-257	-1,557
Dec	30.00	12,024	7,988	20,061	0.68	-454	-2,036
Sum	16.00	144,419				-4,482	-11,378

Obviously the second variant (16 ha vegetable crops on average will be much more beneficial than the constant vegetable area of 11.25 ha. Total losses to the groundwater reduce from about 50,000 m^3 annually to 25,000 m^3 annually. Below the main characteristics of both alternatives are shortly summarized:

	Constant area	Variable area
Vegetable area (ha)	11.25	16.00
Reservoir evaporation (m^3)	16,963	4,482
Irrigation (m^3)	123,987	144,419
Irrigation losses (m^3)	12,399	14.442
Seepage losses (m^3)	38,818	11,378

4.2.2 Nutrient balance

Processes involved in the nitrogen and phosphorus cycle

The fate of nitrogen and phosphorus in the hotel gardens and the associated risk of leaching is determined by the input of nutrients, the uptake by the vegetation and the conversion processes of nitrogen and phosphorus in the soil. The nitrogen cycle involves numerous processes (Figure 12). In the hotel gardens nitrogen is added to the soil by means of irrigation. The dominant from of nitrogen in the untreated sewage water is (> 90 %) NH_4. Part of this NH_4 is lost to the atmosphere by volatilization of NH_3. In the soil NH_4 is partly converted to NO_3 by nitrification. Under anaerobic conditions nitrate may be lost to the atmosphere by denitrification. NH_4 and NO_3 are removed from the soil solution by plant uptake. Depending on the magnitude of the leaching fluxes part of the remaining nitrogen will be lost from the soil by leaching and some nitrogen may be stored in the soil solid phase in the form of organic matter. The nitrogen leached from the soil profile will finally reach the sea as nitrogen because it will not be adsorbed to the underlying coral rock.

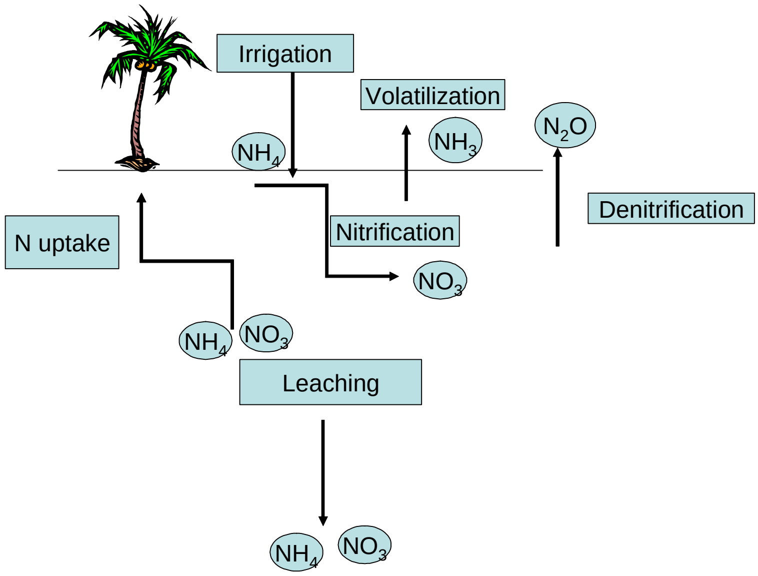


Figure 12 Relevant processes involved in the nitrogen cycle in the hotel gardens in Bonaire

The phosphorus cycle is less complex because gaseous losses of phosphorus do not occur. Phosphorus is added in the form of phosphate by irrigation of sewage water. Phosphorus is less mobile than nitrogen because phosphate is adsorbed to the soil solid phase or precipitates with calcium (apatite). The concentration in the soil solution is kept in equilibrium with the precipitates and the adsorbed amounts. The phosphate which remains in the soil solution can be taken up by the plants and may be leached from the root zone. Phosphate leached from the soil is most probably adsorbed to the underlying coral rock if the residence time is long enough. This process strongly reduces the risk of phosphate leaching to the sea.

Input of nitrogen and phosphate by irrigation

The total nitrogen and phosphate input to the hotel gardens is determined by the quality of the irrigation water and the amount of water used for irrigation (see 4.2.1). In a limited number of hotel gardens (NPK) fertilizers are used. Annual amounts of fertilizers use were not available and have not been taken into account.

Nitrogen and phosphate concentrations in the irrigation water are based on measurements in a small number of septic tanks and local wastewater treatment plants at the various hotels (Table 16). In the septic tanks total-N concentrations were around 70 mg/l except for the tanks at Divi Flamingo. Nitrogen is mainly (94%) present in the form of NH_4. Ortho-P concentrations are around 8.7 mg/l mainly present as ortho-P. Concentrations in the tank at Divi Flamingo were much lower, the reason for this in not (yet) known. The concentrations in the effluents from the wastewater treatment plants (Harbour Village and Plaza) were generally lower compared to the effluents from the septic tanks. An exception is the plant at Captain Don's Habitat.

Table 16 N and P concentrations in sewage water from septic tanks and local wastewater treatment plants

Hotel	Watertype[1]	Concentrations (mg/l)				
		NH_4	NO_3	Total-N	Ortho-P	Total-P
Divi Flamingo	septic	41.7	<0.03	41.7	4.66	5.52
C.D. Habitat	septic	67.2	<0.03	71.1	8.16	8.70
Sand Dollar	septic	66.1	<0.03	71.0	8.61	8.65
C.D. Habitat	WWTP[1]	19.6	47.8	69.2	8.24	8.43
Harbor Village	WWTP[1]	30.9	2.5	32.2	3.88	4.66
Plaza	WWTP[1]	25.9	<0.03	28.5	4.25	4.74

[1] WWTP = wastewater treatment plant

To calculate the present nitrogen and phosphate budgets for the hotel gardens a value of 71 mg/l N and 8.7 mg/l P was used for those gardens which are irrigated with septic tank water. For the gardens at Harbor village and Plaza which are irrigated with water from their wastewater treatment plant the values measured at the plants were used. To construct budgets for the future (after construction of the sewage treatment plant) we used the concentrations provided by Dorsch of 28 mg/l N and 5 mg l/P (Dorsch, 2005).

Uptake of nitrogen and phosphate by the vegetation

Uptake figures of nitrogen and phosphate in tropical areas are widely available for commercial crops like tropical grasses, corn, sorghum, coconut, date palm, bananas and horticultural crops like okra, pepper, watermelon and spinach. Uptake figures for ornamental plants found in the hotel gardens like Bougainvillea, Benjamin fig, rubber tree (Ficus elastica) and Flamboyant (Delonix regia) are not available.

Uptake rates of commercial crops (Table 17) are based on an extensive literature review by Wichmann (1992). Whichmann provided the following data for well irrigated crops in tropical areas: in horticultural crops net uptake ranges from 0 kg N ha^{-1} yr^{-1} for beans to 531 kg N ha^{-1} yr^{-1} for tomatoes. P uptake ranges from 27 kg P_2O_5 ha^{-1} yr^{-1} for eggplant to 253 kg P_2O_5 ha^{-1} yr^{-1} for string beans. The average uptake for horticulture was based on uptake rates of common crops like okra, peppers, spinach and water melon. The average uptake of these four crops is 84 (172) kg N ha^{-1} yr^{-1} and 25 (75) kg P_2O_5 ha^{-1} yr^{-1} at the indicated production level. When more crop cycles and/or higher production rates are achieved the annual nutrient removal from the soil increases proportionally.

For grasses, corn and sorghum average values of approximately 200 kg N ha^{-1} yr^{-1} and 73 kg P_2O_5 ha^{-1} yr^{-1} are found at an average production of 9 ton ha^{-1}. For (fruit) trees average values of 257 kg N ha^{-1} yr^{-1} and 41 kg P_2O_5 ha^{-1} yr^{-1} are found when bananas are included. The average uptake of coconut and date palm is lower: 115 kg N ha^{-1} yr^{-1} and 22 kg P_2O_5 ha^{-1} yr^{-1}.

Table 17 Net uptake rates of commercial crops after Wichmann (1992)

Crop type	Species	Yield	Uptake (kg ha^{-1} yr^{-1})	
		Mg ha^{-1}	N	P_2O_5[1]
Horticulture	Okra	60	237	96
	Pepper (*capsicum annuum*)	63	210	48
	Spinach (*spinazia oleracea*)	63	393	102
	Watermelon *(citrullus lantanus)*	45	168	48
	Field beans (*vicia fabia)*	12 (beans)	0	133
	String beans (*phaseolis vulg.)*	65	0-100	252
	Eggplant (*solanum melongena)*	40	75	27
	Tomato (*lycopersicon esculentum)*	72	531	137
	Cucumber *(cucumis sativus)*	60	117	81
	Average	53	216	102
Agriculture	Grass	8	170	46
	Grass-legumes	8	202	48
	Corn *(Zea Mays)*	19	258	142
	Sorghum *(Sorghum bicolor)*	-	100-250	50-60
	Average	9	183-220	71-74
Trees	Coconut *(Cocus nucifera)*	100 nuts/palm	165	37
	Date palm	12 (fruit + tissue)	65	7
	Banana *(Musa sp.)*	51	284	78
	Citrus *(citrus sp.)*	45	65	18
	Mango *(mangifera indica)*	123 trees/ha	275	275
	Average		170	83

[1] P_2O_5 uptake = 2.29 * P uptake

Table 18 Uptake rates of N and P (kg ha^{-1} yr^{-1}) used for the considered vegetation types on Bonaire in this study and potential ranges in N and P uptake for horticulture and agriculture (between brackets)

Vegetation	Assumption	Uptake (kg ha^{-1} yr^{-1})	
		N	P_2O_5
Horticulture	Average based on okra, pepper, spinach and watermelon (Table 17)	252 *(0-531)*	75 *(27-252)*
Agriculture	Average sorghum production	200 *(100-258)*	73 *(46-142)*
Grass garden with trees	Average of 50% grass uptake and 50% palm uptake	115	28
Tree garden with bare soil or gravel	50% of palm uptake	58	11

[1] P_2O_5 uptake = 2.29 * P uptake

Uptake rates for the different vegetation types addressed in this study have been based on the data from table 17 and expert judgment on the intensity of farming (Table 18). For horticultural and agricultural crops the data of table 17 were used with an average uptake for sorghum. We assumed that the uptake rates of crops/trees in hotel gardens are 50% of those found in commercial use. For ornamental plants we based the uptake figures on 50% of those found for coconut and date palm. We took only 50%, because literature data relate to the commercial use of these crops. In the hotel gardens plants are not grown for maximum production, but only to remain in healthy conditions. All plants grown in the hotel gardens originate from tropical regions (oligotrophic ecosystems) and are used to survive on limited nutrient supplies. To obtain the final uptake values for grass gardens and gardens with bare soils we assumed a soil cover of 50% with ornamental plants. In grass gardens the remaining 50% is covered by grass. Accordingly the uptake for grass gardens is the average of the uptake for non commercially cultivated grass and the uptake rates for the gardens without undergrowth.

Gaseous losses of nitrogen

The use of fertilizers, effluent or animal manure containing NH_4 may lead to emission of NH_3 from the soil. The emission of NH_3 is stimulated by high NH_4 concentrations in the soil or effluent, a high pH of the soil/effluent, a low CEC, a high salt content, a high moisture content of the soil and high evaporation rates (Nelson et al., 1982, Gandi & Paliwal, 1976; Smith et al., 1996).

Losses of NH_3 by volatilization up to 20% have been reported from the application of wastewater with a pH of 7.5-8.5 by spray irrigation (Pettygrove and Asano, 1984). Losses of 31 % were recorded in lysimeter experiments with Sudan grass in Tunisia (Khelil, 2005). On the other hand negligible losses (<1%) were found on corn and peppers in Israel and China (Master et al., 2003; Zhu et al., 2005). However, relatively little is known about volatilization by soils irrigated by drip. Theoretically the ammonia volatilization should be relatively low since the wetted surface area is small (Rolston et al., 1977).

From this literature overview we may conclude that the uncertainty with respect to ammonia volatilization is large and strongly depends on the irrigation method and the irrigation intensity (wetness of the soil). In the hotel gardens at Bonaire most of the conditions are favourable for NH_3 emission (high NH_4 concentrations, high pH, low CEC, a high salt content and high evaporation rates) except for the irrigation method and the moisture content which may limit NH_3 emissions during the dry period. In this study we assumed that volatilization will be 20% when sprinklers are used. In case of drip irrigation we used a factor of 10% in the wet period (October - January) and 5% in the remaining part of the year.

Ammonia lost by volatilization will reduce the amount of nitrogen leached from the hotel gardens. On the other hand NH_3 emission leads to enhanced N-deposition at relatively short distances (< 5 km) from the emitter source. Taking into account the prevailing wind direction at Bonaire (NE), ammonia emission from hotel gardens will lead to N deposition in the sea south west of Bonaire.

Denitrification, the conversion of NO_3 to N_2O, and N_2 is another process leading to gaseous losses of nitrogen from the soil. Denitrification occurs when microbes use nitrate as oxygen donor for decomposing organic matter. The process depends on the organic matter content and the environmental conditions in the soil such as the oxygen content (water saturation) of the soil, temperature and pH (cf. Heinen, 2005). Denitrification increases from 0 at a water filled pore spaces of 0.5 to a maximum value at complete water saturation (e.g. when all pores are filled with water). Denitrification increases exponentially with temperature according to Arrhenius law with a Q_{10} between 2 to 3. A neutral to slightly alkaline pH in the soil solution (pH 6-8) leads to an optimum denitrification.

Denitrification is highly variable in space and time and is difficult to estimate. Accurate measurement of (potential) denitrification rates as well as measurement or simulation of the occurrence of water saturation in the soil is required. In the hotel gardens denitrification will be promoted by the prevailing high temperatures. On the other hand carbon contents (1.85 %) and nitrate contents (8 mg NO_3-N/kg soil) are rather low. On the basis of data for loamy soils in Western Europe with similar carbon contents potential denitrification rates may be in the order of 5 kg N ha^{-1} d^{-1} (Heinen, 2005b). Actual denitrification can be calculated using a simple denitrification model taking into account the water filled pore space, NO_3 content of the soil and temperature (Heinen, 2005a). At a temperature of 30°C actual denitrification rates in the hotel gardens will range between 0.5 kg N ha^{-1} d^{-1} at a water filled pore space of 70 % to 1.9 kg N ha^{-1} d^{-1} at a water filled pore space of 90 %. A study in desert soils in Texas (Fedler et al., 2003), which were saturated with effluent water, showed values at the low end of this range (0.4 - 0.6 kg N ha^{-1} d^{-1}). Temperatures in this study were, however, somewhat lower (25°C) than commonly observed at Bonaire. At 30 °C rates should be approximately 1.6 times as high. Based on the above values we assumed that denitrification on days with a precipitation of more than 20 mm will be 1 kg N ha^{-1} d^{-1}. This situation occurs on average 7 days a year in the wet period (Figure 16).

Nitrogen balances and leaching of nitrogen

The leaching of nitrogen and phosphate from the soils in the hotel gardens is calculated using simple mass balances. The mass balance for nitrogen is expressed as follows:

$$N_{leaching} = N_{input} - (N_{uptake} + NH_{3,volatilization} + N_{denitrification}) - N_{storage}$$

For phosphate the following balance was used:

$$P_{leaching} = P_{input} - P_{uptake} - P_{storage}$$

Nitrogen and phosphate leaching was estimated for two types of hotel gardens: grass gardens and gardens with bare soil or gravel surfaces. Calculations were made for the present management and for the expected leaching when the sewage treatment plant is build and irrigation is optimized. Input and uptake of nitrogen and phosphate and volatilization of nitrogen was calculated using the data presented above. The storage of nitrogen and phosphate was assumed to be zero since calculations were carried out for a sustainable situation. In such a sustainable situation leaching of nitrogen and phosphorus is negligible not only now but also in the future. An (unlimited) build up of N and P in de soil should thus be avoided while increasing the risk of losses to the environment.

In the present situation the use of sewage water in the hotel gardens leads to a strongly positive nitrogen (4570 kg yr^{-1}) and phosphate (600 kg yr^{-1}) balance in the hotel gardens (Table 19). These nutrients will be lost from the soil in winter when the sum of precipitation and irrigation exceeds the evapotranspiration in the gardens (see 4.2.1). Moreover, the use of ammonium rich sewage water leads to emission of NH_3 leading to an additional loss of 275 kg N yr^{-1}. This amount will largely reach the sea by atmospheric deposition.

The nutrient surplus is caused by the present input of nitrogen (4090 kg N yr^{-1}) and phosphate (540 kg P yr^{-1}) by sewage water in the gardens of the 9 hotels examined in this study. The examined hotel gardens cover an area of 6.44 ha. If these gardens are representative for the whole area the total input of N and P by sewage water in hotel gardens in the sensitive zone is 4570 kg N yr^{-1} and 600 kg P yr^{-1}.

The nitrogen input ranges from less than 200 kg ha^{-1} yr^{-1} in hotels with large gardens and few guests to more than 2000 kg ha^{-1} yr^{-1} in hotels with small gardens and a large number of rooms (Figure 13). The emission by leaching and NH_3 emission ranges from less than 30% in hotels with limited fertilization by irrigation water to values between 80 and 95% in the average hotel garden. Nitrogen is mainly removed from the gardens by leaching (75%). Uptake is generally less than 20% of the input except for hotel gardens which use tap water. Gaseous losses of nitrogen may account for another 10% of the annual losses in gardens which use large amount of septic tank water.

Table 19 Present (2005) nitrogen balance for the hotel gardens in the sensitive zone and total emission to the sea by leaching and deposition

Balance term	Annual losses		Investigated area (6.44 ha)		Total hotel garden area in the Sensitive zone (7.19 ha)	
	N (kg ha^{-1} yr^{-1})	P (kg ha^{-1} yr^{-1})	N (kg yr^{-1})	P (kg yr^{-1})	N (kg yr^{-1})	P (kg yr^{-1})
Input	634	85	4090	540	4570	600
Gaseous losses of:				-		-
NH_3	38		245	-	275	-
N_2O	7		45	-	50	-
Uptake	60	6	380	40	425	45
Surplus	529	79	3420	500	3820	555
Emission to sea by leaching and deposition	567		3665	0	4095	0

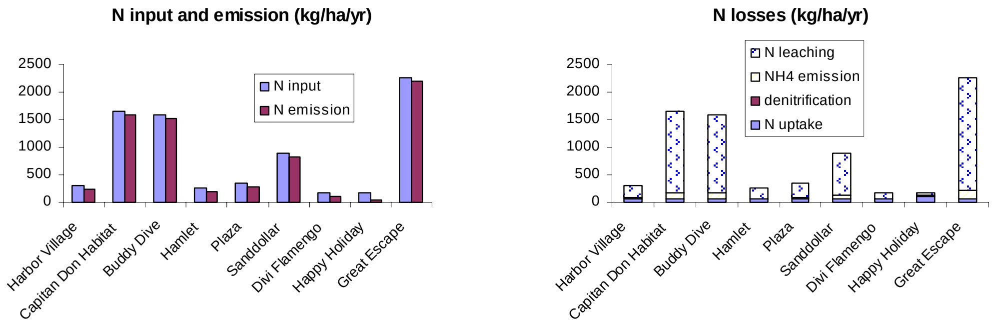


Figure 13 Nitrogen input an emission from the hotel gardens (left) and the contribution of the various processes to the output of nitrogen from the gardens.

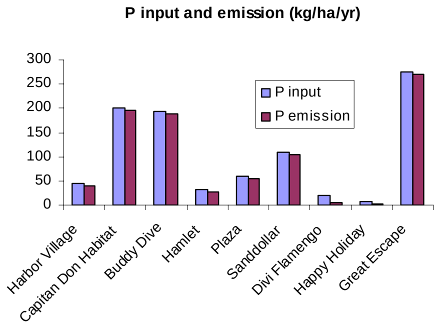


Figure 14 Phosphorus input and emission from the hotel gardens

Comparable conclusions can be drawn for phosphate. The present input of phosphorus far exceeds the uptake of phosphorus (Figure 14). The phosphorus input ranges from less than 10 kg ha^{-1} yr^{-1} to more than 250 kg ha^{-1} yr^{-1}. The losses from the gardens range from less than 20% in hotels irrigated with tap water to more than 90% in some of the hotels with relatively small garden areas. The present fate of the phosphorus surplus is however uncertain as part of the phosphate will be bound to the soil solid phase (see also 3.3) leading to a build up of the amount of phosphate in the soils. Phosphate which is actually leached from the soil may be bound to the underlying coral rock when the residence time is long enough. We expect that the binding of phosphate in the soils and the underlying bedrock is adequate to prevent leaching to the sea. This is confirmed by the low concentrations in the sea water which were negligible.

After implementation of the wastewater treatment plant the annual losses from hotel gardens in the sensitive zone will be 2800 kg N yr^{-1} and 530 kg P yr^{-1}. The use of effluent from the plant will thus lead to a reduction of nitrogen leaching of 33% and a reduction in the phosphate surplus of 6%. This reduction is caused by the lower nutrient contents of the effluent used for irrigation and a reduced and more precise irrigation (see 4.2.1). The impact differs considerable from hotel to hotel depending on the present management and quality of the irrigation water (figure 15). In some hotels the use of effluent will lead to an increase in nutrient leaching due to the fact that today tap water is used for irrigation.

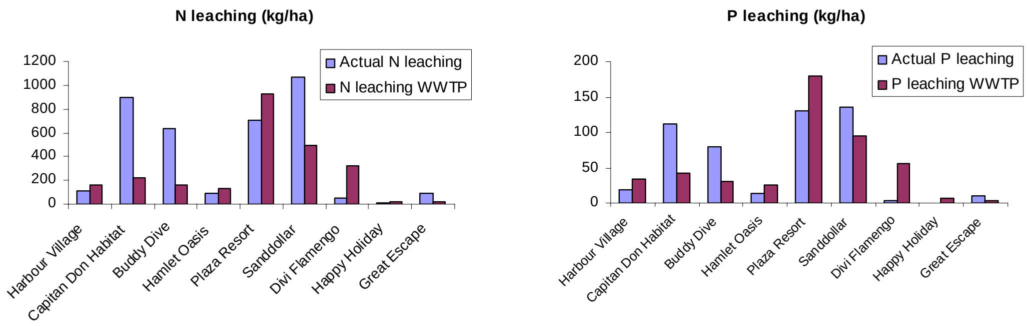


Figure 15 Present and future N-leaching and P surplus in the hotel gardens (future irrigation water with concentrations of 28 mg/l N and 5 mg/l P).

To prevent leaching from the hotel gardens the nutrient concentrations in the effluent from the wastewater treatment plant should be considerably lower or less effluent should be used for irrigation. To avoid leaching only 13 to 18% of the irrigation needs of the hotel gardens can be covered by treated sewage water effluent with a concentration of 28 mg/l (Figure 16). Another alternative is to use grey water or effluent with a much lower nitrogen concentration (3- 5 mg/l). Phosphate is the limiting element because phosphate concentrations in the effluent are relatively high whereas phosphate uptake is low. However, phosphate is strongly adsorbed to the soil and most probably also bound to the underlying bedrock and does not play a role in eutrophication of the sea water at the moment. Accordingly it may be considered to allow a limited P surplus in the hotel gardens and to base the maximum amount of applicable effluent on the nitrogen limitations. Under this assumption approximately 15,000 m^3 of effluent may be used in the hotel gardens combined with approximately 100,000 m^3 of tap water or other clean water sources.

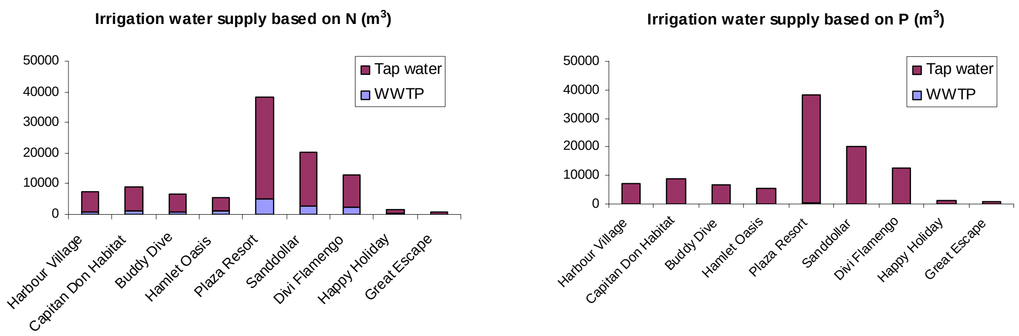


Figure 16 The use of tap_water and irrigation water in the hotel gardens to prevent leaching of N and P

4.3 Nutrient losses due to erosion

4.3.1 Methodology

Within the framework of this study, runoff and erosion from the island of Bonaire should not be neglected as sources of sediment and nutrients to the saliñas and to the sea. The magnitude of this input can be estimated by using computer models to simulate runoff and erosion. Given the limited amount of data available, a simple method was used for modelling. Different parts of the area draining to the Saliñas and to the sea will generate different amounts of runoff and erosion. The model to be used must therefore take such differences into account. The model should have a spatial dimension, i.e. the input to the model should consist of maps. One of the most basic maps for modelling runoff and erosion is the digital elevation model (DEM). A DEM with 90 m resolution was available: the SRTM2 DEM (NASA, 2005). This DEM can be used to calculate slope angle, as well as the flow direction of the water. The following data could be collected during a field visit to Bonaire:

A map of ecophysiographic units was made based on landform, geology, topography and land cover. General vegetation characteristics were determined (type, cover). These units are assumed homogenous and form the basis for creating other input maps that are needed.

Undisturbed soil samples were taken at representative sites. They were used to determine hydraulic conductivity, which to a large extent determines the amount of infiltration. Bulk samples were taken to determine nutrient content (N, P, see section 3.3). Soil texture and organic matter content were estimated in the field. These soil characteristics influence the erodibility of the soil.

It was attempted to obtain daily rainfall data, but only monthly and yearly data could be obtained. Data on discharge and sediment content of discharge were not available. Flow direction as observed in the field was compared with that determined based on a digital elevation model (especially if flow direction was man-made since this cannot be extracted from the DEM). Stone cover and vegetation cover were estimated.

The following modelling work was conducted:

- Predict runoff given estimated rainfall, on a daily basis.
- Predict erosion and sediment yield based on erodibility (which is derived from soil type, texture and hydraulic conductivity).

Data availability determines what exactly could be modelled, and what kind of model could be used. For example, the fact that no daily rainfall data were available limits the possibilities for runoff modelling, and the fact that no discharge data were available means that a runoff model can not be calibrated. Likewise, without data on sediment concentration, it is not possible to validate an erosion model.

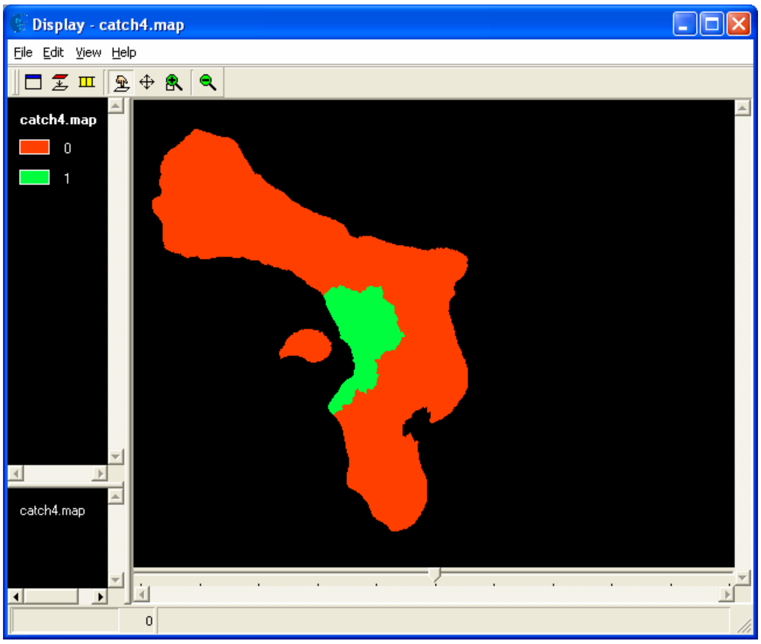


Figure 17 Study area (1= study area, 0=remainder of Bonaire)

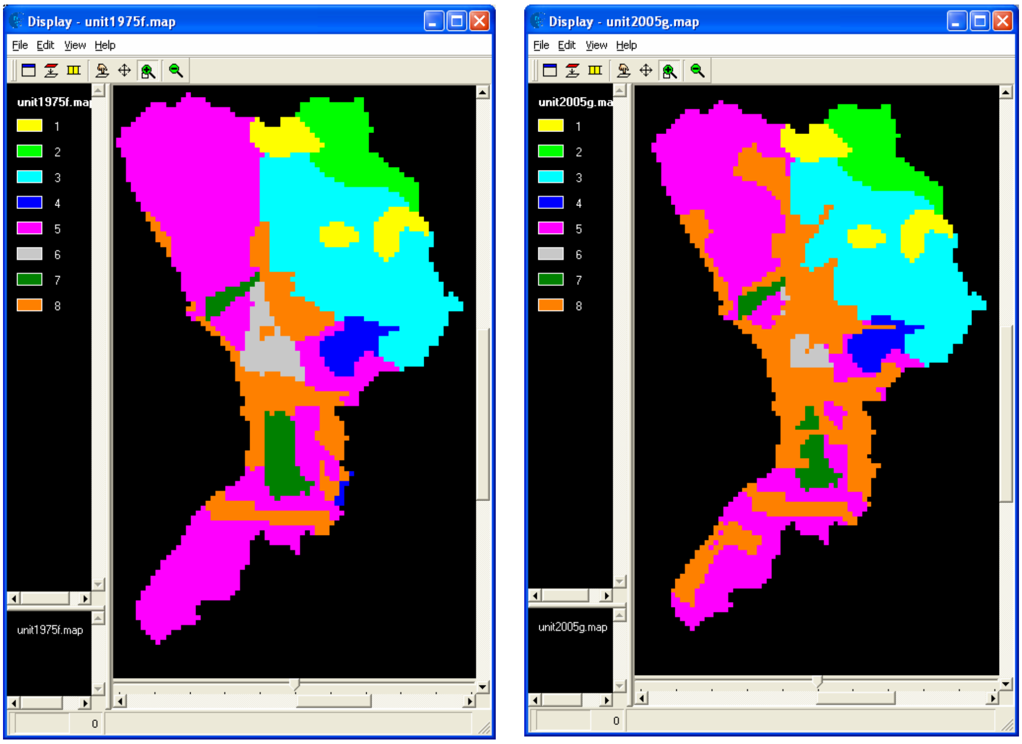


Figure 18 Ecophysiographic units in 1975 (left) and 2005 (right)

Simulations were done for 1975 and for 2005, to compare the current situation with the situation before sediment load and nutrient input to the sea became problems. These simulations were done for the coastal zone around Kralendijk, and for the inland areas that drain to this zone. Figure 17 shows the extent of the study area.

Figure 18 shows the ecophysiographic units for 1975 and 2005. The main difference between the two years is the extension of the urban area (unit 8).

Runoff

To model runoff on a daily basis, daily rainfall data are necessary. However, such data were not available, and therefore daily runoff prediction will be highly uncertain. Some data were available (Flamingo Airport 1971 – 2000) on the number of rainy days a month, and on monthly totals of rainfall (table 20). These data were used to create a rainfall file that matches these data. However, this is only possible to a limited extent since the monthly total could be reached in many different ways. For example if 50 mm has fallen in a certain month, and it has rained on 5 days during this month, it is possible that 10 mm fell on 5 different days, but it is also possible that 46 mm fell in a single day and 1 mm on each of the other 4 days (days with less than 1 mm of rainfall were excluded from the data). Considering the semi-arid nature of Bonaire, it seems likely that rainfall distribution between days will be uneven, and therefore daily rainfall values were assigned to take this into account. The data on maximum amount of rainfall in 24 hours (table 20) were used to make sure that no unrealistically high daily rainfall amounts were assigned. This resulted in the rainfall distribution shown in figure 19. Figure 19 shows that most events that were assumed were quite small, but that on some days, large amounts of rain were assumed to have fallen. The total number of days with rain in figure 19 is 67, and the total rainfall amounts for all months and for the complete year match the data given in table 20. The number of days with rainfall of more than 20 mm/d is estimated at 7 by this method (Figure 19). Data on daily rainfall for the period of 1960/2001 that became available in a later stage in this study indicate that the number of days with more than 20 mm/d is actually only 5, but that on an average 7 days have more than 15 mm/d of rainfall.

Table 20 Rainfall data from Flamingo Airport, 1971-2000

Month	monthly rain (mm)	rain days (days)	24h rain (mm)
January	44.4	9.2	38.1
February	18.3	4.4	25.5
March	13.2	2.5	46.9
April	13.2	1.8	27.8
May	14.8	1.7	81.2
June	14.4	2.8	67.6
July	36.3	5.6	175.8
August	35	4.4	53.3
September	37	5	43.2
October	67.3	7.6	85.5
November	95.9	11.5	108
December	73.6	10.8	78.4
Year	463.3	67.3	175.8

A simple runoff model was used in which it is assumed that rainfall events of less than 20 mm do not cause runoff, and that for rainfall events larger than this, a certain fraction of rainfall will become discharge. The initial 20 mm of rainfall accounts for storage of rainfall, e.g. through interception, in the topsoil and on the soil surface. The fraction above the threshold of 20 mm that does not become runoff takes care of infiltration, and varies with the measured hydraulic conductivity. When discharge was predicted in a certain map pixel it was routed to the sea, assuming that all discharge caused by a certain rainfall event will reach the Saliñas and the sea within one day. This was done using the map of flow direction that was made based on the DEM. This model was implemented in the computer programme PCRASTER.

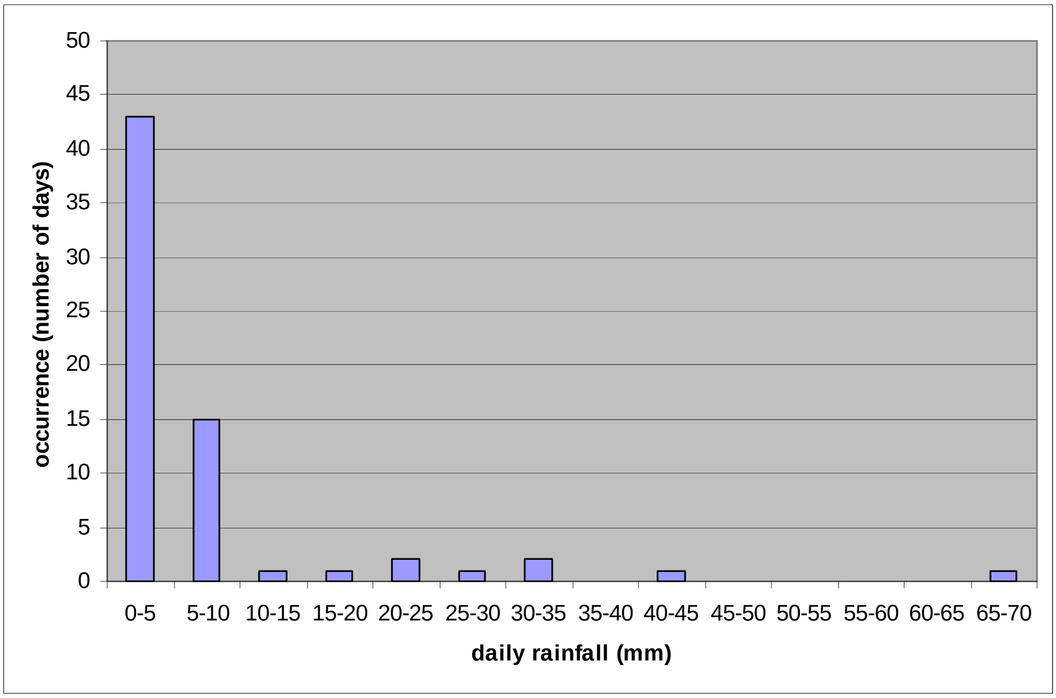


Figure 19 Assumed rainfall distribution

Erosion modelling with RUSLE

One of the most widely used erosion models is the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1997). RUSLE simulates yearly erosion, but does not simulate discharge, which is the reason that the method described above was used for discharge. Besides, RUSLE only gives yearly erosion values, not daily ones. RUSLE is a suitable model to predict erosion because the aim of the study is to simulate yearly sediment load (with associated nutrients) to the saliñas and the sea. The input of RUSLE consists of a number of parameters (R, K, LS, C and P) which are multiplied with each other. R is the rainfall erosivity, K the erodibility, LS the slope length and steepness, C a crop factor and P the management factor.

The resulting erosion should then be routed to the sea (and/or Saliñas), assuming a certain sediment delivery ratio. This ratio will be high close to the streams and low far from them. Similar to the discharge model, RUSLE was implemented in PCRASTER.

Rainfall erosivity, R

The R factor is a multiplication of rainfall energy and I30 (maximum 30 minute rainfall intensity) (Renard et al., 1997). To compute rainfall energy, several equations are available. Van Dijk et al. (2002) compared a number of these that had the same basic form, but different coefficients. They proposed to use the following equation:

$$Ek = 28.3 [1 – 0.52 \exp(-0.042R)]$$

Where R is rainfall intensity (mm/h) and Ek is rainfall energy per unit of rainfall (i.e. per mm). This equation shows that to calculate the R-factor from rainfall data, data on rainfall intensity are needed. Since these data were not available for Bonaire, R could not be calculated in this way. Therefore, a very simple method was used instead to reach an estimate of the R-factor. Table 21 lists some literature data on the R-factor.

Table 21. Some R-values from different sources

Location	R-factor ($MJ\ mm\ ha^{-1}\ h^{-1}$)	Yearly P (mm)	Source
Cape Verde	1517	196	Mannaerts & Gabriels, 2000
Kenyan Highlands	8500	1500	Angima et al., 2003
Central Texas	6000	810	Wang et al., 2003
Colombian Andes	7285	2900	Hoyos, 2005
Three Gorges, China	2880	1016	Shi et al., 2004
Continental USA	170-11914		Renard et al, 1997
Hawaii	1700-27232		Renard et al, 1997

As can be seen from table 21, the R-factor is quite variable. This is not surprising, as next to rainfall amount, the R-factor depends a lot on rainfall intensity. This means that, given the absence of data for Bonaire, it is difficult to come up with a good estimate of R-factor for Bonaire. The data from the first 5 studies were plotted and an equation was fitted. The data from Renard et al. (1997) could not be used, since no yearly rainfall data were available. It was found that the highest R^2 (0.73) was obtained with the following equation:

$$R = 62.989*P^{0.6206}$$

where R is the R-factor ($MJ\ mm\ ha^{-1}\ h^{-1}$) and P is yearly rainfall in mm. This equation allows us to estimate the R-factor from yearly rainfall amount. For Bonaire, with an average yearly rainfall amount of 463 mm (data Flamingo Airport, 1971-2000, see table 20), this equation gives a value for the R-factor of 2842.

Erodibility K

K can be determined from nomographs (p92 of Renard et al, 1997) if texture, OM, structure and permeability are known. More specifically, what is needed is % silt, % very fine sand, % sand, % OM, structure (very fine granular, fine granular, moderate/coarse granular, blocky/platy/massive), permeability (very slow, slow,

slow to mod, mod, mod to rapid, rapid). These parameters were estimated or measured, and the values that were used for the different units are given in table 22.

Slope length and steepness LS

LS is a combination of slope angle and slope length, both of which can be calculated from the DEM.

Table 22 Input data for RUSLE. Data needed to calculate the RUSLE input factors are given in Italics.

Code (section 3.2.3)	1 H	2 O	3 P	4 D	5 R	6 Z	7 S	8 U
R-factor								
R-factor	No data to calculate R, based on literature values elsewhere assumed 2842							
K-factor								
% silt	*35*	*35*	*35*	*35*	*40*	*35*	*30*	*35*
% very fine sand	*15*	*20*	*20*	*15*	*25*	*15*	*10*	*15*
% sand	*45*	*40*	*40*	*30*	*40*	*30*	*30*	*30*
% OM	*1.0*	*1.5*	*2.0*	*2.5*	*1.5*	*2.0*	*0.5*	*1.5*
Structure[a]	*2*	*2*	*3*	*3*	*2*	*4*	*4*	*3*
permeability[b]	*3*	*3*	*3*	*4*	*3*	*5*	*5*	*5*
K-factor	0.050	0.053	0.055	0.038	0.069	0.051	0.045	0.054
LS-factor								
LS-factor	Calculated from DEM, variable within units							
C-factor								
canopy cover (fraction)	*0.3*	*0.4*	*0.4*	*0.7*	*0.6*	*0.5*	*0.1*	*0.5*
plant height (ft)	*5*	*6*	*8*	*1*	*8*	*8*	*5*	*8*
surface cover (%)	*60*	*10*	*25*	*25*	*70*	*30*	*5*	*60*
b (estimate)	*0.04*	*0.04*	*0.04*	*0.04*	*0.04*	*0.04*	*0.04*	*0.04*
surface roughness (inch)	*1.5*	*0.5*	*1.0*	*1.2*	*1.5*	*1.0*	*0.5*	*0.5*
Moisture content (%)	*15*	*25*	*25*	*30*	*35*	*30*	*30*	*30*
residual moisture content (%)	*10*	*15*	*15*	*25*	*25*	*25*	*25*	*25*
saturated moisture content (%)	*45*	*50*	*50*	*52*	*50*	*52*	*50*	*50*
C-factor	0.006	0.129	0.058	0.015	0.011	0.030	0.131	0.014
P-factor								
P-factor	1	1	0.6/ 0.8[c]	0.6/ 0.8[c]	1	1	0.9	0.8
Nutrients								
Total-N (g/kg)	0.67	0.67	0.67	0.83	0.72	0.72	0.76	0.66
Total-P (mg/kg)	254	254	254	442	301	301	524	587

a 1: very fine granular, 2: fine granular, 3: moderate/coarse granular, 4: blocky/platy/massive

b 6: very slow, 5: slow, 4: slow to mod, 3: mod, 2: mod to rapid, 1: rapid

c 0.6 for 1975 and 0.8 for 2005 because tankis are currently less well maintained

The L factor was calculated according to Hickey (2000). This method calculates cumulative slope length by taking into account flow directions: for pixels without upstream area, the flow length is assumed half the pixel size, and for other pixels flow length for a certain pixel is either pixel size or 1.4 times pixel size (if the flow is in a diagonal direction). As recommended by Hickey, the cumulative slope length was reset to 0 to represent deposition, if the downstream slope angle was less than half the slope angle in the current pixel. S was calculated with the equations given by Renard et al. (1997).

Crop factor C
The C factor is calculated from 5 sub-factors, namely prior land use, canopy cover, surface cover, surface roughness and soil moisture. Renard et al. (1997) give equations to calculate values for these sub-factors from plant and soil data. Values for these plant and soil parameters were estimated in the field, and are given in table 22. Total C factor is also given in the table.

Management factor P
P depends on soil conservation measures. Tables exist that can be used to obtain values for P, if such measures are used in the area. On Bonaire, the main conservation measures are the tankis, which store part of the runoff. Since bad maintenance of the tankis has made them less efficient, a value for the P-factor of 0.8 is assumed for 2005, and a value of 0.6 for 1975. For units 7 (saliñas) and 8 (flat urban areas), the P factor was also assumed to be lower than 1, because in these units some barriers are present.

Nutrients
The RUSLE model was extended with a simple method to calculate loss of N and P. It was assumed that loss of N and P could be calculated by multiplying predicted soil loss with the concentration of these nutrients in the topsoil. Which concentrations were used is shown in table 22.

4.3.2 Results

Runoff
Figure 20 shows the simulated depth of runoff in mm per year for 1975 and 2005. Simulated runoff is largest in the urban zone and the Saliñas, which have a low permeability according to table 22. As can be seen from the figure, simulated runoff was larger for 2005 than for 1975. Total runoff from the study area was simulated to have been $1476.5 * 10^3$ m^3 in 1975, and $1669.9 * 10^3$ m^3 in 2005, an increase of 13%, which is mainly due to urbanization (table 23). Yearly runoff amounts of up to 90 mm are predicted, which is 19% of yearly rainfall. The average runoff from the study area was found to be 10.3% of rainfall in 1975 and 11.7% of rainfall in 2005. These values correspond well with the range of runoff given by Borst & de Haas (2005), who stated that about 10-20% of yearly rainfall becomes discharge.

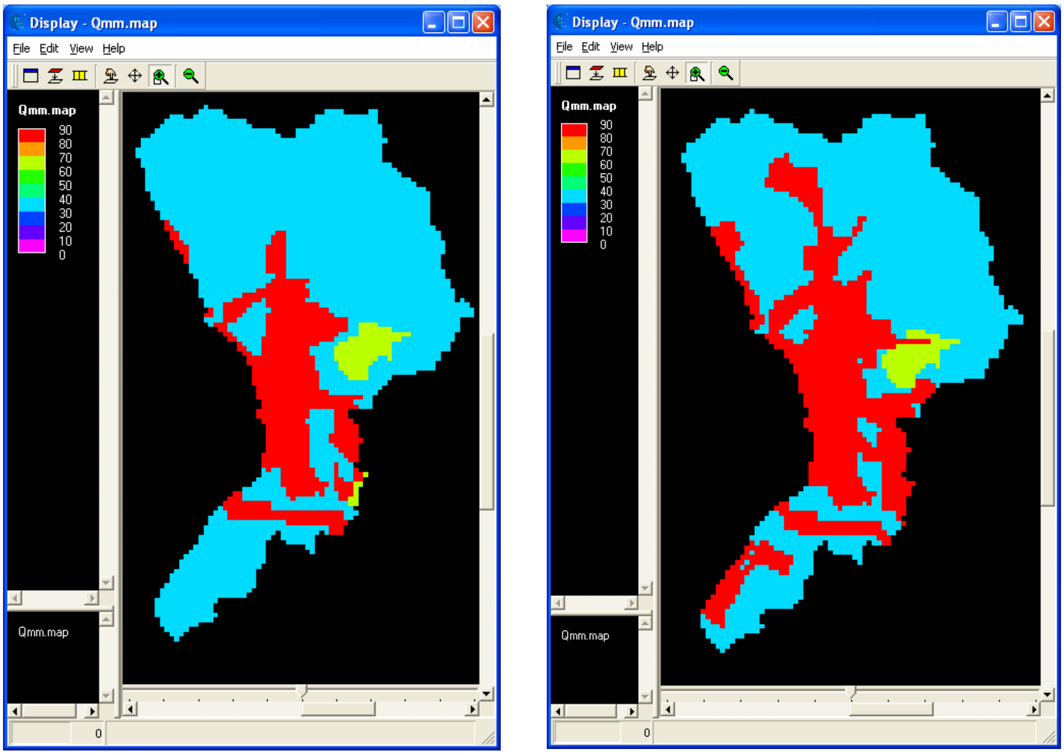


Figure 20 Depth of runoff (mm/year), 1975 (left) and 2005 (right)

Erosion

Figure 21 shows simulated yearly erosion. It shows that erosion mainly occurs on the hilly areas in the north of the study area. The difference between 1975 and 2005 is quite small, and is probably due to the lower efficiency that was assumed for tankis in 2005. Comparison of the maps in figure 21 shows that urbanization did not clearly affect erosion. There are two likely reasons for this. First, urbanization has mainly occurred on the flat areas, which have low erosion anyway. Second, where urban area has replaced other land uses on sloping land (as in the northern part of the study area), it has replaced land unit 5. Table 22 suggests that replacing land unit 5 with land unit 8 might well result in a decrease of erosion instead of an increase, since both K and P are lower for land unit 8. After applying a sediment delivery factor, which was 1 for streams and lower further from the streams, the soil loss for all individual pixels was routed to the saliñas and the sea, resulting in a predicted yearly sediment load of 3510 ton in 1975 and 3613 ton in 2005, an increase of 3% (table 23). This increase is probably due to the smaller effect of tankis that was assumed for 2005. The associated load of N and P was 2.43 and 1.01 ton respectively in 1975, and 2.48 and 1.08 ton in 2005. This represents an increase of N of 2%, and an increase of P of 7%. The increase is larger for P because the urban area, which has increased in size, has high values of P (table 22). About 63% of all sediment discharge to the saliñas and to the sea was found to occur in the northern Saliña, which is indeed known to receive large amounts of sediment during extreme rainfall, as in November 2004 (Borst & De Haas, 2005).

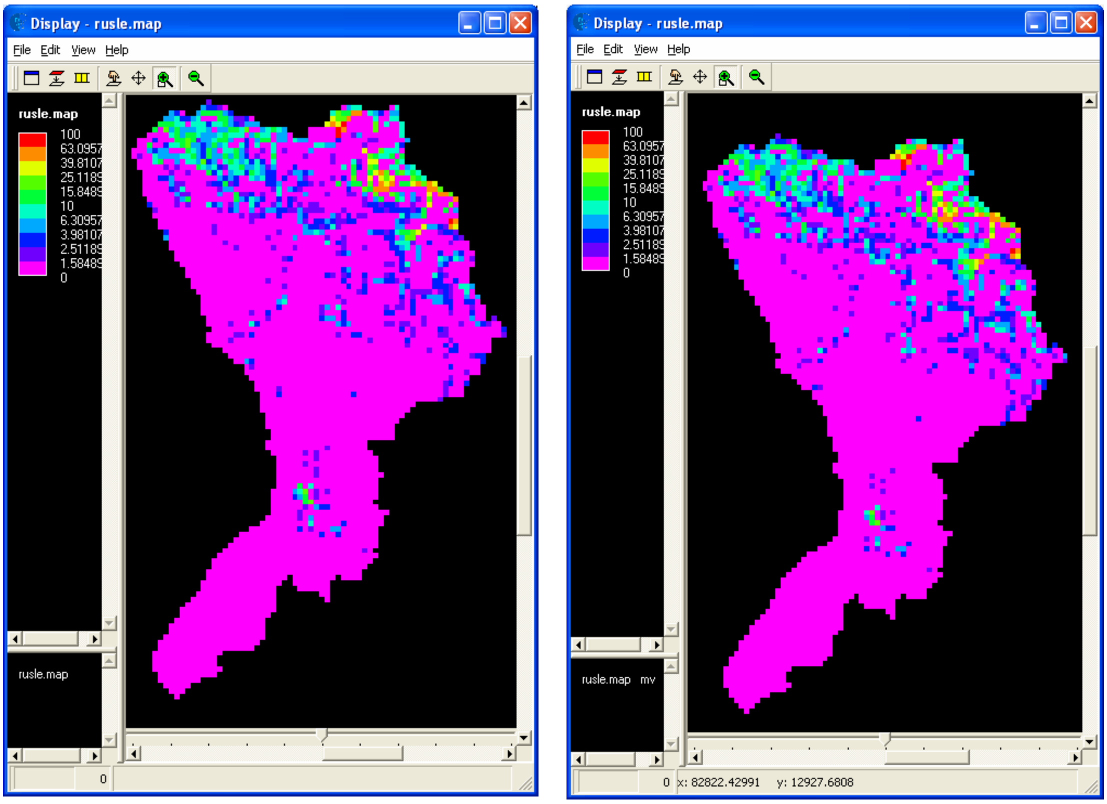


Figure 21 Yearly erosion simulated with RUSLE (t/ha), 1975 (left) and 2005 (right)

Effect of Saliñas

The model that was used simulated runoff, soil loss and nutrient transport to the saliñas, but did not simulate the effect of saliñas on runoff, soil loss and nutrient loss to the sea. To estimate this effect, it was assumed that the saliñas could contain a water depth of 0.5 m (average over the entire area of saliña). Multiplying this value with the surface area of the saliñas in 1975 and in 2005 gave values for the potential storage of water. It was assumed that the same fraction of soil and nutrients would be stored as was the case for water. This procedure allowed us to estimate how much water, sediment and nutrients would remain in the saliñas, and how much would reach the sea. Table 23 shows the results. It shows that the south saliña stores all water, sediment and nutrients that reach it, while the north saliña stores around 70-80%. Other outlets to the sea are not affected. The total discharge to the sea is therefore much smaller than would be case if there were no saliñas. Table 23 also shows that if storage in the saliñas is taken into account, the relative changes between 1975 and 2005 are much larger. The reason is that storage has remained the same, or has even decreased, while the input to the saliñas has increased (as discussed above).

Table 23. Storage in saliñas and discharge to the sea.

		1975			2005			change (%)	
		in	storage	out	in	storage	out	in	out
Water (10^3 m^3)	north saliña	628	484	145	713	507	206	13	42
	south saliña	564	564	0	609	609	0	8	0
	other outlets	285	0	285	348	0	348	22	22
	total	1477	1047	429	1670	1116	554	13	29
Soil Loss (t)	north saliña	2192	1688	504	2275	1618	657	4	30
	south saliña	396	396	0	438	438	0	11	0
	other outlets	923	0	923	899	0	899	-3	-3
	total	3510	2083	1427	3613	2056	1557	3	9
N (t)	north saliña	1.49	1.14	0.34	1.53	1.09	0.44	3	30
	south saliña	0.28	0.28	0.00	0.31	0.31	0.00	9	0
	other outlets	0.66	0.00	0.66	0.64	0.00	0.64	-3	-3
	total	2.43	1.42	1.01	2.48	1.40	1.09	2	8
P (t)	north saliña	0.59	0.45	0.14	0.63	0.45	0.18	8	35
	south saliña	0.15	0.15	0.00	0.15	0.15	0.00	6	0
	other outlets	0.28	0.00	0.28	0.30	0.00	0.30	5	5
	total	1.02	0.60	0.42	1.08	0.60	0.48	7	15

The simulations suggest that runoff has increased between 1975 and 2005 because of increased urbanization. Erosion has increased to a smaller extent, and P-load is simulated to have increased more than N-load. If storage in the saliñas is taken into account, the model results indicate that discharge, soil loss and nutrient loss to the sea have all increased significantly between 1975 and 2005. It should be realized that these results are tentative, since some input data were lacking and others could only be estimated roughly. A more thorough study would be needed to overcome this uncertainty.

4.4 The contribution of discharge of untreated sewage

Septic tanks and cesspits have a typical residence time for wastewater of a few days. The presence of organic material in the raw wastewater causes a slight reduction in the nutrient concentrations. International experience (Mels et al., 2005, Mulder, 2003) indicates a reduction of nitrogen concentration in the order of magnitude of 5 to 10% (Mgana, 2003). The subsoil in Bonaire consists of calcareous material and contains no organic matter. Through this subsoil leaching losses and septic tank discharges are conveyed towards the ocean.

Due to the mineral composition of the aquifer dominated by calcareous materials adsorption and precipitation of phosphorus can be expected. For nitrogen the situation is less favourable. The only way nitrogen can disappear from such a system is through denitrification with the dissolved organic material already contained in the leachate. This will certainly be not more than 5 to 10% of the total nitrogen lost to the groundwater system.

For the evaluation of alternatives it is therefore proposed here to assume a 10% reduction of N-loads for losses through septic tanks.

4.5 Present and future nutrient balances

Coral reef quality is mainly affected by nitrogen pollution. Phosphorus is adsorbed by the soil and will form precipitates during its journey through the groundwater system where calcium is present in large quantities. We will restrict therefore our analysis to the nitrogen discharge to the sea.

The hypothesis of our analysis was that the coral reef ecosystem could cope with the N-loads to the sea during the seventies. Therefore we drafted the land-based nitrogen discharge to the sea in the sensitive zone (Table 24). We took the population density and tourism intensity of 1970 (Table 1) and we assumed a 10% reduction of nitrogen in the septic tanks and cesspits. This is the septage assumed to be transported to the LVV area, where it is stored in cesspits. By adding the nitrogen in the erosion runoff to the sea, the total loading of 7.69 ton in 1970 could be estimated (Table 24).

In the present situation (2005), the population in the sensitive zone and the tourism intensity has increased (Table 1). The reduction of nutrient loads through the septic tanks has been assumed also at 10%. We neglected therefore the effect of the existing wastewater treatment plants in a few hotels. Use of the septic tank water in hotel gardens has a positive effect on the nitrogen balance. We assumed an average uptake by the crop of 62 kg/ha/yr, which is the weighted average of 8% gardens with grass cover and 92% gardens with bare soils or gravel. Denitrification and ammonia losses to the air have been taken from table 19. Based on these assumptions, the total N-load to the sea from the sensitive zone has almost doubled since 1970 to 14.78 ton/yr (Table 24).

Implementation of the sewerage plan according to the design of Dorsch Consult including reuse of wastewater in hotel gardens and in agriculture has been evaluated for 2017. The population density and tourism intensity for 2017 have been taken from Table 1. We assumed all tourist resorts to be connected to the sewerage system and for the residential population in the sensitive zone we assumed 70% connected. All collected sewage water (17.12 ton/yr N) is exported from the sensitive zone to the wastewater treatment plant (Table 24). Purified sewage water with an estimated N concentration of 28 mg/l for irrigation of hotel gardens is imported again. The net export of nitrogen from the sensitive zone by the sewerage plans is therefore about 13 ton/yr (Table 24). For the unconnected residential population the septic tank nitrogen removal of 10% has been applied. Nitrogen uptake by the hotel gardens is more than in 2005, because the area increases. For losses to the air we only accounted denitrification, because the purified water has been aerated and will contain only limited ammonia. Adding all these balances together results in an N-load to the sea in 2017 of 7.22 ton/yr, about 5% below the estimated N-load of 1970 (Table 24).

Table 24 Nitrogen balance (ton/yr) for the sensitive zone

	Sensitive zone			Alternative 2017
	1970	2005	2017	
N-production tourists (t)	0.37	6.61	10.11	10.11
N-production connected residents (t)			7.02	7.02
N-export to WWTP (t)			-17.12	-17.12
N-import from WWTP (t)			3.12	0.00
N-production unconnected residents (t)	7.05	9.47	3.01	3.01
Purification septage (10%)	-0.74	-1.61	-0.30	-0.30
Crop uptake hotel gardens (t)		-0.46	-0.60	0.00
Losses to air hotel gardens (t)		-0.32	-0.07	0.00
Erosion (t)	1.01	1.09	1.09	1.09
Discharge to Sea (t)	7.69	14.78	7.22	3.80
Hotel garden (ha)		7.19	9.43	9.43
Water use hotel gardens (m^3/ha/yr)			15,483	
Crop uptake gardens (kg/ha)		62		
Denitrification (kg/ha)		7		
Ammonia volatilization (kg/ha)		38		

We can therefore conclude that the existing sewerage plan for Bonaire apparently, according to our estimates, is sufficient to reduce the N-loads to the sea in the sensitive zone sufficiently to improve the coral reef ecosystem quality. We can also conclude, however, that in the proposed plans large leaching losses of 2.45 ton/yr N from the hotel gardens directly to the sea would occur. We therefore included an alternative for the irrigation of gardens and agriculture in our analyses.

The total gross water consumption of tourist resorts has been reported at 500 l/c/d. About 290 l/c/d was assumed to be directly guest related and 210 l/c/d for filling of swimming pools, beach showers, laundry, kitchen departments, irrigation etc. The 290 l/c/d assumed to be directly guest related will involve the use of showers and the use of water for toilet flushing. If hotels would use the grey water from kitchens, laundry departments and showers directly for irrigation, only the black water (and the excess grey water) would need to be delivered to the WWTP. The purified sewage water could then be used exclusively in agriculture near the LVV premises. Whether this excess water is sufficient for garden irrigation depends on the ratio between hotel guests and gardens and needs further study, which is beyond the scope of the present assignment.

Using the same assumptions as before we can see that the effect of irrigating the hotel gardens with grey and tap water and using all treated sewage water in agriculture could reduce the N-load from the sensitive zone with about 50% (compared to 1970) till 3.80 ton/yr (Table 24).

Since there is some confusion on the amount of septage that is transported to the LVV area (10% has been assumed in the present analysis), an alternative calculation has been performed assuming 40% of the septage to be transported to LVV. The resulting nitrogen loads to the sea from the sensitive zone changes into 5.46 ton/yr in 1970; 9.95 ton/yr in 2005; 6.31 ton/yr in 2017 with the present sewerage plans for Bonaire and 2.89 ton/yr if the effluent would be used in horticulture.

We should keep in mind that nitrogen lost to the groundwater system outside the sensitive zone will eventually reach the sea. No denitrification losses in the calcareous subsoil can be expected. We do not know whether the transport route of groundwater will end up close to the sensitive zone or far away from it. Because of all this uncertainty, we decided also to draft also the land-based nitrogen balance for the complete island of Bonaire (Table 25).

For the Bonaire nitrogen balance we used the same assumptions and data as for the balance of the sensitive zone. Only for the discharge by erosion we simply assumed this balance term 5 times larger that that for the sensitive zone. According to this assessment (Table 25) the N-load to the sea in 1970 was 34.29 ton/yr. Similarly for the present situation (2005) the estimated total N-load from Bonaire to the sea increased with almost 50% to 50.03 ton/yr in 2005 (Table 25).

Table 25 Nitrogen balance (ton/yr) for Bonaire Island

	Bonaire			Alternative
	1970	2005	2017	2017
N-production tourists (t)	0.37	7.29	10.11	10.11
N-production connected residents (t)			7.02	7.02
N-removal WWTP (t)			-8.76	-8.76
N-discharge WWTP (t)			8.37	8.37
N-production unconnected residents (t)	32.12	43.12	38.97	38.97
Purification septage (10%)	-3.25	-5.04	-3.90	-3.90
Crop uptake hotel gardens (t)		-0.46	-0.60	0.00
Losses to air hotel gardens (t)		-0.32	-0.07	0.00
Crop uptake agriculture (t)			-4.03	-7.69
Losses to air agriculture (t)			-0.11	-0.21
Erosion (t)	5.05	5.45	5.45	5.45
Discharge to Sea (t)	34.29	50.03	44.07	40.99
Hotel garden (ha)		7.19	9.43	0
Agriculture (ha)			16.00	30.50
Crop uptake gardens (kg/ha)		62		
Denitrification (kg/ha)		7		
Ammonia volatilization (kg/ha)		38		
Crop uptake agriculture (kg/ha)			252	

For the situation in 2017 with implementation of the sewerage plan for Bonaire we can subtract the nitrogen removal by the WWTP. We assumed a WWTP effluent nitrogen concentration of 28 mg/l. The resulting removal rate of nitrogen by the WWTP would then be about 50% (Table 25). The difference with the expected performance (70%) can then account for the additional nitrogen transported to the WWTP in the form of septage sludge. In the balance we have now to take care also of the nitrogen uptake and losses by agriculture. An average area of 16 ha can be grown with vegetables near the LVV area, using the available storage reservoirs. The nitrogen crop uptake of this 16 ha has been accounted as well as the denitrification for losses to the air (Table 25). The resulting estimated N-load to the sea in 2017 would reduce with about 12% to 44 ton/yr, compared to the present (2005) situation (Table 25).

Also the effect of our alternative (irrigating hotel gardens by grey water and using the treated sewage in agriculture) on the land based N-balance of Bonaire has been estimated. We repeated the analysis of crop and reservoir optimization as described in chapter 4.2.1., but now with the total produced treated sewage water available for agriculture. This resulted in a cropped area varying from 50 ha during the rainy winter period to 20 ha during the dry periods immediately preceding the rainy season. The average area that could be grown with vegetables was estimated at 30.5 ha. The N-load to the sea of this alternative would be reduced with another 7% to 41 ton/yr (Table 25).

4.6 Evaluation of the proposed water quality norms

Dorsch (2005) proposes water quality norms for BOD5 of 50 mg/l, COD of 125 mg/l, Ptot of 5 mg/l, Ntot of 28 mg/l and bacteria of 1000 MPN/100 ml (Table 26). The proposed norm for BOD5 is in agreement with the World Bank and is slightly higher than the LBS protocol indicates. The treated sewage water is not directly discharged to the sea, but used in irrigation. It is expected that in the soil the BOD will be oxidized largely due to microbiological activities in the soil. The proposed norm for COD is below the World Bank guideline and the TSS performance is far below the LBS protocol guideline (Table 26).

Table 26 Guidelines for unrestricted irrigation

Parameter	Unit	Dorsch (2005)	WHO (1989)	WB (1994)	LBS[1] (1999)
BOD	(mg/l)	50		50	30
COD	(mg/l)	125		150	
TSS	(mg/l)	5			30
Ntot	(mg/l)	28			
Ptot	(mg/l)	5			
Bacteria	(MPN/100ml)	1000	1000		200

[1] The LBS protocol guidelines are not for irrigation, but for discharge into sensitive waters (Class I)

For nitrogen and phosphorus no guidelines are given by WHO, World Bank and the LBS protocol. The LBS protocol stipulates, however, that all sewage water should be treated according to best practicable practices and reuse of its effluent to be encouraged and promoted. In the previous chapters an analysis has been made of the nutrient uptake capacity of hotel gardens and horticultural crops. When carefully irrigated, minimizing the leaching, about 15,500 m^3 of water for hotel gardens and 12,500 m^3 for horticulture is required. This results in safe norms for nitrogen of 5 mg/l N for hotel gardens and 25 mg/l for horticulture. For phosphorus the safe norms are 0.7 mg/l P for hotel gardens and 2.6 mg/l P for horticulture. Under Bonaire conditions, however, with abundant calcium in the subsoil, excess phosphorus will be adsorbed and precipitate in the subsoil.

The norms proposed by Dorsch for bacteria are in line with the WHO guidelines of 1989. The LBS protocol has a stricter norm of 200 MPN/100ml, but that norm accounts for direct discharge to the sea. Because the wastewater effluent is used for irrigation, nearly all bacteria are expected to be retained in the soil.

5 Conclusions and recommendations

The norms for wastewater effluent proposed by Dorsch consult have been evaluated for suitability for irrigation of hotel gardens and for agriculture. The proposed phosphorus concentrations exceed the crop uptake for both hotel gardens and agriculture. This is not considered as a major problem because P-adsorption and precipitation with calcium in the calcareous subsoil and aquifer is expected to reduce the concentrations. The proposed nitrogen norm of 28 mg/l will cause serious problems in hotel garden irrigation due to the limited nitrogen uptake by the crops. On average 433 kg/ha/yr nitrogen (15,480 m^3 with 28 mg/l N) would be supplied to hotel gardens, while the crop nitrogen uptake is estimated at 64 kg/ha/yr and the losses to the air of about 7 kg/ha/yr, leaving 362 kg/ha/yr for leaching.

To satisfy the crop uptake and the unavoidable nitrogen losses the nitrogen norm should be about 5.1 mg/l N. Total nitrogen input would then be about 79 kg/ha/yr N. About 80% would be for crop uptake, about 10% for denitrification and about 10% for leaching. These conclusions are subject to a more detailed analysis using daily rainfall data. Most probably unavoidable leaching will be higher due to the occurrence of heavy rainfall showers.

The treated effluent water is better used for agriculture, but also here the nitrogen supplied with the irrigation water exceeds the crop needs. To avoid unnecessary leaching, drip irrigation systems are therefore recommended. In total 309 kg/ha/yr (11,020 m3 with concentration of 28 mg/l) nitrogen would be supplied to drip irrigated vegetables, while the crop nitrogen uptake is estimated at 252 kg/ha/yr and the losses to the air about 7 kg/ha/y, leaving 50 kg/ha/yr for leaching. Crop water management is recommended in such a way that a soil moisture deficit of 20 mm is maintained. If this is implemented, only rainfall showers exceeding 20 mm will cause leaching.

To satisfy the crop uptake and the unavoidable nitrogen losses the nitrogen norm should be about 26 mg/l N. Total nitrogen input would then be about 286 kg/ha/yr N. About 90% would be for crop uptake, about 2% for denitrification and about 8% for leaching. These conclusions are subject to a more detailed analysis using daily rainfall data. Most probably unavoidable leaching will be higher due to the occurrence of heavy rainfall showers.

Most probably the effluent of the proposed treatment plant will have nitrogen concentrations lower than the proposed norm of 28 mg/l. Literature indicates that the process configuration proposed by Dorsch is capable of removing up to 75% of nitrogen when operated properly. Examining the average nitrogen loads to the proposed WWTP and comparing to the effluent norm of 28 mg/l results in a nitrogen efficiency removal of 50% only. This means that there is a safety factor included in the design and most probably the nitrogen concentrations in the effluent will be somewhat lower.

In the undisturbed situation in 1970, when the coral reefs were still in a healthy condition, the total N-load from the sensitive zone is estimated in this study at about 7.7 ton/y. For the present, polluted, situation this nitrogen load has increased with 90% to about 14.8 ton. The major increase is caused by the tourism sector (6 ton) and by the residential sector (2 ton). Implementation of the Dorsch sewerage plans improves the situation considerably and results in a reduction of the N-load with 50% till about 7.2 ton/yr. This is slightly below the 'pristine' situation of 1970.

Because irrigation of the hotel gardens with purified sewage water is not recommended, it is recommended to investigate the possibility for hotel owners to use the grey water from showers, kitchens and laundry departments for irrigating the gardens. This could be topped up with tap water if necessary. In this way the purified sewage water could be used completely in agriculture. Instead of 16 ha of vegetables on average in the original plans, 30 ha of agriculture could be grown on average. The savings in nitrogen discharge to the sea would be considerable: the total N-discharge to the sea would reduce till 3.8 ton/y, a 50% reduction of the 1970 load.

Because nitrogen losses to the groundwater system in the remaining part of the Bonaire island (in the non-sensitive part) will eventually also find its way to the sea, also the balance for the complete island has been drafted. In 1970 the total N-discharge to the sea is estimated in this study at 34 ton/y. In the year 2005, this has increased with about 45% until 50 ton/y. Until the year 2017, with the plan Dorsch implemented the N-discharge to the sea stabilizes or reduces slightly with 3%. On the long term therefore there may be more efforts required to further reduce nitrogen loads to the sea. A reduction of the N-load to the sea with the alternative plan to use all treated sewage water for agriculture of 10% to 44.6 ton/y was estimated.

In this study we assumed the removal of septic sludge from the unconnected residents to be transported to the WWTP. We assumed that only about 10% of the nitrogen load would be removed this way from the septic tanks. In the final design (Dorsch 2005) it is not clear how much septage is assumed to be collected for transport to the WWTP. It is not recommended to remove septage sludge too frequently, because also the anaerobic stabilization capacity is also removed in that case.

In the design of the WWTP is further stated that the septage sludge is diverted towards the wastewater reactors if the sludge is very watery. If it is already dry it would be diverted directly to the sludge drying beds. This latter option is considered the better solution, but as a precaution for pollution of the groundwater below the sludge drying beds, it is recommended to construct a drainage system below the sludge drying beds, The drainage effluent can than be diverted to the WWTP for subsequent treatment.

If the treated sewage water is to be used for hotel garden irrigation, it is recommended to consider an additional denitrification step in the process design for the WWTP. This could possibly be done by constructing an autotrophic denitrification step (Anammox) in the last cycle of the SBR reactor. For use in horticulture the effluent concentration of 28 mg/l is acceptable on the condition that irrigation is done very carefully using drip or bubbler systems to avoid unnecessary leaching.

The model study performed to evaluate the risks of erosion hazards to the sea indicates that the erosion contribution is small compared to the other pollution sources. The model study however is indicative only, because it is based on model parameters taken from the literature and limited field data.

A few samples taken from the seawater in the sensitive zone indicated elevated nitrogen concentrations, compared to the samples taken at the other side of the island.

Nutrient accumulation in the hotel garden soils could not be established for nitrogen despite the high rates of nitrogen application with sewage water in the hotel gardens. This is most probably caused by the fact that nitrogen is quite mobile in the soil and leaches easily when excess water is applied. Just before sampling in November an intensive rainfall event took place. For phosphorus, accumulation was measured, but due to the high variations between different sampled locations, the accumulation was not statistically significant.

Nitrogen soil water concentrations were not measured directly, but derived from the 1:2 dilutions measured in the laboratory. Nitrogen soil water concentrations showed an increasing range: inland lowest; saliñas second, agriculture third and hotel gardens highest. Due to the variations between the different sampled locations, the differences were not statistically significant.

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PROJECT

Sewerage & Sanitation System Bonaire

(SSSB)

Terms of Reference

for a

Critical Review of the proposed

Effluent and Irrigation Standards

CONSULTING SERVICES for a Critical Review of the proposed Effluent and Irrigation Standards during the Detailed Technical Design (DTD) phase of the project Sewerage & Sanitation System Bonaire (SSSB).

TERMS OF REFERENCE

1. Introduction

1.1 General

Bonaire, one of five islands of the Netherlands Antilles is approximately 288 km² and has a population of about 10,100 inhabitants. The Capital Kralendijk and its direct surroundings account for 75% of the population.

The economy of the island is mainly dependent on tourism and tourism is therefore its main economic pillar. Because of Bonaire's attractive natural marine environment with its protected coral reefs, especially dive tourism is attracted. Protection of the environment is therefore of utmost importance for the island's economic development.

At present, wastewater disposal is causing pollution and poses a serious threat to Bonaire's marine life and seawater quality. Bonaire has no central sewage collection and treatment system, therefore nutrients diluted in the sewage find their way into the sea and provides algae growth, which causes serious damage to the reef. During the last decade it could be observed that the quality of Bonaire's coral reef is declining. Live coral cover has been decreased, and algae growth increased. Recent studies concluded that the quality of the reef is deteriorating also as a result of the inflow of surface water and untreated sewage.

Intervention has therefore become necessary as irreparable damage could result to this ecosystem thus also jeopardizing Bonaire's economic development.

Therefore the Government of the Netherlands Antilles has requested the European Commission to assist the Authorities of the island of Bonaire with financing the implementation of a central sewage collection and treatment system, whereby the effluent will be used for landscaping and irrigation purposes at hotel premises and for crops growing a the Island Service of Agriculture, Cattle Breeding and Fisheries (LVV).

A feasibility study (see par. 3.1 below) carried out in 2002/2003 by Dorsch Consult mbH has proposed certain effluent and irrigation standards. The feasibility study was approved by the Territorial Authorizing Officer (TAO), subject to a critical review of these standards in the DTD phase. This ToR provides the basis to undertake a study (to review the effluent and irrigation standards to be implemented with special reference to the norm of 40 kg N /ha/year proposed for the sensitive zone and concentration level of 28 mgN/l) in addition to the critical review as provided for in the service contract for the TA-DTD/SSSB. This service contract is now being executed by Dorsch Consult mbH.

The Consultant[1)] shall perform all the services described in this ToR in close co-operation with the locally established representatives of the TAO, called Steering Group Sewerage Kralendijk (SRK). It has been attempted to outline the Consultant's tasks during execution of his services as detailed as possible. However, the Consultant shall bear in mind that the list of tasks and activities can by no means be considered as the complete and comprehensive description of the Consultant's duties. It is rather the Consultant's responsibility to critically verify the scope of services indicated and to extend, reduce or amend it in consultation with the SRK wherever it deems such necessary according to his own professional judgment and the knowledge he will acquire during preparation of this proposal. It is understood that the Consultant performs all work as necessary to fulfil the objectives of the Project.

During the Consultant's assignment other institutions, consultants and advisors may provide services to the SRK and/or other local authorities in the project area. It is the duty of the Consultant to meet and co-ordinate his activities with the operations of others relevant to the Project. It is to be ensured that the 'newly' proposed standards, systems, methods, etc. are compatible as much as possible and duplication of efforts is avoided.

2. Objectives

2.1. Main objectives of the project Sewerage & Sanitation System Bonaire

The objective of the project is to contribute towards installing a **sustained** centralized sewer system and wastewater treatment plant, upgrading the existing storm water network for downtown Kralendijk and establishing modern standards of sewage treatment on the island of Bonaire in order to protect the marine environment and improve public health. It will be important to dispose off the collected and treated sewage in an ecologically and economically safe and reliable manner, so as to prevent any harmful effects, which such disposal might have on the environment. Especially nutrients originating from wastewater are regarded as the main reason for the on-going reef decline. The storm water runoff and the discharged sediments, which include nutrients and other pollutants, are also a hazard to the coral reefs. Therefore the project includes sedimentation tanks to hold back sediments and floating matters to retain the run off water for a while.

Within the SSSB the following main objectives have been established for the provision of sustained wastewater and storm water services:

- to gradually install wastewater collection facilities in high population density areas near coastal zones and in sensible areas at the coast;
- to install wastewater collection facilities in the harbours and at the piers where ships can dispose off their wastewater;
- to increase the wastewater treatment capacity commensurate with increasing flows;
- to provide and maintain established requirements on effluent quality;

1) Consultant can be a University or Expert Institution

- to enable effluent reuse for irrigation purposes;
- to have a financial and ecological sustainable sewage system;
- to prevent the downtown Kralendijk from floods after heavy storms;
- to upgrade and to expand the existing storm water network in downtown Kralendijk.

Furthermore by execution of the abovementioned works modern standards of handling sewage water and sewage treatment will be established, which will result in a protection of the marine environment, the aquatic ecosystem and the groundwater resources, while the health risks for the population will be reduced.

2.2. Main objectives of the study of the Effluent and Irrigation Standards.

The overall objective of the study to be undertaken is to provide a sound scientific foundation of standards for the use of effluent for irrigation purposes, taking into special consideration the local circumstances and conditions (including climate and soil characteristics) of the "Sensitive Zone" of Bonaire as defined in the Master Plan 2002, while complying with the ultimate goal of the SSSB, the protection of the marine environment and public health.

Part of the study is to investigate those technical parameters that are specific to Bonaire's climate, soil, vegetation and geological conditions, especially within the so called "Sensitive Zone" and that are crucial to review the standards proposed in the feasibility study or otherwise to develop 'new' technical standards for the effluent and irrigation purposes.

3. Background

3.1. General background of the SSSB project

3.1.1 Overall information

Besides tourism, oil-transhipment, salt production and small industries and the public sector (services, construction, agriculture and fisheries), contribute to a minor extent to Bonaire's economy and provide for opportunities.

The Government of Bonaire aims at an independent economic development of the islands and therefore is implementing a policy directed towards consolidation and further extension of the (dive) tourism sector. In this policy high priority is put on the conservation of the natural and living environment in general and on the preservation and protection of the marine biological habitat in particular. Furthermore this policy is geared towards a tourism product with a high added value, and in-built safeguards for the quality of life of its inhabitants and visitors, by improving its physical and legal infrastructure in the area of environmental management and protection, especially regarding solid and liquid waste management.

In this context the implementation of a sewerage network provided with treatment plant(s) in the island has become necessary in order to preserve the natural heritage consisting of the delicate marine habitat surrounding Bonaire. The latter is also an important factor for the present and future economic development of the island.

3.1.2 <u>Location and Population</u>

Bonaire is located in the south-eastern Caribbean Sea. The access to Bonaire is limited to air and sea transport.

The study area comprises the coastal areas of Kralendijk and surroundings. The island is an arid region with scarce water resources and high evaporation.

Current total population in the project area is about 10,100 inhabitants, about 2,200 shall be connected to the new system. Around 1,800 daily tourists accommodated in the great seaside hotels shall be connected to the system, too.

Population growth on Bonaire is low and up to the year 2017 it is expected that the population on the island will be about 11,500.

Unemployment rates are high and industrial activities exist only on a rudimentary base. The main employers are the tourist and the public sector.

For the purposes of sewage collection, Bonaire has been divided into two main drainage areas (Kralendijk and surroundings and Rincon) according to the relevant Master Plan. The Project Area for the first phase covers the coastal area in the populated areas of Kralendijk where most of the hotels are located.

3.1.3 Existing Water and Sanitation Services

Practically, the whole population of Bonaire is connected to water distribution networks. The average water quantity billed is about 130 l/c/d. Water quality is good due to sophisticated treatment process (seawater desalination, reverse osmosis).

Sanitation systems are restricted to septic tanks, cesspits and a few treatment units at selected hotels. Sewage services urgently need improvement. Pollution of water and soil resources through sewage infiltration represents a potential hazard for the health of the population and impairs the marine environment.

3.1.4 Institutional Set-up

WEB (Water & Electricity Corporation Bonaire) is a state-owned (government of Bonaire) enterprise responsible for production and distribution of water and electricity on the island.

The Island Government will be the future owner of all sewage disposal assets on Bonaire. The Island Government has established a Project Organization consisting of a Project Manager, a Steering Group Sewerage Kralendijk (SRK), workgroups and a Soundboard group consisting of the concerned administrations, non-governmental organizations (NGO's) and other stakeholders in order to facilitate a smooth flow of information, overall co-ordination and the necessary support for the SSSB. The SRK is consultative and advising body for the Island Government, the Contracting Authority (C.A.), his Supervisor and the Supervisor's representative. All communications with groups/stakeholders on Bonaire go via SRK where necessary with the consent of the Supervisor.

3.1.5 State of Preparation/Available Documentation

The following studies are related to this project:

- A Master plan, preparatory studies for Bonaire sewage system on the Netherlands Antilles, by Dorsch Consult (2002)
- A Feasibility study, sewerage and sanitation system for Bonaire island, by Dorsch Consult (2002/2003) [1)]
- Pre-Feasibility Study Sewage Kralendijk Bonaire by Vos-Visser-Noppeney (January 1999)
- Draft project document "Riolering Kralendijk Bonaire', C.E.C., February 1996 and March 1995
- Report on the status of Bonaire's Coral Reefs, C.M. Roberts and J.P. Hawkins, Eastern Caribbean Center, Univ. of .I., St. Thomas, 1994
- Environmental Assessment, impacts of current waste water disposal practices and construction practices on the Fringe Reef System of Bonaire, Dutch Antilles, Robert J. Goldstein & Ass., Inc., 1993
- Rapport Integrale Sociaal-Economische aanpak Bonaire, Commissie Pourier, 1992
- Milieustructuurplan Riolering Bonaire, CEC, 1991
- Afvalwater Kralendijk, Ascon N.V., 1990
- Environmental assessment end environment development plan Bonaire 1988
- Project Cycle Management published by European Commission (February 1993)

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1) The Feasibility Study is approved subject to a critical review and verification. The matters to be reviewed and verified have been incorporated in this ToR. in paragraphs 4. Scope of Services, the most important of which being the proposed effluent and irrigation standards and the proposed uptake rate of nutrients. An exhaustive review thereof is warranted.

3.2 Background of this study

3.2.1 <u>Nutrient and pollutant levels in coastal waters</u>

Recent scientific investigations indicate that increased nutrient levels in the coastal waters is one of the damaging factors to the marine environment. The most probable way on Bonaire how wastewater constituents reaches the sea is when wastewater from the island trickles through the porous limestone underground and enters the ocean below sea level, besides some illegal discharges. Also drainage water from cesspits, leach holes, sewage irrigation/landscaping in residential and hotel gardens bordering the sea is running off directly into the sea. As this wastewater contains a high amount of nutrients and other pollutants it is deemed to contribute to the damage of the coral reefs.

It is the general opinion that nutrients and other wastewater related pollutants generally reduce the vitality of the stone coral and diseases like the coral bleaching are increasing. The observation of strengthened algae growth is a strong indication of increasing nutrient levels. Other sources of nutrient pollution are the storm water outfalls along the coast and the outlet of the saliñas.

The upper 10-meter of the reef has massively been damaged by the Hurricane “Lenny” in November 1999. The re-colonization of stone corals in this area is much slower than it should be. It is well known, that the reproduction ability and the re-colonization of deserted reef areas is heavily impaired by nutrients.

3.2.2 Wastewater

Sewage production in the Project Area (coastal zone near Kralendijk, target year 2017) is around 800 m^3/d with a BOD_5 load of 320 kg/d. These amounts should be gathered and treated at a central treatment plant.

The sewage of the remaining population of the island is nowadays still collected in cesspits or septic tanks, from where it infiltrates under ground. Due to the scarcity of water and the high drinking water prices a big portion of the untreated wastewater is actually used for garden irrigation.

Faecal sludge partly collected from septic tanks will be treated by the planned waste treatment plant in future.

3.2.3 Parties Involved in this study

The following institutions are in one or the other way involved in this study:

<u>At Central Government level</u>:

- TAO: Territorial Authorizing Officer (Contracting Authority (C.A.), represented by his Supervisor –Deputy TAO- and Project Officer)
- DevCo: Dept. for Development Cooperation
- VSO: Ministry of Public Health and Social Development

At Island Government level:

- ExCo: The Executive Council/Government of Bonaire
- SRK: Project Steering Group Sewerage Bonaire
- DROB: Dept. of Physical Planning and Management, Bonaire
- LVV: Dept. of Agriculture and Fisheries, Bonaire
- Selibon: Garbage Collection Company of Bonaire
- WEB: Water and Power Company of Bonaire
- DGH: Dept. of Hygiene, Bonaire
- DOW-CUR Department of Public Works, Curaçao
- P.M. Project Manager

Other Stakeholders:

- EC AIDCO, B-1049, Brussels, Belgium

  Delegation in Guyana

Also are involved in the working group Nutrients:

- ALIANSA: Nature Alliance, Bonaire
- BONHATA: Bonaire Hotel Association
- BHG Bonaire Hospitality Group
- STINAPA: Foundation Natural Parks, Bonaire

4. Scope of Services

The study area is the sensitive zone that is the strip of 500 m wide running from Hato to Punt Vierkant as defined in the Master plan 2002.

The consulting services for this study comprise, but not necessarily are limited to the performance of the following main tasks:

- Critical review of irrigation and effluent standards regarding nutrients to be applied to the irrigation area where effluent is planned to be delivered (namely the sensitive zone of 500m and LVV) with special reference to the norm of 40 kg N/ha/year as proposed in the Masterplan and Feasibility Study. Proposed effluent standards are:

● Biochemical Oxygen Demand	50 mg/l
● Chemical Oxygen Demand	125 mg/l
● Suspended Solids	5 mg/l
● Bacteria (E. Coli)	1,000FC/100 ml (1,000MPN/100 ml)
● Nitrogen	28 mg/l
● Phosphate	5 mg/l

- Critical review of the irrigation needs, maximum uptake rate of nutrients for specific the vegetation and climate conditions in the study area. The load of dead and rotten vegetation has also to be taken in consideration.

- Collection of sufficient soil (for an approximate estimated area of 30 Ha. at least 70 samples should be taken) and groundwater samples at relevant and representative/characteristic spots in the sensitive zone, including the saliñas and laboratory analysis to determine but not limited to:

  - ♦ Soil type and soil texture;
  - ♦ Organic fraction;
  - ♦ Nutrient concentration in soil and groundwater;
  - ♦ Porosity, permeability and infiltration rate;
  - ♦ Water content in soil;
  - ♦ Groundwater level;
  - ♦ Degree of total and plant available N, P and Fe as minimum factors in a marine environment;
  - ♦ Presence of cracks and leaching holes.
  - ♦ Degree of Phosphate saturation

- Determine the risk of surface runoff in the sensitive zone by measuring vegetation cover, nutrient uptake capacities, infiltration rates and angles of inclination among others.

- Determine the risk of nutrient input from the existing saliñas, wadis and within adjacent to the sensitive zone.

- Base irrigation standards for the sensitive zone on soil study as mentioned above, on soil processes (i.e. mineralization, nitrophication, denitrophication, sorption etc.), on nutrient uptake by vegetation as mentioned above, and on hydrogeological processes (i.e. infiltration, runoff, etc.).

- Give recommendations on irrigation methods in order to prevent or minimize negative effects of effluent use on the coral reefs and seawater quality.

- Adaptation of the treatment process design to comply with the effluent standards as dictated by the LBS protocol (Pollution from Land Based Sources, Cartagena Convention, 1983)

- Give a detailed overview of the removal of nutrients from provision of effluent for hotels, irrigation of plants, nutrient uptake by plants, absorption capacities of the soil processes, to possible nutrients discharge into the sea.

- Presentation and discussion of the Draft and Final Report of the results of the study with SRK, TAO representatives and other relevant stakeholders.

- Incorporation of possible comments into a Final Report.

The study is to be carried out under supervision of the Consultant, by experts, experienced in conducting similar studies and shall take place parallel to the DTD phase.

5. Preparation of Quotation by the Consultants

The Consultant shall prepare a detailed quotation comprising the following:

- Work plan, indicating the duration of the study, tasks to be carried out, allocated human resources and milestones.

- Resources input, unit and total prices.

- References (CVs and experience details) of expert(s), which will carry out the study.

- Any other information, which the Consultant deems necessary and relevant for the assessment of his quotation.

6 Outputs

The following outputs are expected from the Consultant:

- Draft Report of the results of the study (5-fold)

- Final Report of the results of the study (10-fold) including an Executive Summary.

- Hardcopy and electronic copy (MS Word/Excel/PowerPoint, etc) of all report, calculations and presentation on CD-ROM, including all gathered data, results from study, lab research etc.

The outputs warrant approval by the C.A. The approval time is as indicated under chapter 9.

7. Expertise required

The following expertise is deemed required to carry out the study:

- Profound knowledge of and experience with flora, soil biology, nutrient uptake by and irrigation needs of vegetation.
- Profound knowledge of and experience with soil processes, hydrology, modelling soil processes and nutrient behaviour in soils.
- Profound knowledge of and experience with sample taking of soils and subsequent analysis.

Requirements of expertise:

- A minimum working experience of 10 years in relevant fields.

- Academic degree in relevant fields.

8. Standards

The technical standards to be used shall be Netherlands Antilles standards and, where not available, suitable standards of member states (e.g. Netherlands) of the European Union normally used for sewage projects. Also the effluent standards have to comply with the LBS Protocol (Pollution from Land Based Sources, Cartagena Convention, 1983). The standards to be used shall be proposed by the Consultant in his quotation. They shall be agreed upon before commencement of the study.

9. Period of Performance shall be:

- A maximum of 2 months for the study including submission of the final draft report
- 4 weeks for approval of the final draft report to be submitted directly (see table 1) to the SRK, TAO and EC/DelGuy
- A maximum of 2 weeks to incorporate possible comments/remarks on the final draft report in the final report
- 2 weeks for approval of the final report

The Consultant shall include in his offer a global schedule of works based on the aforementioned and if necessary in consultation with the TAO and SRK amend (extending or reducing) the scope of service in accordance with his own professional judgment and knowledge during the preparation of his proposal.

Table 1: Submissions of reports

Description	PM/SRK	TAO	EC/DelGuy	Total
Draft report	3	1	1	5
Final report	6	2	2	10
Executive Summary	6	2	2	10

Appendix 2 Approach and methods

BONAIRE PROPOSAL

Consulting Services for a Critical Review of the proposed Effluent and Irrigation Standards during the Detailed Technical Design phase of the Sewerage and Sanitation System Bonaire (SSSB)

1 Understanding of the Terms of Reference

The main objective of the requested consultancy study is to provide a critical review of the Effluent and Irrigation Standards that have been proposed by Dorsch Consult GmbH as a basis for the design of the Sewerage and Sanitation System Bonaire (SSSB).
The purpose of the review is to provide a sound scientific foundation of the effluent standards, taking into consideration:

- The purpose of the SSSB, which is the protection of the marine ecosystem and the improvement of public health;
- The intended use of the effluent, which is for landscaping and irrigation at hotel premises and crops grown at the Island Service of Agriculture, Cattle Breeding and Fisheries (LVV);
- The technical parameters that are specific to Bonaire's climate, soil vegetation and geological conditions and are crucial for developing location-specific standards for financially and ecologically sustainable sewage and storm water disposal systems;
- The knowledge, experience and standards developed by the local authorities and their consultants, to ensure compatibility and operational efficiency.

Standards for irrigation water quality
While the SSSB might reduce the amount of nutrients in the sewerage, depending on the design, the concentrations of N and P in the effluent are still too high to consider direct discharge into the sea. In addition, irrigation water is a scarce commodity in Bonaire, which makes the use of effluent from the SSSB for irrigation economically more attractive than discharging it into the sea. The first issue to be considered, therefore, is whether the proposed effluent standards meet the internationally accepted standards for irrigation water quality. Water quality here has two aspects: agriculture and human health. The agricultural aspect is fairly straightforward, as standards are available for practically all crops, climates and soil conditions. The human health aspect is a little more complicated. The "Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture" (World Health Organization, Geneva 1989) include a discussion on Wastewater Quality for Agricultural Use. This discussion makes it clear that WHO at the time was reluctant to indicate a strict limit for faecal coliform. On the one hand, they refer to the Engelberg guidelines, which indicate that a microbial standard of some 1000 faecal coliforms per 100 ml for unrestricted crop irrigation is both epidemiologically sound and technologically feasible. Also, it is much in line with the actual river water quality used for unrestricted irrigation and bathing in Europe and the US with no known ill effects[2]. On the other hand, it is stated in the WHO guidelines that "effluents of higher quality (<100 faecal coliforms per 100 ml) may be required for wastewater used to irrigate public parks and hotel lawns to protect the health of those, especially tourists and young children, who come into contact with recently irrigated grass."[3]
In order to prevent "tourists and young children to come into contact with recently irrigated grass" it may be worthwhile to propose in this study to explore the possibility of subsurface irrigation methods in the hotel lawns.

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[2] Box 4.2 (p.81-82) in: *Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture*. World Health Organization, Geneva 1989.
[3] Ibid, p. 80

While the Engelberg meeting concluded that the risks of irrigation with well treated wastewater were minimal and that current bacterial standards were unjustifiably restrictive, they did recognize that in many developing countries the main risks were associated with helminthic diseases and that the safe use of wastewater would require a high degree of helminth removal. Thus the Engelberg guidelines represent a new, stricter approach concerning the need to reduce the helminth egg levels in effluents to 1 or less per litre. This represents a requirement to achieve a very efficient helminth removal of some 99.9%. Stabilization ponds are particularly effective in achieving this goal but other technologies are also available. The very strict Engelberg guidelines on helminthes also take care of removal of protozoa of public health importance, such as Amoeba and Giardia.

Given the importance of helminth removal for public health, it may be necessary to include them in the effluent standards. At present, they are neither considered in the effluent standards proposed in the ToR, nor in the LBS protocol.

Standards for safe disposal of effluent in a marine environment

While part of the nutrients in the irrigation water will be fixed by the soil and crops, another part will be leached out of the root zone by excess irrigation or rainfall. This fraction will percolate through the subsoil and eventually reach the sea. For the purpose of this study, it will therefore be necessary to quantify this fraction and to assess its potential effects on the marine ecosystem. In addition to the leached nutrients, there will also be sediments – also containing nutrients – that will reach the sea through surface runoff.

Moreover, the sewage treatment plant could be tuned to remove as much N and P to leave a concentration adjusted to the crops and vegetation needs (“effluent design”).

It is supposed that the waste sludge from the sewage treatment plant (rich in organics and nutrients) is disposed off in an environmentally friendly way.

In the introduction to the Terms of Reference it is stated that “recent studies concluded that quality of the reef is deteriorating also as a result of the inflow of surface water and untreated sewage.” The negative impact of sediments and nutrients on coral reefs has since long be recognized. The Protocol concerning pollution from Land-Based Sources (LBS), which was adopted at Aruba on 6 October 1999 by the Parties to the Convention for the Protection and Development of the Wider Caribbean Region (Cartagena de Indias on 24 March 1983) specifically mentions nitrogen and phosphorus compounds as primary pollutants of concern.

The Protocol also obliges its members to design and construct domestic wastewater treatment facilities for preventing discharges of untreated sewerage into waters containing coral reefs, sea grass beds or mangroves. It does not, however, specify maximum N and P concentrations in the effluent.

In a recent review article in the international scientific journal *Nature*, Bellwood *et al.* indicated increased nutrient and sediment runoff from land as factors contributing to instability of coral reef ecosystems worldwide.[4] They are among the causes of a transition of coral reefs from a healthy state towards a stressed state where they are dominated by fleshy seaweed (also called macro algae state). The authors also indicate, however, that the extent to which alternate states are stable or reversible is poorly understood and represents a major challenge for research and management of reefs.

After transition from the healthy state, coral reefs are more vulnerable to a whole range of diseases. One of these diseases is Rapid Wasting Disease, which was first observed in 1996 by Kalli de Meyer (Director of the Marine Park in Bonaire) and Prof. Rolf Bak (Netherlands Institute for Sea Research).

This demonstrates that it is highly relevant to preserve the healthy state; yet there are no readily available standards for safe disposal of nutrients and sediments.

[4] Bellwood, D.R. et al. Confronting the coral reef crisis. Nature. Vol. 429, 24 June 2004: 827-833.

Our Alterra colleague, Dr. Erik Meesters, together with the above mentioned Prof. Rolf Bak have developed and tested a model to predict changes in coral cover and diversity as affected by nutrient enrichment and sedimentation. The model uses seven input variables: dissolved inorganic nitrogen and phosphate, suspended particulate matter, maximum colony size, substratum available for colonization, coral cover and coral diversity. The model was initially developed and tested for the fringing reefs of Curacao, where it appeared to reflect accurately the current knowledge and experience of local reef dynamics. The model gives an indication of the effects of various nutrient and sedimentation levels and thereby provides a first approximation for local standards.

Another approach for quantification of the above standard is based on the calculation of the N and P loads at the time that the Bonaire reefs were still known to be in pristine condition. The loads in this base year will be compared with the present load and the load expected by the year 2017. This will enable a quantification of the amount of N and P that needs to be removed and safely disposed of, thereby providing an approximate local standard.

Risks and assumptions affecting the execution of the contract
It is assumed that the authorities of Bonaire and hoteliers grant permission to the team of experts to enter the land and allow soil characterization and sampling.

2. Strategy

In this study the impact of the proposed SSSB on the nutrient and sediment loads from the sensitive area to the sea will be assessed. In order to estimate the risks of erosion and losses of irrigation water to ground- and surface water, the physical and ecological characteristics of the study area will be investigated. Furthermore the proposed irrigation and effluent standards will be evaluated in the context of degradation of the marine environment.

2.1 Approach and activities

Ecophysiographic characterization and soil sampling
(Soil characterization of the study area, soil sampling of proposed irrigation sites, surface characteristics of study area; groundwater sampling, soil and water sample analysis)

Based on landform, geology and topography, physiographic units will be established within the sensitive zone. Within the physiographic units, the main soils will be characterized through angering up to max. 1.20 m depth or to the depth of the bedrock. Methods follow FAO guidelines (FAO, 1977. Guidelines for soil profile description). Soil texture and organic matter content will be estimated in the field through expert judgment. Soils will be classified according to the FAO/Unesco legend of the Soil Map of the World (ISRIC, 1989. FAO-Unesco soil map of the world. Revised legend. Reprint of World Soil Resources Report 60, FAO, Rome, 1988). Soil descriptions will concentrate on hotel gardens and salinas. At representative sites, samples will be taken for chemical and physical analysis, again concentrating on hotel gardens and salinas.
Both topsoil and subsoil samples will be collected at each location. In some cases an additional sample might be necessary to properly take into account the different layers of the soil. Samples will be taken at some 20 sites in the hotels gardens, 6 sites in the salinas and 10 sites in the remaining area. Furthermore, 5 samples will be taken in the area with volcanic soils since part of the storm runoff that enters the sensitive area will be generated there. Since these soils are volcanic, they are likely to have characteristics different from the soils developed on the limestone near the coast. Therefore, to assess how much runoff is generated there, data on these soils are also needed. Total number of samples will be 70. The location of all sampling points will be registered on topographical maps.
Within the physiographic units, the main vegetation characteristics (type of vegetation, main species, and ground cover) will be determined, leading to ecophysiographic units.

Bulk samples will be taken for chemical analysis. This analysis will include determination of N, P and Fe levels in the samples (see hereafter for more details on analysis). In addition, at some 18 representative sites, intact soil samples will be collected using small (100 cc) sampling rings. These ring samples will be used to determine soil density and hydraulic conductivity. Data on hydraulic conductivity are needed to determine how much water will infiltrate, and how much runoff can be expected during rainfall events.

Review the effluent standards in relation to LBS protocol
The updated version of the LBS protocol (Adopted at Aruba on 6 October 1999) specifies parameters and their effluent limits for discharge into Class I waters. Class I waters include waters containing *coral reefs*, sea grass beds or mangroves and waters used for recreation.

Parameter	**Effluent Limit**
Total Suspended Solids	30 mg/l *
Biochemical Oxygen Demand (BOD_5)	30 mg/l
pH	5-10 pH units
Fats, Oil and Grease	15 mg/l
Faecal Coliform (Parties may meet effluent limitations either for faecal coliform or for *E.coli* (freshwater) and enterococci (saline water)	Faecal Coliform: 200 mpn/100 ml; or a. *E.coli*: 126 organisms/100 ml; b. enterococci: 35 organisms/100 ml
Floatables	Not visible
* Does not include algae from treatment ponds	

Comparison of the proposed effluent standards in the ToR and the (updated) LBS protocol suggests that the proposed standard for Bacteria (E.coli) does not meet the required LBS standards by a considerable margin. The "Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture" (World Health Organization, Geneva 1989) indicate, however, that a microbial standard of some 1000 faecal coliforms per 100 ml for unrestricted crop irrigation is both epidemiologically sound and technologically feasible.

Determine surface runoff.

During the field campaign the following data will be collected:

1. A general map will be made of flow directions of the surface water, especially if these directions are influenced by man-made structures.
2. Slope angle will be measured and indicated.
3. A general map will be made of stone cover and vegetation cover.

A simple digital elevation model (DEM) of the study area and the larger area draining to it will be acquired. This DEM will be based on satellite images. It will be used to determine which area is draining to the study area, and in particular to the Salinas, taking into account the modification of the natural drainage system as determined from field mapping. In a Geographical Information System (GIS), the DEM will be combined with the maps obtained in the field to run a hydrological model that predicts the amount of runoff given the amount of rainfall, on a daily basis. It will also be simulated how much erosion will result from the runoff and how much sediment will reach the salinas and/or the sea. This will be done by assigning erodibility to the soil based on soil texture and hydraulical properties. Since nutrient content of the eroded soil will also be known (from chemical analysis of soil samples), this also results in an estimate of the amount of nutrients delivered to the salinas.

Soil and water analysis
Nutrient concentrations in soil and groundwater, total amounts and the degree of phosphate saturation will be determined for 70 samples in the laboratory. The following analyses will be carried out:

- Samples will be air dried and sieved over a 2mm sieve;
- Nutrient concentrations in the soil water will be determined by centrifugation of the soil samples. NO_3, NH_4, Nt and PO_4 will be determined by FIA. Pt concentrations will be determined by ICP;
- Total N and P will be determined by destruction with H_2SO_4/H_2O_2/Se.

Concentration in the groundwater (if at all within reach) will be determined at the same sites where soil samples are collected. Samples will be analyzed for NO_3, NH_4, Nt and PO_4 and P_{tot}.. NO_3, NH_4, Nt and PO_4 will be determined by FIA. Pt concentrations will be determined by ICP.

Climate and irrigation study
Based on the crops grown in the area to be irrigated with the treated wastewater and based on the climate data, the net crop water needs will be determined. Crop water requirements for the different seasons need to be matched with the available time distribution of the produced treated waste water. Crop water requirements will not always match with the seasonal distribution of waste water production. The expected variation needs to be investigated. This mismatch can be addressed in two ways:

1. By mixing treated sewage water with other water sources, in a variable mixing ratio in such a way that all sewage water is used for irrigation. Advantage of this solution is that external water sources are added and a larger area can be irrigated.
2. By creating storage of water during periods of excess sewage water production and using this water in periods of high irrigation demand. A disadvantage of storing water is that losses may occur. By combining water storage with ecological functions (wetlands), health risks may be reduced due to natural purification during storage.

Both options will be explored during the study.

Nutrient leaching from irrigated agriculture is the result of two management actions: either by excess rainfall or by excess irrigation. In the case of sewage water irrigation, the nutrients are largely applied with the irrigation water. To minimize leaching of nutrients two irrigation water management measures could be taken by the irrigators:

1. Provide only the minimum required amount of irrigation water with optimum spatial distribution.
2. To maintain a soil moisture storage capacity in the unsaturated soil to accommodate (unexpected) rainfall events.

To achieve this, modern irrigation methods are required, as well as modern (soil moisture) observation techniques.

Nutrient budget study
The load of N and P in the sewage treatment plant effluent is relatively low compared to the nutrient uptake rates of highly productive agricultural crops. However, the uptake rates of pristine vegetations like forests are generally much lower. To predict the uptake of N and P by the vegetation, estimates on growth rates and element contents have to be made. On basis of an investigation of the occurring vegetation a number of typical vegetation groups will be distinguished. For each group a growth rate and element contents will be estimated using available literature.

For each of the distinguished ecophysiographic units a nutrient budget will be determined. The Nutrient load to the marine environment equals:
$Nutrient_{load} = Nutrient_{load, leaching} + Nutrient_{load, runoff}$

The nutrient leaching is strongly determined by the amount and the rate of application of the sewage effluent and the release and binding of nutrients to the soil solid phase, such as mineralization and sorption and the uptake by the vegetation. Nitrogen and phosphorous are applied to the soil in inorganic and organic form. The sewage effluent will lead to an input of both organic and inorganic components. Dead vegetation and animal manure may also contribute to organic forms of N and P. Inorganic nitrogen and phosphorous can be taken up directly by the vegetation. Organic forms have to mineralize to become available for plant uptake. Mineralization rates depend on temperature, moisture and type of organic material. At Bonaire rates may be high due to high temperature, however drought may hamper the mineralization rate.
Phosphate and nitrogen may be bound to the soil by sorption processes. This may hamper the availability of the nutrients for uptake. The mineralization and nutrients form the sewage sludge and the retention of element in the soil system will be based on the measured (general) soil characteristics and literature data. Measuring the mineralization rates and adsorption isotherms directly is not proposed in the ToR and is too time consuming within the proposed time frame.

The nutrient load by leaching will be based on a simple mass balance calculation.
$Nutrient_{load, leaching} = Nutrient_{input} * fr_{inorg} + Nutrient_{input} * fr_{org} * kr_{min} - Nutrient_{uptake} - Nutrient_{binding}$

Evaluate effect on coral reef
The nutrient and sediment loads expected by the year 2017 will be compared to those at the time that the Bonaire reefs were still known to be in pristine condition. The latter will be estimated from the population figures and number of tourists at both times. This will enable a quantification of the amount of N and P that needs to be removed and safely disposed of, thereby providing an approximate local standard.

3. Timetable of activities

A timetable of the proposed activities is given in table 1.

Table 1. Timing of activities

No	Timeframe Activity	week 1	2	3	4	5	6	7	8	9	10-13	14-15	All
0	Preparatory work	9											9
1	Ecophysiographic mapping and soil sampling			12									12
2	Soil analysis												0
3	Evaluation of irrigation and effluent standards and methods						6						6
4	Evaluation of irrigation needs and uptake rates						9						9
5	Determining Surface runoff						4						4
6	Determining nutrient leaching and budgets						4						4
7	Evaluate effect on coral reef						2						2
8	Reporting								13				13
9	Presentation and discussion of Draft Report										4		4
	Total	9		12			25		13		4		63

In the first week after signing the proposal preparatory work will be carried out to obtain necessary material and information for the visit to Bonaire and to make an appointment with the SKR. The second and third week will be spent on a mission to the study area and for the ecophysiographic mapping and soil sampling. The mission will start with a visit to the SKR to discuss the plan. At the end of the mission, the mission report will be discussed with the SKR. In week 4 and 5 samples will be analyzed for physical and chemical properties. The interpretation of the results, evaluation of the obtained material and model calculations will be carried out in week 5 to 7. The results will be reported in week 8 and 9. A draft report will be send to SKR, TAO representatives and other relevant stakeholders at the end of week 9. The above representatives will send their comments on the report within 4 weeks (end of week 13). These comments will be incorporated within the final draft before the end of week 16. A presentation for either the draft or the final report of the study with the SRK, TAO representatives and other stakeholders will take place between week 10 and 16 according to the preferences of SRK, TAO representatives and other stakeholders.

The expected numbers of working days for the various experts on the mentioned activities are indicated in table 2.

Table 2 Working days

No	Activity	Roest	Kekem	Salm	Lier	Ritsema	Snellen	Meesters	Bak	All
		Working days								
0	Preparatory work	3	2	2			2			9
1	Ecophysiographic mapping and soil sampling		12							12
2	Soil analysis									0
3	Evaluation of irrigation and effluent standards and methods	4			2					6
4	Evaluation of irrigation needs and uptake rates	5		4						9
5	Determining Surface runoff					4				4
6	Determining nutrient leaching and budgets			4						4
7	Evaluate effect on coral reef							2		2
8	Reporting	2	2	2		1	4	1	1	13
9	Presentation and discussion of Draft Report	4								4
	Total	18	16	12	2	5	6	3	1	63

4. Logical framework

Project description	Indicators	Source of verification	Assumptions
Overall objective Improve the quality of the coral reefs in Bonaire as a key factor for the economic and social development of the Island.	Spatial coverage of coral: Part of substrate covered by healthy coral	Measurements by the relevant authorities and stakeholders.	Authorities and stakeholders use internationally accepted methods
Project goal Safe disposal of the treated sewage water of Kralendijk and tourist resorts, including by irrigation of hotel gardens and agriculture to remove nutrients.	-Treated sewage water effluents conform to the LBS standards. - Number of ha of hotel gardens and agriculture irrigated with treated waste water. -Amount of irrigation water per ha applied.	-Sewage water treatment effluent monitoring. -Hoteliers and LVV -Water distribution data to end users	Other nutrient sources are less important and do not disturb coral quality. Lowering of the nutrient loads by the safe disposal of sewage water results in better coral reef quality.
Project results -A critical review of the proposed waste water standards. -Recommendations for the safe reuse of treated waste water. -Estimation of its effect on the nutrient loads to the coral reefs.	-Standards of sewage water effluent. -Irrigation methods. -Less nutrients leached to the sea in 2017 than at present results in healthier coral.	- Table in final report -Methods reported in final report -Calculations given in report. Healthier coral is long term effect (see above).	Recommendations are implemented: Hoteliers and LVV will invest in modern irrigation techniques. Hoteliers and LVV will reduce fertilizer application based on nutrients in sewage water. Hotel garden irrigation with treated sewage water is accepted by stakeholders.
Activities *) 1,2 Ecophysiographic mapping, soil sampling, soil analysis. 3,4 Evaluation of irrigation and effluent standards and methods; evaluation of irrigation needs and uptake rates. 5 Determining surface runoff. 6 Determining nutrient leaching and budgets. 7 Evaluate effect on coral reef 8 Reporting	Map; No of soils samples taken and analyzed of hotel gardens, salinas and LVV. Plant water requirements. Water balance. Compliance with international effluent standards. Nutrient budgets. Surface and soil characteristics measured and/or estimated. Surface runoff catchment of Salinas determined Nutrient budgets of irrigated areas. Nutrient loads to the sea in: • Pristine situation • Future (2017) Report written and approved	Map in report and soil data in report. Water requirement and balance data in report. Irrigation methods proposed in report. Effluent standards in table in report. Nutrient budgets in report. Data, e.g. on storm water quantity, in report Nutrient budgets calculated and reported. Effect on coral reef reported. Hard copy and CD rom with report available	Overall: Local authorities and stake-holders cooperate and provide data.

*) Numbers correspond with table 1 in Ch.3.

Appendix 3 Itinerary

Itinerary Nutrient Study Bonaire 21 Nov. – 7 Dec.

21 Nov 2005	Departure 23.25 h. Messrs. Koen Roest and Arie van Kekem (Alterra) Amsterdam – Bonaire.
22 Nov 2005	Arrival Bonaire 04.30 h. Accommodation Kadushi Bungalow. Morning: Meeting with DOS, DROB, STINAPA, LVV (* for names and affiliations see end of itinerary). Presentation of approach and discussions. Lunch with DOS at Casa Blanca. Afternoon: Reconnaissance tour sensitive zone and first appointments with hotels (accompanied by Ramon de Leon and Anthony Emerenciana).
23 Nov 2005	Morning: Meeting at LVV (Anthony and Rocky); Site visit LVV Afternoon: Reconnaissance tour through watershed "sensitive zone Kralendijk". Study of available documentation. Selection of hotels to be sampled.
24 Nov 2005	At selected hotels; accompanied by Anthony: Gathering information on the treatment of sewage water. Carrying out soil descriptions and soil sampling.
25 Nov 2005	- idem –
26 Nov 2005	- idem – Afternoon 17.00 h.: Arrival of Mrs. Caroline van der Salm.
27 Nov 2005	Morning: Discussions among mission team members; reading documentation; preparation draft contents of mission report. Afternoon: sight seeing.
28 Nov 2005	Van Kekem and Van der Salm. At selected hotels: Gathering information on the treatment of sewage water. Carrying out soil descriptions and soil sampling. Roest: Calculation of water balance and irrigation requirements for hotel gardens and horticultural land. Departure Mr. Roest at 15.00 h. for Amsterdam. 15.00 h. DROB. Meeting Van Kekem and Van der Salm with Peter Montanus, Frank van Slobbe, Ramon de Leon and Anthony Emerenciana. Progress reported and Van der Salm introduced.
29 Nov 2005	Continuation visits to and sampling at hotels. Soil descriptions and sampling at LVV
30 Nov 2005	Soil descriptions and sampling at LVV and in sea At selected hotels: Gathering information on the treatment of sewage water. Carrying out soil descriptions and soil sampling in salina.
01 Dec 2005	Morning: Van Kekem water sampling at hotels. Van der Salm preparation of presentation for meeting of 3 Dec. Afternoon: Soil description and sampling within the watershed of Kralendijk.
02 Dec 2005	9.00 h: Meeting at DROB with Messrs. Reno Pieters; Michael Martis and Frank van Slobbe for debriefing and preliminary discussions of first results of water and nutrient balances. Continuation of preparation of presentation. 13.15 h. Meeting at DROB with DOS and Frank van Slobbe on terms of reference for an additional study to include biological analysis of waste water. 14.00 h. Meeting at Captain Don's Habitat with DOS, STINAPA, DROB and some hoteliers. Presentation of first indications of water and nutrient balances for hotels, followed by discussions.
03 Dec 2005	Last visit to the field. Sight seeing and ocean water sampling at East Coast of island. Reading documentation and snorkelling.
04 Dec 2005	Morning: Sorting out samples, mixing, weighing and packing soil. 15.05 h. Departure Van der Salm for Amsterdam.
05 Dec 2005	Morning: Shipping soils samples to Amsterdam through Bonaire Air Services. Return of documentation to DROB and LVV. Afternoon: Report writing.

06 Dec 2005	Morning: Report writing Afternoon: 15.05 Departure Van Kekem for Amsterdam.
07 Dec 2005	Arrival Amsterdam 04.30 h.

<u>* Names and affiliations</u>

SRK: Stuurgroep project Riolering Kralendijk
- Mr. Pieters, Reno: Coordinator.

DOS: Departement Ontwikkelings Samenwerking, Curaçao, Netherlands Antilles
- Mr. Poulina, Edil
- Mrs. Chârmi Middelhof.

DROB: Dienst Ruimtelijke Ontwikkeling en Beheer, Bonaire
- Mr. Martis, Michaël
- Mrs. Sint Jago, Alca (BCW)
- Mr. Van Slobbe, Frank (Milieu en Natuurbeheer)
- Mr. Montanus, Peter (Milieu en Natuurbeheer)

LVV: Ministerie van Landbouw, Veeteelt en Visserij
- Mr. Emers, Rocky
- Mrs. Frans, Gracia
- Mr. Emerenciana, Anthony

STINAPA: Stichting Nationale Parken Nederlandse Antillen
- Mrs. Beukenboom, Elsmarie
- Mr. De Leon, Ramon.

Appendix 4 Soil descriptions and analytical data

Soils of the hotel gardens

In this annex we present the soil descriptions with analytical data. In addition we give information, as presented to us by the hotel management, on water use and irrigation. Appendix 4b gives the details of the soil profile descriptions.

All soils of the hotel gardens we described and sampled are composed of brought up material, with only one exception being Great Escape. Here, the soil is very shallow over limestone. The brought up material is generally known as diabase. It consists of well to moderately well drained, gravely clay loam (texture range loam to clay) and lies over hard coral limestone. In the following we give soil descriptions of most of the hotels we visited. As soil formation continued in the brought up material, soil classification (FAO-Unesco, 1988) is given for the new soil. All soils of the hotel gardens described below are classified as *Eutric Cambisols, lithic phase*, unless otherwise mentioned.

Buddy Dive

Formerly Buddy Dive consisted of two separate hotels. The northern part, according to the soil and vegetation characteristics, being the older one. Here vegetation cover of the borders is high.

Buddy Dive produces its own drinking water of about 40 to 60 m^3 per day. All water goes trough septic tanks and is used for drip-irrigation of the hotel gardens (during the night).

The soils are developed from diabase which was brought up to cover the hard coral limestone. Trees and shrubs cover 30 – 50% and 40 – 50% is covered with gravel (southern part of the hotel). In the northern part the vegetation cover of the borders up to 100%. No grass.

Coco palm trees are getting additional fertilizer.

The topsoil is a 15 to 25 cm thick, dark reddish brown, gravely clay loam to clay with a good, granular structure. Organic C contents are 1 - 2 % in the southern part to 1-4% in the northern part.

The subsoil, to a depth of about 45 cm, is a gravely to extremely gravely, reddish brown, clay loam to clay.

Divi Flamingo

Divi Flamingo has grass lawns with shrubs and trees (coco palm along the beach and more fancy palms inside the gardens). The hotel produces its own drinking water. All water goes into septic tanks which are regularly emptied to be brought to LVV. Part of the hotel garden is irrigated with laundry water. The rest of the gardens is drip-irrigated with tap water.

The soils are developed from diabase which was brought up to cover the hard coral limestone. In the subsoil limestone fragments are present . The lawns and borders receive regularly fertilizer.

The topsoil is 10 to 15 cm thick, dark reddish brown to very dark brown, gravely clay with a moderate, sub-angular blocky structure. Organic C contents are 1 - 4 %.
The subsoil, to a depth of about 45 cm, is a gravely to extremely gravely, reddish brown, clay. In one place the former topsoil, developed in limestone, was encountered. This one consists of dark reddish brown, gravely clay with limestone fragments.

Captain Don's Habitat
Habitat has a well developed garden, partly gravel covered, with shrubs, palms and trees (no lawns). All water waste water goes into septic tanks and partly in a leach hole. The water from the septic tanks is pumped to a small, central waste water treatment plant (4 stage treatment with active sludge). The effluent, and partly laundry water, is used for drip irrigation of the gardens.

The soils are developed from diabase which was brought up to cover the hard coral limestone. In the subsoil limestone fragments are present . Soil depth varies from 10 to over 50 cm. Where the soil is deeper, however, it is very gravely.
The topsoil is 10 to 15 cm thick, dark reddish brown to very dark brown, gravely clay loam to clay with a moderate, sub-angular blocky structure. Organic C contents are 0.5 to 3 %.
The subsoil, to a depth of about 45 cm, is a gravely to extremely gravely, dark yellowish brown, clay loam to clay.

Hamlet Oasis
Hamlet Oasis has gravel covered parts of the garden with few palm trees and borders with shrubs, palms and trees (no lawns). All water waste water goes into septic tanks. The water is pumped from the septic tanks for drip irrigation of the gardens. No tap water is used.

The soils are developed from diabase which was brought up to cover the hard coral limestone. Soil depth varies from 10 to over 50 cm. Where the soil is deeper, however, it is very gravely.
The topsoil is 10 to 15 cm thick, dark brown, very gravely clay loam to clay with a moderate, sub-angular blocky and granular structure. Organic C contents are 0.5 to 1 %.
The subsoil, to a depth of about 35 to 45 cm, is a gravely to extremely gravely, dark yellowish brown, clay loam to clay.

Harbour Village
Harbour Village has a well developed garden, with shrubs, palms (coco palms near the beach) and trees. The borders have a high vegetation cover. A small strip of lawn is present near the parking. All water waste water goes into septic tanks. The water from the septic tanks is pumped to a central waste water treatment plant. The effluent, and partly tap water in case of a water deficit from the effluent, is used for drip irrigation of the gardens. NPK fertilizer are used in the garden.

The soils are developed from diabase which was brought up to cover the hard coral limestone. In the subsoil limestone fragments are present and locally (beach) sand was encountered on top of the coral limestone. Soil depth varies from 30 to about 50 cm.
The topsoil is 10 to 15 cm thick, dark reddish brown to very dark brown, gravely sandy loam to sandy clay loam with a strong, sub-angular blocky structure. Organic C contents are 1 to 3%. Near the parking, the subsoil is sandy loam.
The subsoil is a gravely to extremely gravely, dark yellowish brown to strong brown, sandy clay loam to sandy clay.

Plaza Resort
Plaza Resort has well developed gardens, with shrubs, palms (coco palms near the beach) and trees. The gardens have a medium to high vegetation cover. A small strip of lawn is present between the parking and the fitness centre. All water waste water goes into collection tanks. The water from the tanks is pumped to a large central waste water treatment plant. The effluent is used for drip irrigation in the gardens.

The soils are developed from diabase which was brought up to cover the hard coral limestone. Below the subsoil locally (beach) sand was encountered on top of the coral limestone. Soil depth ranges from 30 to about 50 cm. Near the fitness centre soil depth goes up to 75 cm.
The topsoil is 10 to 30 cm thick, dark reddish to dark brown, gravely clay loam with a moderate, sub-angular blocky and granular structure. Organic C contents are 0.5 to 1%. Near the fitness centre, the organic carbon content is about 2%.
The subsoil is a gravely to extremely gravely, dark brown to reddish brown, clay.

Sand Dollar
Sand Dollar has a medium high density garden, with shrubs, (coco) palms and trees. All water waste water goes into septic tanks; the grey water straight into the last chamber. The water from the septic tanks is used for surface irrigation of the gardens. Additional drip irrigation is applied with tap water.

The soils are developed from diabase which was brought up to cover the hard coral limestone. In the soil some limestone fragments are present. Soil depth ranges from 30 to about 50 cm.
The topsoil is 10 to 20 cm thick, dark yellowish brown, gravely clay loam with a moderate, sub-angular blocky to granular structure. Organic C contents are 0.5 to 1.5%.
The subsoil is a gravely to extremely gravely, dark yellowish brown, clay loam. In one place, on top of the limestone, a 10 cm thick original topsoil with found, consisting of dark brown loam.

Sunset
Sunset is a special case and could be used as a reference as this hotel has been empty for about 10 years and recently was demolished. The garden now is covered with grasses and a few trees are left.

The soils are developed from diabase which was brought up to cover the hard coral limestone. In the soil some limestone fragments are present. Soil depth ranges from 20 to about 30 cm.
The topsoil is 10 to 20 cm thick, dark reddish brown, sandy loam to clay loam with a moderate to strong, sub-angular blocky to granular structure. Organic C contents are 1 to 3%.
The subsoil is a gravely to extremely gravely, yellowish red, loam to clay loam. In one place, away from the beach, the original soil developed on limestone was present. This soil has a 10 cm thick topsoil, dusky red, gravely clay topsoil over a 15 cm thick dark red gravely clay subsoil, resting on coral limestone.

Soils of the saliña's

In the large saliña south of Kralendijk we could not describe a soil profile as this one was constantly flooded during our stay. In the Salina North we described and sampled two soil profiles.
The soils are developed in alluvial sediments derived from volcanic and limestone rock. They are poorly drained and flooded during the main rainy season after heavy rains. The most important feature of the soils is their high salinity throughout the soil profile. In addition these soils are stratified with alternating sandy, loamy or clayey layers, and show grey reduction colours in the subsoil due to a high groundwater table. At the sampling sites groundwater was at a depth of about 100 cm. Most soil layers have a texture of clay loam. Soils are classified as Gleyic Solonchaks.

Soils at LVV

At LVV the soils can be divided in two main units. The moderately deep (around 40 – 60 cm) soils developed on diabase and the deep soils (over 100 cm) developed on limestone. At the valley bottom, occupying only a small part, alluvial soils are present. Here temporarily after rains, groundwater is present within 120 cm from the surface. (Mainly because of a dam; groundwater level in the valley bottom is from 0 [near dam} to over 120 cm away from the dam).

The moderately deep soils (near the office buildings) are well drained. The top soils are 10 to 20 cm thick, dark reddish brown, gravely sandy loam to sandy clay loam with 1 to 2% organic C. The sub soils are 20 to 40 cm thick, dark reddish brown to brown, very gravely clay loam. These soils are classified as Eutric Cambisols (partly lithic phase).
The deep soils (partly from colluvium at the transition with the shallow soils, but basically developed from limestone) are well drained. The top soils are about 20 cm thick, (dark) reddish brown, non to slightly gravely, clay loam to clay with 1 – 2% organic C.
The sub soils to over 1 m depth, are non to slightly gravely, strong brown, clay loam to clay. In places these soils are calcareous. Most likely, these soils are classified as Calcic or Chromic Luvisols.

Other soils

(here we describe only those soils that we sampled)

Soils developed on limestone, of the lower and middle terrace, are well drained and very shallow to moderately deep (10 -50 cm). Rock outcrops are few to many. The vegetation consists of thorn bush with some cactuses. After rains, grass is present as well.

Top soils are 5 to 10 cm thick, gravely, dark reddish brown, and loam to clay loam. Sub soils are gravely to stony, reddish brown to red, loam to clay loam. Below the subsoil the hard limestone occurs. Soils classify as Eutric Cambisols, lithic phase.

Soils developed on diabase are well drained and have a very gravely and stony surface. Soil depth varies from shallow to moderately deep (20 – 70 cm). The vegetation consist of thorn bush and some cactuses. After rains grasses are present as well.

Top soils are 5 to 20 cm thick, gravely to very gravely, dark reddish brown, loam to clay with 0.5 to 1% organic C. Sub soils are very gravely to stony, reddish brown to red, clay loam to clay. The soils classify as Eutric Cambisols, partly lithic phase.

Soil physical data

Determination of the saturated hydraulic conductivity using the falling head method.

The saturated hydraulic conductivity K_s is determined by measuring the volume of water, which percolates through a saturated soil sample in time while the corresponding hydraulic head gradient changes continuously.

The undisturbed soil samples are saturated for 2 weeks. After saturation a water level of several centimetres is applied on the top of the sample. Water can now move freely through the sample. The outflow of water at the bottom of the sample is collected in a scaled cylinder, while date and time of readings are recorded. The water level on top of the sample will decrease in time during percolation causing a decreasing gradient of the hydraulic head during the measurements. While accounting for the average hydraulic head gradient the saturated hydraulic conductivity can now be calculated using Darcy's Law, resulting in:

$$K_s = \frac{l_0 - l_e}{t} \cdot \frac{l_s}{l_s + l_a}$$

l_0 = water level on top of the sample at the start of the measurement
l_e = water level on top of the sample at the end of the measurement
t = time of percolation
l_s = height of the soil sample
l_a = distance between the top of the soil sample and the average height of the water level on the sample during percolation

At each point, 3 rings of 100 cm^3 were taken (triplicate sample). Outliers in the Ks were left out as this points to a disturbed sample.

Location	Saturated hydraulic conductivity (cm/day)	Bulk density (g/cm^3)	Moisture fraction at saturation (v/v)
Harbour Village 2	240	1,35	0,49
Plaza Resort 5	13	1,47	0,44
Plaza Resort 8	25	1,39	0,48
Plaza Resort 9	30	1,37	0,54
Sand Dollar 1	15	1,48	0,45
Sand Dollar 3	18	1,39	0,47
LVV 3	32	1,41	0,47
LVV 4 bottom*	18	1,29	0,54
LVV 4 ridge*	24	1,24	0,52
LVV 7	15	1,33	0,50
Bon inland 1	18	1,41	0,50
Bon inland 4	216	1,07	0,60

* bottom of tillage furrow; top of tillage ridge.

A saturated conductivity of less than 20 cm/day is very slow; between 20 and 50 cm/day is slow. Over 200 cm/day is rapid.
A bulk density of 1,3 – 1,4 is considered normal for top soils. Below 1,1 is very low, especially as this topsoil was under natural vegetation.
Saturated moisture contents of all samples are good to high, indicating a good porosity.

Appendix 4-b. Details of soil profile descriptions

Soils of the hotel gardens

In this annex we present the soil profile descriptions. We follow the guidelines and definitions of the FAO (1977). All soils of the hotel gardens we described and sampled are composed of brought up material, with only one exception being Great Escape. Here, the soil is very shallow over limestone. The limestone is very hard and groundwater was never found in the soil. The brought up material is generally known as diabase. It consists of well to moderately well drained, gravely clay loam (texture range loam to clay) and lies over hard coral limestone. In the following we give the soil descriptions as were carried out during the fieldwork. As soil formation continued in the brought up material, soil classification (FAO-Unesco, 1988) is given for the new soil. All soils of the hotel gardens described below are classified as *Eutric Cambisols, lithic phase*, unless otherwise mentioned. Soil colours (Munsell, 1973) are in moist condition.

Buddy Dive

Description number: **BD 1**

Location: South of rooms 201-210

Depth (cm)	Horizon	Description
00-15	Ah	Dark reddish brown, gravely clay with a strong, medium, granular structure
15-35	Bw	Reddish brown, gravely clay
35-45	C	Dark yellowish brown, extremely gravely, clay loam
>45	R	Limestone rock

Divi Flamingo

Description number: **DF 1**

Location: N lawn close to beach

Depth (cm)	Horizon	Description
00-10	Ah	Dark reddish brown, gravely clay
10-25	Bw	Dusky red, gravely clay
25-40	IIAh	Dark reddish brown, gravely, clay with limestone fragments
> 40	R	Limestone rock

Description number: **DF 2**

Location: S of casino

Depth (cm)	Horizon	Description
00-15	Ah	Very dark brown, gravely clay with a moderate, medium, sub-angular structure
15-40	Bw	Reddish brown, very gravely clay with some limestone fragments
> 40	R	Limestone rock

Captain Don's Habitat

Description number: **CD 1**

Location: W of 2005

Depth (cm)	Horizon	Description
00-10	Ah	Dark brown, gravely clay loam with a moderate, sub-angular blocky structure
10-40	BC	Dark yellowish brown, very gravely clay loam to clay
40>45	C/R	Extremely gravely/rocky stones (diabase)

Hamlet Oasis

Description number: **HO 2**

Location: W of apartment 17

Depth (cm)	Horizon	Description
00-20	Bw	Dark brown, very gravely, clay loam to clay, with a moderate to strong, fine and medium, granular and sub-angular blocky structure
20-35	BC	Dark yellowish brown, very gravely, clay loam to clay
>35	R	Limestone rock

Harbour Village

Description number: **HV 1**

Location: Near Magnolia block

Depth (cm)	Horizon	Description
00-15	Ah	Dark reddish brown, very gravely sandy clay loam to clay loam
15-25	AC	Dark brown, gravely clay
25-45	C	Gravely clay
>45	R	Limestone rock

Description number: **HV 2**

Location: Plaso di Oro

Depth (cm)	Horizon	Description
00-15	Ah	Dark reddish brown, gravely (with some limestone), sandy loam to sandy clay loam with strong, medium and fine, sub-angular blocky and granular structure
15-30	AC	Dark reddish brown, gravely (with some limestone), sandy clay loam to sandy clay
30-35	IIC	Coarse beach sand
>35	R	Limestone rock

Plaza Resort

Description number: **PR 1**

Location: Fitness Centre

Depth (cm)	Horizon	Description
00-10	Ah	Dark reddish brown, gravely clay loam with weak, medium and fine, sub-angular blocky and granular structure
10-20	AB	Dark reddish brown, gravely clay
20-75	IIBw	Yellowish red, slightly gravely (diabase), sandy loam
>75	R	Limestone rock

Description number: **PR 2**
Location: Between Toucan diving and tennis courts

Depth (cm)	Horizon	Description
00-15	AB	Dark reddish brown, slightly gravely clay, with moderate, fine, sub-angular blocky and granular structure
15-35	Bw	Dark reddish brown, slightly gravely clay
35-40	IIC	Coarse beach sand
>75	R	Limestone rock, weathering

Description number: **PR 4**
Location: In front of J 001 - 009

Depth (cm)	Horizon	Description
00-20	Bw	Dark red, gravely clay, with moderate, medium, sub-angular blocky structure
20-35	C	Reddish brown, extremely gravely, sandy clay loam
>35	R	Limestone rock

Description number: **PR 5**
Location: Near Coconut beach bar

Depth (cm)	Horizon	Description
00-20/30	Ah	Dark brown, gravely clay, with moderate, sub-angular blocky and granular structure
>20/30	R	Limestone rock

Description number: **PR 7**
Location: Behind G 022

Depth (cm)	Horizon	Description
00-20	AB	Reddish brown, very gravely clay, with moderate, fine, sub-angular blocky and granular structure
20-40	BC	Dark brown, very gravely clay
>40	R	Limestone rock

Sand Dollar
Description number: **SD 1**
Location: S part of garden, about 20 m from beach

Depth (cm)	Horizon	Description
00-10	Ah	Reddish brown, gravely clay loam to clay, with moderate, medium, sub-angular blocky structure
10-35	C	Reddish brown, very gravely, clay loam to clay
35-45	IIAh	Dark brown, slightly gravely (limestone fragments), silt loam to loam
>45	R	Limestone rock

Description number: **SD 2**
Location: Middle part of garden, about 20 m from beach

Depth (cm)	Horizon	Description

00-30	Ah	Dark greyish brown, very gravely, clay loam, with strong, medium, granular structure
>30	R	Limestone rock

Description number: **SD 3**
Location: N part of garden, about 20 m from beach

Depth (cm)	Horizon	Description
00-20	AB	Dark reddish brown, gravely loam to silt loam, with moderate to strong, fine, granular structure
20-40	CR	Dark yellowish brown, extremely gravely, clay loam
>40	R	Limestone rock

Sunset
Description number: **SS 1**
Location: N side, about 200 m from beach

Depth (cm)	Horizon	Description
00-05	AC	Reddish brown, slightly gravely, sandy clay loam, with moderate, fine, granular structure
05-15	IIAB	Dusky red, gravely clay
15-30	IIB	Dark red, gravely clay
30-40	R	Limestone rock, weathering
>40	R	Limestone rock, hard

(AC is the brought up material, II.. is soil developed in limestone)

Description number: **SS 2**
Location: SW part, about 20 m from beach

Depth (cm)	Horizon	Description
00-20	Ah	Dark reddish brown, gravely clay loam, with strong, fine, granular structure
20-35	C	Yellowish red, very gravely and stony, loam to clay loam
>35	R	Limestone rock

Soils of the saliña's

In the Salina North we described and sampled two soil profiles. The soils are developed in alluvial sediments derived from volcanic and limestone rock. They are poorly drained and flooded during the main rainy season after heavy rains. The most important feature of the soils is their high salinity throughout the soil profile. In addition these soils are stratified with alternating sandy, loamy or clayey layers, and show grey reduction colours in the subsoil due to a high groundwater table. At the sampling sites groundwater was at a depth of about 100 cm. Soils are classified as Gleyic Solonchaks.

Description number: **SN 1**
Location: near bridge

Depth (cm)	Horizon	Description

00-40	BC	Strong brown, alternating layers of 5 – 10 cm coarse sand with layers of 2 to 5 cm clay loam to clay, without structure
40-60	C	Dark brown, (loam) to clay loam with few carbonate concretions
60>120	IIAC	Very dark brown, (loam) to clay loam with few carbonate concretions

Description number: **SN 2**
Location: between bridge and DROB, middle of saliña

Depth (cm)	Horizon	Description
00-10	C	Dark brown, silt loam
10-30	AC	Dark brown to brown, silt
30-70	IIAh	Very dark grey, clay loam with thin sand layer at 70 cm (full of water)
70-80	IICR1	Dark greyish brown silty clay loam to loam
>80	IICR2	Gray clay loam to clay

Soils at LVV

At LVV the soils can be divided in two main units. The moderately deep (around 40 – 60 cm) soils developed on diabase and the deep soils (over 100 cm) developed on limestone. At the valley bottom, occupying only a small part, alluvial soils are present. Here temporarily after rains, groundwater is present within 120 cm from the surface. (Mainly because of a dam; groundwater level in the valley bottom is from 0 near dam to over 120 cm away from the dam).

The moderately deep soils (near the office buildings) are well drained. These soils are classified as Eutric Cambisols (partly lithic phase). The deep soils (partly from colluvium at the transition with the shallow soils, but basically developed from limestone) are well drained. Most likely, these soils are classified as Calcic or Chromic Luvisols.

Moderately deep soils on diabase

Description number: **LVV 1**
Location: Garden near office
Physiography: Lower slope in gently undulating area
Slope: 2%

Depth (cm)	Horizon	Description
00-10	Ap	Dark reddish brown, gravely sandy loam to sandy clay loam, with moderate, fine, sub-angular blocky structure
10-20	AB	Dark brown, gravely, clay loam
20-40	BC	Strong brown, very gravely, clay loam to clay
>40	CR	Hard and weathering diabase

Description number: **LVV 2**
Location: Sorghum field near office
Physiography: Lower slope in gently undulating area
Slope: 2%

Depth (cm)	Horizon	Description
00-20	Ap	Dark reddish brown, gravely loam
20-40	BC	Reddish brown, very gravely, clay loam
>40	CR	Dark yellowish brown, extremely gravely, clay loam going over into weathering diabase

Description number: **LVV 4**
Location: Upper sorghum field near office
Physiography: slope in gently undulating area
Slope: 1%

Depth (cm)	Horizon	Description
00-15	Ap	Dark reddish brown, gravely, clay loam to clay
15-30	AB	Dark reddish brown to dark brown, gravely, clay
30>100	BC	Dark brown, very gravely, sandy clay loam to clay loam going over into weathering diabase

Deep soils in valley bottom and soils developed on limestone

Description number: **LVV 3**
Location: Valley bottom in lower field near tree
Physiography: Valley bottom in slightly undulating area
Slope: 0-1% to W
Groundwater: stagnates at 40 cm on top of firm layer

Depth (cm)	Horizon	Description
00-20	Ap	Dark reddish brown, gravely loamy sand with weak, fine, granular structure
20-40	AB	Brown, gravely, loamy sand
40-60	IIAh1	Very dark grey, slightly gravely, very firm, clay loam to clay, few carbonate concretions
60-80	IIAh2	Dark greyish brown, slightly gravely, firm, heavy clay
80-120	IIAC	Brown, very gravely, clay loam
>120		Weathering diabase

Description number: **LVV 6**
Location: Lower grass field with buffalo grass and few thorn bush
Physiography: Valley bottom in slightly undulating area
Slope: 0-1% to NW

Depth (cm)	Horizon	Description
00-25	Ap1	Reddish brown to yellowish red, slightly gravely (colluvial diabase) clay loam to clay
25-40	Ap2	Reddish brown, very slightly gravely, clay, very few carbonate concretions
40-60	AB	Reddish brown, clay loam, few carbonate concretions
60-80	Bt1	Strong brown, slightly gravely clay, few carbonate concretions

80>120	Bt2	Strong brown, slightly gravely, clay, few carbonate concretions

Description number: **LVV 7**
Location: Upper grass field with buffalo grass
Physiography: slightly undulating area
Slope: 0-1% to N

Depth (cm)	Horizon	Description
00-20	Ap1	Dark reddish brown, clay loam to clay
20-40	Ap2	Yellowish red, clay loam to clay
40-60	Bw1	Yellowish red to strong brown, clay loam
60>120	IIBw2	Strong brown, silt loam

Other soils

Soils developed on limestone, of the lower and middle terrace, are well drained and very shallow to moderately deep (10 -50 cm). Rock outcrops are few to many. The vegetation consists of thorn bush with some cactuses. After rains, grass is present as well.
Soils classify as Eutric Cambisols, lithic phase.

Description number: **Bo 1**
Location: Bella Vista
Physiography: middle terrace, nearly flat
Slope: 0-1% to W
Surface: gravely and some rock outcrops

Depth (cm)	Horizon	Description
00-12	Ah	Dark reddish brown, slightly gravely, loam to clay loam
12-20/70	Bw	Dark red, loam to clay loam
>20/70	R	Limestone rock

Description number: **Bo 6**
Location: E of power plant
Physiography: lower terrace, nearly flat
Slope: 0-1% to W
Surface: extremely stony and many rock outcrops

Depth (cm)	Horizon	Description
00-05	Ah	Dark reddish brown, very gravely and stony, loam
05-10/20	Bw	Reddish brown, stony loam
>10/20	R	Limestone rock

Soils developed on diabase are well drained and have a very gravely and stony surface. Soil depth varies from shallow to moderately deep (20 – 70 cm). The vegetation consist of thorn bush and some cactuses. After rains grasses are present as well.

The soils classify as Eutric Cambisols, partly lithic phase

Description number: **Bo 2**
Location: NW of Yatu Baku
Physiography: dissected plateau, local slope 0-2% to W
Surface: stony and gravely and some rock outcrops

Depth (cm)	Horizon	Description
00-10	AB	Dark reddish brown, very gravely, loam to clay loam
10-15	Bw	Dark red, very gravely, loam to clay loam
15-40	BC	Strong brown, very to extremely gravely, loam to clay loam
>40	CR	Very stony, weathering diabase

Description number: **Bo 3**
Location: SW of Guatemala
Physiography: gently undulating plateau, local slope 0-1%
Surface: stony and extremely gravely and few rock outcrops

Depth (cm)	Horizon	Description
00-15	AB	Reddish brown, very gravely, clay loam to clay
15-30/40	Bw	Reddish brown, gravely, clay loam to clay
30/40>70	C	Yellowish brown, very gravely and stony, sandy clay loam to clay

(most soils are shallower in this area)

Description number: **Bo 4**
Location: E of Den Tuna
Physiography: gently undulating plateau, slope 0-2% to SW
Surface: stony and very gravely

Depth (cm)	Horizon	Description
00-07	AB	Dark reddish brown, slightly gravely, loam
07-30	BC	Strong brown, loam
>30	CR	Very gravely, stony and rocky loam going over into rock

Description number: **Bo 5**
Location: N of Angola
Physiography: gently undulating plateau, locally dissected, local slope 1-2 % to W
Surface: stony and very gravely

Depth (cm)	Horizon	Description
00-20	Ah	Dark reddish brown, gravely, clay loam to clay
20-50	Bw	Reddish brown, gravely, clay
50-70	BC	Yellowish red, gravely clay
>70	CR	Weathering rock

Appendix 5 Soil chemical analyses

Table 26 Soil chemical analysis of the soil solid phase

Code	Location	Sample	Soil solid phase				
			Total analyses		Oxalate extractable (mg/kg)		
			N (g/kg)	P (mg/kg)	Al	Fe	P
BD1	**Buddy Dive**	topsoil 0-20	0.8	369	919	1238	164
BD2	**Buddy Dive**	topsoil 0-20	0.9	406	851	1329	205
BD3	**Buddy Dive**	topsoil 0-20	0.8	538	835	1349	319
DF1	**Divi Flamingo**	topsoil 0-20	1.2	919	1023	1369	692
DF2	**Divi Flamingo**	topsoil 0-20	0.8	426	1079	968	245
DF3	**Divi Flamingo**	topsoil 0-20	1.4	589	814	1636	353
DF4	**Divi Flamingo**	topsoil 0-20	0.9	608	797	1463	311
DF5	**Divi Flamingo**	topsoil 0-20	1.9	628	1034	2048	456
CD1	**Captain Don's Habitat**	topsoil 0-20	0.7	482	869	973	268
CD2	**Captain Don's Habitat**	topsoil 0-20	0.4	435	576	695	253
CD3	**Captain Don's Habitat**	topsoil 0-20	0.5	907	645	759	634
CD4	**Captain Don's Habitat**	topsoil 0-20	0.9	922	580	777	652
CD5	**Captain Don's Habitat**	topsoil 0-20	0.5	407	724	885	268
HO1	**Hamlet Oasis**	topsoil 0-20	0.3	482	724	759	335
HO2	**Hamlet Oasis**	topsoil 0-20	0.2	401	657	681	260
HV1	**Harbour Village**	topsoil 0-20	0.4	649	663	1040	278
HV2	**Harbour Village**	topsoil 0-20	0.8	1307	635	951	917
HV3	**Harbour Village**	topsoil 0-20	1.5	1919	693	1280	1254
HV4	**Harbour Village**	topsoil 0-20	0.7	1581	623	968	909
HV5	**Harbour Village**	topsoil 0-20	0.8	1006	611	895	564
PR1	**Plaza Resort**	topsoil 0-20	1.2	653	857	1053	330
PR3	**Plaza Resort**	topsoil 0-20	0.7	395	1084	1023	142
PR4	**Plaza Resort**	topsoil 0-20	0.5	416	742	767	143
PR5	**Plaza Resort**	topsoil 0-20	0.4	313	988	1114	95
PR6	**Plaza Resort**	topsoil 0-20	0.3	366	626	1126	129
PR7	**Plaza Resort**	topsoil 0-20	0.5	361	865	1064	147
PR8	**Plaza Resort**	topsoil 0-20	0.3	295	927	880	110
PR9	**Plaza Resort**	topsoil 0-20	0.5	323	906	1236	101
PR 10	**Plaza Resort**	topsoil 0-20	0.6	303	677	1086	101
PR 11	**Plaza Resort**	topsoil 0-20	0.5	289	1010	1024	80

Table 27 Soil chemical analysis of the soil solid phase, continued

Code	Location	Sample	Soil solid phase				
			Total analyses		Oxalate extractable (mg/kg)		
			N (g/kg)	P (mg/kg)	Al	Fe	P
PR2	**Plaza Resort**	subsoil 20-40	0.2	477	797	868	154
SD1	**Sand Dollar**	topsoil 0-20	0.3	446	768	924	221
SD2	**Sand Dollar**	topsoil 0-20	0.2	550	595	719	266
SD3	**Sand Dollar**	topsoil 0-20	0.1	349	468	438	166
SD4	**Sand Dollar**	topsoil 0-20	0.2	430	580	678	189
SS1	**Sunset**	topsoil 0-20	1.1	518	1180	1469	229
SS2	**Sunset**	topsoil 0-20	0.2	277	950	541	154
SS3	**Sunset**	topsoil 0-20	1.2	715	1026	1734	482
SS2	**South Salina**	topsoil 0-10	1.5	620	2102	660	327
SN1	**Salina North**	topsoil 0-10	0.4	492	532	952	253
SN2	**Salina North**	topsoil 0-10	0.3	461	696	931	283
LVV1	**LVV**	topsoil 0-20	1.0	870	829	1114	628
LVV2	**LVV**	topsoil 0-20	1.0	475	646	1212	210
LVV3	**LVV**	topsoil 0-20	0.7	276	602	978	90
LVV4	**LVV**	topsoil 0-20	0.8	434	879	1695	144
LVV5	**LVV**	topsoil 0-20	0.7	371	995	1688	73
LVV6	**LVV**	topsoil 0-20	0.7	303	927	1835	91
LVV7	**LVV**	topsoil 0-20	0.9	366	1232	2080	110
LVV6	**LVV**	subsoil 20-40	0.4	263	906	1302	88
LVV6	**LVV**	subsoil 40-60	0.2	213	853	966	98
LVV8	**LVV**	subsoil 40-60	0.9	519	816	1623	186
BO1	**Bonaire inland**	topsoil 0-20	1.0	297	1481	794	38
BO2	**Bonaire inland**	topsoil 0-20	0.5	350	726	1190	40
BO3	**Bonaire inland**	topsoil 0-20	0.6	248	629	1069	34
BO4	**Bonaire inland**	topsoil 0-20	0.5	447	958	1389	49
BO5	**Bonaire inland**	topsoil 0-20	0.7	260	598	827	68
BO5	**Bonaire inland**	topsoil 0-20	0.6	257	1024	1948	77
GE1	**Great Escape**	subsoil 0-20	0.6	577	685	944	192
SD5	**Sand Dollar**	topsoil 0-20	0.2	550	595	672	260
HH1	**Happy Holiday**	topsoil 0-20	0.2	375	590	636	159

Table 28 N and P concentrations in 1:2 soil:water extracts

Code	Location	Sample	1:2 extracts (mg/l)						
			$N\text{-}NO_3$ + $N\text{-}NO_2$	$N\text{-}NH_4$	Nts	$P\text{-}PO_4$	P	EC (µS/cm)	pH
BD1	**Buddy Dive**	topsoil 0-20	5.8	0.3	7.9	0.21	0.28	1328	8.11
BD2	**Buddy Dive**	topsoil 0-20	1.6	0.2	2.8	0.54	0.52	1618	7.97
BD3	**Buddy Dive**	topsoil 0-20	7.3	0.3	9.0	0.57	0.6	335	7.78
DF1	**Divi Flamingo**	topsoil 0-20	1.9	5.0	10.2	10.97	6.42	425	8.24
DF2	**Divi Flamingo**	topsoil 0-20	1.8	0.3	4.3	0.82	0.66	341	7.95
DF3	**Divi Flamingo**	topsoil 0-20	3.6	2.6	13.6	3.55	2.2	437	8.13
DF4	**Divi Flamingo**	topsoil 0-20	2.3	0.7	4.3	1.75	0.66	291	8.21
DF5	**Divi Flamingo**	topsoil 0-20	5.5	0.9	11.0	0.42	0.54	461	7.76
CD1	**Captain Don's Habitat**	topsoil 0-20	3.9	0.5	6.0	0.41	0.48	217	8.02
CD2	**Captain Don's Habitat**	topsoil 0-20	2.2	0.4	3.3	0.55	0.36	279	8.57
CD3	**Captain Don's Habitat**	topsoil 0-20	2.9	0.4	3.7	1.92	0.96	334	8.53
CD4	**Captain Don's Habitat**	topsoil 0-20	4.6	0.2	6.7	2.29	1.54	304	8.27
CD5	**Captain Don's Habitat**	topsoil 0-20	0.8	0.4	2.0	5.05	4.22	311	8.28
HO1	**Hamlet Oasis**	topsoil 0-20	28.3	0.3	31.6	0.76	0.64	637	7.43
HO2	**Hamlet Oasis**	topsoil 0-20	6.4	0.1	8.5	0.44	0.26	499	8.99
HV1	**Harbour Village**	topsoil 0-20	0.5	0.1	1.3	1.76	0.92	306	8.53
HV2	**Harbour Village**	topsoil 0-20	3.9	0.2	6.0	0.95	0.86	377	8.09
HV3	**Harbour Village**	topsoil 0-20	12.1	0.6	15.3	1.73	1.7	444	7.76
HV4	**Harbour Village**	topsoil 0-20	2.4	0.1	5.4	0.51	0.52	297	8.16
HV5	**Harbour Village**	topsoil 0-20	3.6	0.5	6.5	0.52	0.6	350	8.15
PR1	**Plaza Resort**	topsoil 0-20	7.4	<0.04	8.6	2.22	1.88	412	8.14
PR3	**Plaza Resort**	topsoil 0-20	2.0	0.1	3.1	0.33	0.4	679	8.02

Table 29 N and P concentrations in 1:2 soil:water extracts, continued

Code	Location	Sample	1:2 extracts (mg/l)						
			$N-NO_3$ + $N-NO_2$	$N-NH_4$	Nts	$P-PO_4$	P	EC (µS/cm)	pH
PR4	**Plaza Resort**	topsoil 0-20	4.3	<0.04	4.8	0.98	0.62	484	8.58
PR5	**Plaza Resort**	topsoil 0-20	5.4	0.3	8.5	<0.02	<0.02	2411	7.72
PR6	**Plaza Resort**	topsoil 0-20	6.9	0.3	9.6	0.38	0.4	1250	8.16
PR7	**Plaza Resort**	topsoil 0-20	2.2	<0.04	2.7	0.23	0.24	324	8.38
PR8	**Plaza Resort**	topsoil 0-20	2.4	<0.04	4.2	<0.02	0.04	1261	7.84
P9	**Plaza Resort**	topsoil 0-20	1.6	0.1	3.3	<0.02	<0.02	1741	7.94
PR10	**Plaza Resort**	topsoil 0-20	2.4	<0.04	3.6	0.58	0.56	903	8.08
PR11	**Plaza Resort**	topsoil 0-20	1.2	0.1	2.0	0.16	0.14	357	8.4
PR2	**Plaza Resort**	subsoil 20-40	0.8	<0.04	1.5	0.08	0.04	307	8.7
SD1	**Sand Dollar**	topsoil 0-20	1.0	<0.04	1.2	0.11	0.16	491	8.66
SD2	**Sand Dollar**	topsoil 0-20	0.4	0.1	3.0	0.18	0.14	208	9.11
SD3	**Sand Dollar**	topsoil 0-20	2.2	<0.04	2.6	<0.02	<0.02	771	8.98
SD4	**Sand Dollar**	topsoil 0-20	0.9	<0.04	1.2	0.23	0.18	368	9.11
SS1	**Sunset**	topsoil 0-20	3.7	<0.04	4.6	0.32	0.38	223	8.19
SS2	**Sunset**	topsoil 0-20	0.3	0.1	1.3	0.19	0.12	566	9.31
SS3	**Sunset**	topsoil 0-20	5.3	0.1	8.9	0.78	0.96	331	6.96
SS2	**South Salina**	topsoil 0-10	5.8	0.2	8.4	<0.02	0.02	443	8
SN1	**Salina North**	topsoil 0-10	3.5	0.6	6.2	0.05	0.2	22655	7.56
SN2	**Salina North**	topsoil 0-10	0.7	0.1	2.4	0.30	0.32	27342	8.29
LVV1	**LVV**	topsoil 0-20	5.7	0.2	6.8	3.65	1.36	421	8.86
LVV2	**LVV**	topsoil 0-20	5.4	0.3	8.4	0.45	0.48	916	8.27
LVV3	**LVV**	topsoil 0-20	3.9	0.3	5.1	0.12	0.1	632	8.34
LVV4	**LVV**	topsoil 0-20	2.9	4.6	10.1	3.40	2.3	243	7.65
LVV5	**LVV**	topsoil 0-20	2.6	0.5	3.7	0.08	0.08	160	7.37
LVV6.	**LVV**	topsoil 0-20	1.4	0.2	10.7	1.07	0.36	190	8.09
LVV7.	**LVV**	topsoil 0-20	1.3	0.5	9.6	0.46	0.08	117	7.49
LVV6	**LVV**	subsoil 20-40	0.3	0.7	15.9	0.88	<0.02	641	8.65
LVV6.	**LVV**	subsoil 40-60	0.0	<0.04	0.5	0.02	0.1	2210	8.52
LVV 8	**LVV**	subsoil 40-60	1.7	0.6	2.7	1.57	0.78	224	7.94

Table 30 N and P concentrations in 1:2 soil:water extracts, continued

Code	Location	Sample	1:2 extracts (mg/l)						
			$N\text{-}NO_3$ + $N\text{-}NO_2$	$N\text{-}NH_4$	Nts	$P\text{-}PO_4$	P	EC (µS/cm)	pH
BO1	**Bonaire inland**	topsoil 0-20	2.3	0.1	3.5	<0.02	-0.02	176	7.59
BO2	**Bonaire inland**	topsoil 0-20	0.4	0.1	2.0	<0.02	0.08	36	6.97
BO3	**Bonaire inland**	topsoil 0-20	0.7	0.1	2.2	<0.02	0.06	42	6.74
BO4	**Bonaire inland**	topsoil 0-20	1.1	0.5	2.5	<0.02	0.1	55	7.3
BO5	**Bonaire inland**	topsoil 0-20	1.0	0.7	2.2	0.18	0.1	63	7.07
BO 5-2	**Bonaire inland**	topsoil 0-20	3.1	0.4	4.5	0.34	0.3	292	8.03
GE 1	**Great Escape**	subsoil 0-20	1.4	0.3	2.5	0.43	0.14	279	8.5
SD5	**Sand Dollar**	topsoil 0-20	18.5	0.1	19.8	<0.02	-0.04	1060	8.16
HH1	**Happy Holiday**	topsoil 0-20	0.2	0.1	1.4	<0.02	0.04	206	8.65

Detection limits for the various N and P components are respectively 0.03 (NO_3), 0.02 (NH_4), 0.3 (Nts) and 0.02 for PO_4 and P.

Table 31 Concentrations in surface water, groundwater, seawater and effluents

Location	Water type	Sample	pH	EC µS/cm	N-NO_3+N-NO_2 (mg/l)	N-NH_4 (mg/l)	N_{ts} (mg/l)	P-PO_4 (mg/l)	P (mg/l)
Salina South	Surface water	SS1	7.07	4480	<0.03	<0.04	0.53	<0.02	0.02
	Surface water	SS2	7.39	878	<0.03	<0.04	0.75	<0.02	<0.02
LVV	Groundwater	LVV3a	8.16	329	1.30	<0.04	1.79	<0.02	<0.02
	Surface water	LVV3b	8.05	137	0.09	0.14	0.98	0.26	0.26
Salina North	Groundwater	SN1a	7.51	34300	<0.03	0.56	1.15	0.10	0.04
	Surface water	SN1b	7.82	25700	<0.03	<0.04	0.49	<0.02	<0.02
	Groundwater	SN2a	8.09	45900	0.10	0.14	0.36	0.25	0.17
	Surface water	SN2b	7.81	24200	<0.03	<0.04	0.84	0.03	0.02
Divi Flamenco	septic	DF1	8.26	990	<0.03	41.73	41.66	4.66	5.52
	sea	DF2	7.90	44400	<0.03	0.08	1.35	0.05	<0.02
	effluent waterworks	DF3	7.89	58500	<0.03	0.82	0.82	<0.02	<0.02
Habitat	Septic	CD1	8.40	1170	<0.03	67.15	71.09	8.16	8.70
	WWTP	CD2	7.16	860	47.75	19.61	69.22	8.24	8.43
	Sea	CD3	7.88	45000	0.86	0.04	0.27	0.09	<0.02
Harbor Village	WWTP	HV1	8.37	800	2.46	30.88	32.18	3.88	4.66
Sand Dollar	Septic	SD1	8.48	1150	0.02	66.08	70.97	8.61	8.65
Plaza	WWTP	PR1	8.29	1270	<0.03	25.86	28.47	4.25	4.74
	Sea	PR2	7.88	45000	<0.03	0.06	<0.3	0.04	<0.02
Lagoon	Sea	EC1	7.89	37300	<0.03	<0.04	<0.3	<0.02	<0.02
Vuurtoren	Sea	EC2	7.93	37100	<0.03	<0.04	<0.3	<0.02	<0.02
Punt 3	Sea	EC3	7.95	44500	<0.03	<0.04	<0.3	<0.02	<0.02

Detection limits for the various N and P components are respectively 0.03 (NO_3), 0.02 (NH_4), 0.3 (Nts) and 0.02 for PO_4 and P.

Appendix 6 Tourist arrivals

	Tourist arrivals Bonaire				
	2001	2002	2003	2004	Average
Jan	5,595	3,385	4,612	8,440	5,508
Feb	5,094	4,976	5,693	5,982	5,436
Mar	5,645	5,567	5,277	3,152	4,910
Apr	5,243	3,446	6,045	6,539	5,318
May	3,710	3,571	4,216	5,130	4,157
Jun	3,729	3,720	4,317	4,352	4,030
Jul	4,093	4,540	5,544	4,736	4,728
Aug	4,036	3,704	4,558	4,387	4,171
Sep	2,661	3,766	4,401	3,624	3,613
Oct	3,756	4,541	5,648	5,836	4,945
Nov	3,730	5,257	6,081	5,492	5,140
Dec	3,130	6,004	5,787	5,486	5,102
Total	52,423	54,479	64,182	65,160	4,755
				Year	59,061

Average length of stay:	9.23	(2003)
	9.15	(2004)

Appendix 7 Calculation of N balances for hotel gardens

The leaching of nitrogen and phosphate from the soils in the hotel gardens is calculated using simple mass balances. The mass balance for nitrogen is expressed as follows:

$$N_{leaching} = N_{input} - (N_{uptake} + NH_{3,volatilization} + N_{denitrification}) - N_{storage}$$

For phosphate the following balance was used:

$$P_{leaching} = P_{input} - P_{uptake} - P_{storage}$$

The N and P input by irrigation in a certain year is equal to the water use for irrigation in that year times the N and P concentration in the irrigation water:

$$N/P_{input,x}\,(kg/yr) = water\ use\ for\ irrigation_x\,(l/yr) * concentration\ N/P_x\,(mg/l) * 10^{-6}$$

The water use in 2005 is determined by the availability of waste water and thus by the water use of the hotel guests:

$$water\ use\ for\ irrigation_{2005}\,(l/yr) = number\ of\ guests\,(c/d) * 365 * water\ use_{guests}\,(l/c/d)$$

The water use of the guests which becomes available for irrigation was assumed to be 290 l/c/d (cf. chapter 2).

The N and P concentrations in 2005 are based on the measured concentration given in table 16.

The water use for irrigation after implementation (2017) of the waste water treatment plant is based on optimal irrigation as described in chapter 4.2.1:

$$water\ use\ for\ irrigation_{2017}\,(l/yr) = I\,(mm/d) * 365 * evaporating\ area\,(m^2)$$

in which *I* is the irrigation water requirement (pg. 39). The N and P concentration in the irrigation water are based on the standards provided by Dorsch 28 mg/l N and 5 mg/l P).

The N and P uptake are based on table 18.

NH_3 volatilization is calculated as:

$$NH_{3,volatilization} = N_{inp} * volatilization\ fraction$$

The volatilization fraction is equal to 0.05 in the dry season (January - September) and 0.1 in the wet season (October – December).

The loss of nitrogen by denitrification is calculated as the denitrification rate (1 kg /ha/d) times the number of days with a precipitation of more than 20 mm:

$$N_{denitrification} = denitrification\,rate(kg/ha/d) * days(P > 20mm)$$

Calculation of average water requirements (mm/d) hotel gardens in 2005

Month	Peff (mm/d)	Pebbles/drip (10%) Etc (mm/d)	Pebbles/drip (10%) Wreq (mm/d)	Baresoil/drip (82%) Etc (mm/d)	Baresoil/drip (82%) Wreq (mm/d)	Grass/sprinkler (8%) Etc (mm/d)	Grass/sprinkler (8%) Wreq (mm/d)	Average Wreq (mm/d)
Jan	1.14	3.25	2.35	4.18	3.38	4.88	4.98	3.40
Feb	0.54	3.70	3.51	4.76	4.69	5.55	6.69	4.73
Mar	0.35	4.01	4.07	5.16	5.34	6.02	7.55	5.39
Apr	0.43	3.96	3.92	5.09	5.18	5.94	7.35	5.23
May	0.40	3.80	3.77	4.88	4.98	5.70	7.06	5.03
Jun	0.37	3.96	3.99	5.09	5.24	5.93	7.42	5.29
Jul	0.92	4.00	3.42	5.14	4.69	6.00	6.77	4.73
Aug	0.83	4.06	3.60	5.23	4.89	6.10	7.02	4.93
Sep	0.96	3.98	3.35	5.11	4.61	5.96	6.67	4.65
Oct	1.68	3.74	2.29	4.81	3.47	5.61	5.23	3.49
Nov	2.67	3.33	0.73	4.28	1.79	4.99	3.09	1.78
Dec	1.94	3.10	1.29	3.99	2.28	4.66	3.62	2.29
Average	1.02	3.74	3.02	4.81	4.21	5.61	6.12	4.24

Calculation of water use in hotel gardens (7.19 ha; 2084 hotel beds; 290 l/cap/d)

occupancy	Month	Available water m3/d	Needed water m3/d	Excess m3/d	Excess Irrigation (%)
70	Jan	420	245	175	72
69	Feb	415	340	74	22
62	Mar	374	388	-13	-3
67	Apr	406	376	30	8
52	May	317	361	-44	-12
51	Jun	307	380	-73	-19
60	Jul	361	340	21	6
53	Aug	318	354	-36	-10
46	Sep	276	334	-59	-18
62	Oct	377	251	126	50
65	Nov	392	128	264	205
64	Dec	389	164	225	137
60	Average	363	305	57	36

Multiplication of the produced water with the average N concentration of 45.8 mg/l gives the N load of 4570 kg/yr and with the average P concentration of 6 mg/l gives the P load of 600 kg/yr.