Soil permeability, interflow and actual acidity in acid sulphate soils, South Kalimantan, Indonesia

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Abstract

Pumping tests in shallow wells and a drainage test revealed very high KD-values of up to 3500 m²/day in Pulau Petak, Kalimantan, Indonesia. Such high values make significant groundwater flow likely, even with the minor hydraulic heads found in the Indonesian tidal lands.

The top and subsoil with many cracks and rootholes are the main contributors to the high transmissivity. The very deep layers are unripe and mainly fine to medium textured soils, formed below low water level. The thickness and ripeness of the oxidized part of the soil profile (the so-called brown layer), the presence of large pores (diameter > 5 mm), the orientation and shape of the pores, and the actual depth of the groundwater, strongly correlate with the permeability. Actual acidity in a soil may be the result of the balance between the influx of toxic groundwater from the higher parts (interflow) and the net outflow of surface and groundwater into adjoining drainage canals. Water in tidal schemes is usually in direct, open connection with the tidal rivers. Accumulation of acids in canals and reduced tidal effects are likely in areas at more than 5-7 km from the river. The reduced tidal flushing capacity with good quality river water contributes to the accumulation of toxic groundwater and gradually increases the actual acidity in the soil-profile of relatively low lying sites.

It appears that actual acidity caused by interflow is difficult to distinguish from actual acidity caused by in situ oxidation of pyrite. It is thought that the acidity caused by interflow can be removed quickly by intercepting, leaching and flushing by an intensive shallow drainage, and a supply system with good quality canal water.

Introduction

During the first phase (1988-91) of the AARD/LAWOO research on acid sulphate soils in the Pulau Petak region, South Kalimantan, Indonesia, it became evident that the acidification of the soils and groundwater is not so much caused by in situ pyrite oxidation, but mainly by inflow of acid water. This was in line with previous experiences in tidal lands throughout Indonesia.

Permeability

Pumping tests in Pulau Petak in shallow pits were carried out to determine the permeability (Hamming et al. 1990). Earlier, a drainage test was performed in the same
Tests done with lower groundwater levels showed much smaller transmissivities although still dramatic: 200 – 500 m²/day. Observations of recovery tests in soil pits revealed that the peaty top layer, if present, and the brown oxidized layer (which overlays the grey, reduced, pyritic layer) contribute most to the groundwater flow. These brown layers are usually ripened and contain many cracks. The cracks can easily develop in the kaolinite clays of Pulau Petak: under saturation, swelling is limited due to the clay’s low absorption capacity whereas shrinkage occurs during dry spells.

Many big rootholes (formed by the roots of mangrove trees like *Rhizophoria, Bruguiera* and *Nipa* with an anisotropic distribution) were observed and they also contribute significantly to the high permeability. Much lower in permeability are the areas with many small woody remnants from *Sonneratia* which show mainly a vertical orientation. For the brown layer a hydraulic conductivity of 800 m/day was determined at the Unit Tatas experimental site.

A numerical hydraulic model of the Unit Tatas irrigation/drainage system confirmed that water levels are highly influenced by groundwater flow.

Poor drainage restricts the ripening of the grey layer; few cracks were generally observed. Even with abundant wood remnants present, permeability was relatively low. The highest permeabilities were found in soils having numerous cracks in the brown layer, combined with an anisotropic orientation of the rootholes in the grey layer.

### Actual acidity

Most tidal swamp clays contain pyrite at various depths. The danger of acidification depends on the hydrological characteristics of the site. For this reason Van den Eelaart (1991) and Kselik et al. (1993) made proposals for a division of the tidal lands in Water Management Zones, based on the hazard of acidification, to indicate the agricultural potentials. The most productive soils are the tidal swamp clays which can be irrigated at high tide. They have the smallest risks of rapid deterioration under cultivation, independent of the presence and depth of pyrite in the profile. Tidal irrigation potential is mainly limited by the capacity of the canal system. Densely spaced and sufficiently large canals are needed to convey large amounts of water in a short time. Only the lower locations within 3 km from the river have potential for tidal irrigation.

The highest risk of acidification is found in places at more than 5-7 km from the river. The tidal influence is limited here and low velocities and small tidal ranges prevail. In these slack water conditions acid, stagnant water accumulates easily. Topography and hydrology determine the spatial variation of actual acidity. Acidity produced in the dry season is mobilized after rainfall and accumulates by interflow in the lower areas where acid, stagnant slack water conditions in the canals contribute heavily to the problem. This type of actual acidity cannot be distinguished from actual acidity caused by in situ oxidation of pyrite.

Figure 1 shows the variations in time and space of acidity between two secondary canals with slack water problems in Belawang, South Kalimantan. Figure 2 suggest
that a high groundwater level in the dry season at km 2.5 (low area with most severe acidity problems) is related to interflow from higher areas. Table 1 indicates a significant difference in Total Actual Acidity (TAA) between places near and further from
Table 1 Chemical soil parameters of transects Belawang, dry season (1989) with slack water conditions in adjoining canal sections

<table>
<thead>
<tr>
<th>Depth</th>
<th>0-20 cm depth</th>
<th>20-40 cm depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>near canal*</td>
<td>from canal**</td>
</tr>
<tr>
<td>Org.matter %</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>pH (water)</td>
<td>4.2</td>
<td>3.9</td>
</tr>
<tr>
<td>TAA (me/kg)</td>
<td>280</td>
<td>360</td>
</tr>
<tr>
<td>TPA (me/kg)</td>
<td>420</td>
<td>430</td>
</tr>
<tr>
<td>EC dS m⁻¹</td>
<td>0.11</td>
<td>0.22</td>
</tr>
</tbody>
</table>

* From km 0 to 1.5 (6 data) TAA = Total Actual Acidity
** From km 1.5 to 3.8 (6 data) TPA = Total Potential Acidity

...canals, but no such difference was found in Total Potential Acidity (TPA).

The actual acidity problem related to the lateral inflow of acids from nearby sources was also noted by Janssen et al. (1992), who discuss the problem that Soil Taxonomy does not provide solutions to characterize actual acidity caused by interflow of acid in the spatial and dynamic system of a tidal development scheme. In fact, in situ acidification as a cause of severe actual acidity might be unimportant for most of the tidal lands of Indonesia. This requires that land evaluation should pay more attention to the hydrological land qualities and less to in situ soil characteristics.

Removal of acidity

It is thought that the acidity caused by interflow can be removed quickly by intercepting; leaching and flushing in an intensive shallow drainage and supply system with good quality canal water.

At the Unit Tatas experimental fields, an interceptor drain, which was constructed to avoid the acid inflow from the adjoining gelam forest, lowered the SO₄²⁻ concentrations in the fields at the start of the wet season. Agronomic experiments showed that with an interceptor drain, yields increased 0.6 ton per hectare (Sevenhuysen 1991). Similar effects of fast improvements by leaching and interception were found by van den Eelaart and Boissevain (1986).

Replacing groundwater with good quality canal water is essential for improvement. Consequently, the possibilities for improvement in the water management zone with slack water conditions are bleak, unless sources of good quality water can be found elsewhere.

Locations with acid, stagnant slack water conditions in the adjoining canals which are impossible to improve, are only suitable for tree crops and timber plantations. The tree crops should be planted on 1 m high raised mounds to safeguard proper drainage. In South Kalimantan Rambutan fruit trees thrive well in these conditions and provide a good cash income.
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Water management on rice fields at Hoa An, Mekong Delta, Vietnam

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Abstract

In the past, attempts to reclaim severe acid sulphate soils in the Mekong Delta for cultivation of rice or a rainfed, short-duration, summer-autumn crop have resulted in repeated failures. Recently, farmers have been able to grow an irrigated winter-spring crop followed, directly, by a rainfed summer-autumn crop. Field experiments at Hoa An station aim to develop a set of agronomic and water management practices that will be useful to farmers. Initial results highlight the importance of controlling the water status of highly organic raw acid sulphate soils by levelling, as opposed to leaching. Pollution of surrounding surface water has also been monitored.

Introduction

Since 1980, the University of Can Tho, Vietnam, and the Wageningen Agricultural University, The Netherlands, have cooperated to develop reclamation strategies of acid sulphate soils in the Mekong Delta. In 1989, experiments were started on the effect of water management practices on rice performance on a severe acid sulphate soil in Hoa An station, Hau Giang Province, 30 km from Can Tho.

Hoa An is situated in the broad depression of the Camau peninsula, and is connected to the Mekong river and the Gulf of Thailand by the Cung canal which was dug in the thirties to facilitate transport, drainage of surplus water during the rainy season, and irrigation. Since salinity has not moved up to the point where fresh water is taken from the Mekong river, the canal carries fresh water all year round. However, due to siltation and encroachment of houses into the canal, the capacity of the canal for irrigation and drainage has decreased considerably.

The experimental field is connected to the main Cung canal by a secondary canal dug in 1981. This has a width of 5 m and a depth of 1.5 m but is almost completely blocked by water hyacinth. For the irrigated winter-spring crop, water is pumped from the secondary canal into a tertiary irrigation ditch. The field is drained by ditches into the same secondary canal but at some distances from the intake. The drainage and irrigation possibilities of the Hoa An station are limited due to the low elevation, the bad condition of the canals and its location at a meeting point of tides from the East China Sea and the Gulf of Thailand. This situation is typical for many acid sulphate lands in the Mekong Delta.

Land use

Traditionally, farmers have transplanted a long-stem rice variety during the flood.
Yields are low, less than 1 t ha\(^{-1}\), probably due to toxicities associated with deep reduction. Other farmers attempted to broadcast a summer-autumn crop. Yields were very low or plants died due to severe Fe and Al-toxicity at the start of the rainy season, followed by toxicities associated with deep reduction in later growing stages. In the water management experiments described hereafter, an irrigated winter-spring crop is directly followed by an early summer-autumn crop. In 1990, the mean yield of the winter-spring crop was 2 t ha\(^{-1}\). In 1991, a new field was reclaimed and the winter-spring crop yielded 3.8 t ha\(^{-1}\). The summer-autumn crop looked very promising but was drowned in last year’s deep flood. This year, 1992, farmers around the station are changing to the winter-spring, summer-autumn cropping system.

Soils

At Hoa An, the soils are raw acid sulphate soils with a sulfuric horizon less than 40 cm from the surface. Under *Eleocharis dulcis* reed, a ripe topsoil, rich in organic matter, about 20 cm thick, is developed. Below this is a firm, ripe or nearly ripe layer of slow permeability. This slowly-permeable layer is not caused by ploughing, since the land has never been cultivated before. Cultivation for rice produces a soft, puddled topsoil but the remaining firm layer below is crucial to water management.

The sulfuric horizon can be recognized easily by the striking yellow mottles of jarosite and orange/brown iron hydroxides. At a depth of about 1.2 m, the grey, permanently reduced, sulfidic layer is found.

The clay content of the Hoa An soil varies between 55 to 65 per cent. The bulk density of the cultivated topsoil and sulfuric horizon is 0.9-1.0 g cm\(^{-3}\) while that of the firm layer is somewhat higher: 1.1-1.2 g cm\(^{-3}\). In Table 1, saturated hydraulic conductivities for the various soil layers are presented. Note the great difference between the saturated conductivities within the profile. The conductivity of the topsoil is low, but increases strongly in the course of the dry season when cracks develop. The conductivity of the firm layer is very low so water can be kept on the field easily and the topsoil is separated well from the severely-acid horizon below. The high conductivity of the sulfuric horizon is caused by a system of interconnected pores and cracks. At the end of the dry season, cracks are found well into the sulfuric horizon. Also, 1-2 mm diameter round root channels of the *Eleocharis dulcis* reed vegetation are found, even in the sulfidic layer. The cracks and pores are usually lined with jarosite and ped faces are stabilized by iron oxides.

<table>
<thead>
<tr>
<th></th>
<th>(K_{\text{sat}}), m day(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>horizontal</td>
</tr>
<tr>
<td>Topsoil</td>
<td>0.015</td>
</tr>
<tr>
<td>Firm layer</td>
<td>0.002</td>
</tr>
<tr>
<td>Sulfuric horizon</td>
<td>1.064</td>
</tr>
<tr>
<td>Sulfidic horizon</td>
<td>21.542</td>
</tr>
</tbody>
</table>
Acidification of the topsoil and the role of deep cracks

The amount of KCl-extractable acidity in the sulfuric horizon is roughly 200 mmol (+) kg\(^{-1}\) dry soil. The overlying topsoil, which originally did not contain any acidity, contains around 120 to 150 mmol (+) kg\(^{-1}\) KCl-extractable acidity. The acidification of the topsoil by the underlying sulphuric horizon is probably caused by three processes (Figure 1).

A) Diffusion of acidity through the firm layer. Due to the very low permeability of this layer, diffusion is very slow but in the course of years it may be an important contribution to acidity in the topsoil;

B) In the course of the dry season, cracks develop which, at the end of the dry season, extend into the sulphuric horizon. Due to the strong evaporative conditions at the end of the dry season, acid water moves to the cracks, bringing acidity which precipitates as soluble Al- and Fe-salts along the crack wall. When the rainy season starts, the acid salts are dissolved by water ponding in the cracks and the acidity is mixed with the surface water by diffusion, mixing of the water by raindrops and closing of the cracks, pushing the acid water out of the soil;

C) Acidification of the surface water by acidity leaching from canal spoil. Especially the first years after the digging of a canal, strong pollution of surrounding topsoil takes place.

Cracking of the firm layer at the end of the dry season and, thereby, yearly re-acidification of the topsoil, can be prevented by the cultivation of an irrigated winter-spring crop. The winter-spring crop should be followed directly by an early summer-autumn crop. In the absence of a close network of tertiary canals, dry season water levels
fall deep due to evapotranspiration. In the presence of tertiary canals, at small drain
distance, groundwater levels are controlled by the canal water levels, influenced by
the Mekong river (Thuan 1989). Cultivation of a winter-spring + summer-autumn
cropping system and digging of tertiary canals are, therefore, the first and, probably,
most important steps in improving severe acid sulphate soils.

Composition of the soil solution in the topsoil during the year

The concentration of acidity in the soil solution of the sulphuric horizon is constant
throughout the year. The pH is around 3.5, the concentration of soluble aluminum
100 to 400 mg l\(^{-1}\) and the concentration of Fe\(^{2+}\) is 300 to 600 mg l\(^{-1}\) (Bakker et al.
1990). However, the amount of acidity and toxic components in the topsoil changes
very strongly during the year. The climate in the Mekong Delta is characterized by
a dry season from January to May, followed by a rainy season from June to December.
The composition of the soil solution is strongly influenced by the seasonal changes,
inducing oxidation and reduction processes. The soil solution of the topsoil in Hoa
An was measured from time to time over several years of experimentation. Based
on these observations, a possible explanation of the seasonal variation of the composi-
tion of the soil solution is given below. Further year-round monitoring is needed to
confirm this.

From the redox point of view, a year can be divided into three periods (Figure 2):
I Continuous oxidation during the dry season, starting at the recession of the flood;
II Alternating oxidized and reduced conditions during the first part of the rainy season;
III Continuously-reduced conditions during the flood or submerged period.

In general, acidity is liberated by oxidation processes in the topsoil. Acidity is, however,
consumed as a result of reduction processes in the topsoil. In this respect, the oxidation
and reduction of iron plays a major role:

\[
\begin{align*}
\text{Fe}^{2+} + \frac{1}{4} \text{O}_2 + \frac{5}{2} \text{H}_2\text{O} & \rightarrow \text{Fe(OH)}_3 + 2\text{H}^+ \quad (1) \\
\text{Fe(OH)}_3 + \frac{1}{4} \text{CH}_2\text{O} + 2\text{H}^+ & \rightarrow \text{Fe}^{2+} + \frac{1}{4} \text{CO}_2 + \frac{11}{4} \text{H}_2\text{O} \quad (2)
\end{align*}
\]

*Period I, continuous oxidation during the dry season*
After the recession of the flood during the dry season, and in the absence of an irrigated
winter-spring crop, the watertable falls below the soil surface, resulting in strong oxida-
tion of the topsoil, and the pH decreases to values below 4. At decreasing pH levels,
aluminumhydroxides are increasingly hydrolysed to, respectively, \(\text{Al(OH)}_2^+\),
\(\text{Al(OH)}_3^+\) and \(\text{Al}^{3+}\) (Raupach 1963). At the end of the dry season, the pH of the soil
solution is below 4 and the concentration of soluble aluminum reaches its peak. The
high concentration of soluble aluminum is, furthermore, attributed to the low water
content at the end of the dry season.

*Period II, alternating oxidized and reduced conditions during the first part of the rainy
season*
The first rains dilute the soil solution. In the presence of a low drain level, soluble
Figure 2 Schematic presentation of the seasonal redox and leaching processes influencing the composition of the soil solution in the topsoil of an uncultivated raw acid sulphate soil at Hoa An.

Aluminum is leached into the drainage system through interconnected cracks to the drains. Upon gradual closing of the cracks, acidity is removed by surface runoff. When the topsoil becomes submerged after a heavy rainfall, temporary soil reduction takes place. Two to three weeks after submergence, the concentration of ferrous iron reaches a peak (Ponnamperuma 1972). Usually, an early season drought occurs in July/August and, during this time, the topsoil may be re-oxidized. Several oxidation/reduction cycles may occur, each of them followed by a peak in ferrous iron. During this period, the concentration of soluble aluminum will gradually decrease due to leaching, surface flushing and a gradual rise in pH upon soil reduction.

Period III, continuous reduction during the flood
Usually in September, the amount of rainfall can no longer be drained off and a prolonged period of waterlogging persists until January. In Hoa An, the flood reaches a maximum depth of 50 cm. Now, in turn, nitrates, manganese, IV, iron III, ferric-iron,
sulphate and carbon-dioxide are reduced by decomposing organic matter in the order of their respective redox-potentials (Ponnamperuma 1972). Since all reduction reactions consume acidity, the pH rises and the last soluble aluminum precipitates as aluminum-hydroxides. The concentration of iron II ferrous iron decreases due to diffusion into the flood water and the precipitation as FeS. Locally, sulphate reduction takes place in the presence of decomposing root remnants, and hydrogen sulphide is formed which can be toxic to rice roots at low concentrations (Tanaka and Yoshida 1970). At the end of the flood, the pH of the soil solution is near neutral, soluble aluminum is very low, iron II ferrous iron around 100 ppm, and there is no H₂S.

Figure 2 indicates that the highest concentrations of soluble aluminum and iron II ferrous iron are found at the start of the rainy season. This may explain the failure of farmers' attempts to grow early summer-autumn crops. Furthermore, the incorporation of the root remnants of the reed vegetation triggers strong reduction upon submergence resulting in other toxicities, which would affect traditional rice varieties transplanted in August.

The optimal time to start the cultivation of a crop is, therefore, at the end of the flood. Continuous submergence of the topsoil by irrigation preserves the optimal conditions throughout the cultivation of the winter-spring crop. Furthermore, the yearly re-acidification of the topsoil by deep cracks is prevented. At the end of the winter-spring crop, the soil is dried for two weeks to facilitate ripening. A summer-autumn crop can be grown directly after harvesting the winter-spring crop. The dry period should be kept as short as possible to prevent acidification of the topsoil and cracking of the underlying firm layer.

Field experiments

The objective of the field experiments at Hoa An during the dry seasons of 1990–1992 is to develop agronomic and water management strategies for farmers on severe acid sulphate soils. Based on the considerations mentioned above, after reclamation a winter-spring rice crop was broadcast before the recession of the flood. This crop was directly followed by a summer-autumn crop but monitoring was concentrated on the winter-spring crop.

Before the recession of the flood in 1990, a 1.4 ha field was reclaimed. The reed was cut manually and carried to the side of the field. The field was ploughed and puddled by four-wheel tractor but not levelled. Rice was broadcast and continuously irrigated until ripening. The mean yield was 2 t ha⁻¹. The rice plants growing along the sides of the field, however, yielded 4 t ha⁻¹. Explanations were sought in three directions:

- Deep reduction
  The centre of the field was lower than the sides. The soil was continuously submerged, attempts to drain the centre of the field failed due to low elevation. Plants may have suffered from a nutritional disorder associated with deep reduction;

- Leaching
  The topsoil along the drains was better leached than in the centre;

- Oxygen flow
  Along the sides of the fields, the water flow through the topsoil to the drain is higher compared to the center and brings oxygen into the soil, preventing deep reduction of the topsoil.
1991 dry season experiment

The 1991 experiment attempted to test the explanations mentioned above. To validate the deep reduction hypothesis, two irrigation treatments were applied:
- \( W_i \): Alternating wet and dry conditions in the topsoil. Regular drying of the field was achieved using a long irrigation interval;
- \( W_c \): Continuous submergence of the topsoil (farmers' practice).

The 'leaching effect' and 'oxygen flow effect' were investigated in two ways. Firstly, two inter-drain spacings were compared:
- \( D_{15} \): 15 m;
- \( D_{30} \): 30 m.

The effect of the drain on the leaching rate, the composition of the soil solution and the redox-potential within the field were studied in transects:
- \( S_1 \): Along the side of the field;
- \( S_2 \): At one-fourth of the field length;
- \( S_3 \): At the centre of the field.

The water management and drain spacing treatments were randomized in one block consisting of four plots (Figure 3). The transect study is executed in block 2, in 4 plots. In order to prevent disturbance of the soil during the measurements, bridges were built along the transects. The size of a plot was 30 \( \times \) 30 m. In order to cope with the high spatial variability observed in acid sulphate soils, 12 measuring points were installed per plot. Land preparation and cultivation were identical to the 1990 trial. Before broadcasting the rice, the topsoil was flushed four times to remove acid surface water developed after the land preparation.

In the main experiment, the following were monitored:
- Daily water levels in canals and fields;
- Composition of the soil solution and the surface water. The soil solution was taken
from a depth of 15 cm by suction from ceramic cups buried in topsoil. The soil solution was taken:
2 days before sowing (DBS): before the seedling stage;
8 days after sowing (DAS): at the end of the seedling stage;
42 DAS: at the end of the vegetative stage;
64 DAS: during the reproductive stage;
85 DAS: during the ripening stage.
The soil solution was analyzed for pH, EC, soluble aluminum, total titratable acidity after complete oxidation of the sample, and content of dissolved iron II estimated using indicator paper.

In the transect study, the following were monitored:
- Leaching rates through the topsoil, determined by the measurement of pressure heads in the topsoil and sulfuric horizon using piezometers. Leaching rates were calculated by a water flow model based on the finite element method;
- Redox potential in the topsoil at 5, 10 and 15 cm;
- Composition of the soil solution as in the main experiment.

Results of the 1991 winter-spring crop

Water levels
The irrigation schedule in the two water management treatments is shown in Figure 4. In the alternating submerged/dry treatment 6 distinct dry periods can be observed. In the continuously submerged treatment, the soil was left dry during the seedling stage, to prevent floating of rice seeds, and during the ripening stage. In the first period of cultivation, it was possible to keep water on the field for 8 days. During the reproductive stage, this period was reduced to 4 days due to a higher evaporative demand and occurrence of shallow cracks in the topsoil in the Wt treatment.

Composition of the soil solution
The composition of the soil solution in the water management treatments is presented in Figure 5. The pH in the Wc treatment remained at around 5 during the submergence of the soil, but pH decreased sharply after drying of the soil. In the Wt treatment,
the pH decreased directly to values around 4 during the vegetative and reproductive stages. During the ripening stage, the pH further decreased to 3.7.

The concentration of soluble aluminum fluctuated between 5 to 10 ppm in the Wi treatment, it increased steadily to reach 80 ppm during the ripening stage.
Table 2 Plant performance in the water management- and drainage-treatments

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plant height (cm)</th>
<th>Tiller number per 0.25 m²</th>
<th>Yield (ton ha⁻¹)</th>
<th>Tiller number per 0.25 m²</th>
<th>Weight per panicle (grams)</th>
<th>Empty grains (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>li</td>
<td>34.4*</td>
<td>200*</td>
<td>3.8</td>
<td>183</td>
<td>0.532</td>
<td>9.4*</td>
</tr>
<tr>
<td>lc</td>
<td>39.5*</td>
<td>234*</td>
<td>3.6</td>
<td>196</td>
<td>0.453</td>
<td>14.3*</td>
</tr>
<tr>
<td>n</td>
<td>48</td>
<td>48</td>
<td>12</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
</tbody>
</table>

Note: The values indicated by * are significantly different at an 0.05% interval

In the Wc treatment, the estimated level of Fe²⁺ remains at a low level of 10 to 20 ppm. The low concentration may be explained by precipitation as ferrous sulphide. In the Wl treatment, the estimated concentration is higher compared to the Wc treatment: 40 to 60 ppm, perhaps due to repeated peaks after periods of oxidation. No significant differences were found in the D15 and D30 drain spacing treatments and S1, S2, S3 locations in the transect study.

Plant performance
In the Wl treatment, plant development was normal during the seedling stage but, during the vegetative stage, both roots and shoots were stunted. At the start of the reproductive stage, plant height and number of tillers were low (Table 2). However, the plants recovered and showed normal development until harvest.

In the Wc treatment, early development was luxuriant but, in the reproductive stage, plants/roots lost their brown colour, turned white, then black and, finally, died.

There was no significant difference between the yields of the Wl and Wc treatments. The percentage of empty grains in the Wc treatment was, however, significantly higher compared to the Wl treatment.

Results of the transect study
No significant differences in redox potential, composition of the soil solution and leaching rate were found at varying distances from the side of the field. The calculated leaching rates were rather erratic.

Economics
In Table 3, the initial investments needed to reclaim the land, together with the variable costs of cultivation and yield are presented. The break-even point of cultivation is at 2.15 t ha⁻¹. With the production of 3.9 t ha⁻¹, the profit is sufficient to pay back the initial investments for canal digging and land preparation. It is expected that yields in the future crops will improve due to gradual leaching of toxic substances and better levelling.

Pollution
The quality of the irrigation water was good throughout the cultivation of the crop. The quality of the drainage water was, however, very bad (Table 4).
Table 3 Economic parameters of the 1991 winter-spring in thousands VND ha\(^{-1}\) and kg rice ha\(^{-1}\)

<table>
<thead>
<tr>
<th>Unit</th>
<th>Initial investments</th>
<th>Variable costs</th>
<th>Yield of</th>
<th>Yield of</th>
<th>Yield of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>moving roots</td>
<td>cutting reed</td>
<td>pulling leveling</td>
</tr>
<tr>
<td></td>
<td>digging of canals</td>
<td></td>
<td>846</td>
<td>176</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>kg rice/ha</td>
<td></td>
<td>940</td>
<td>196</td>
<td>196</td>
</tr>
</tbody>
</table>

The pH of the drainage water varied between pH 3.4 and 2.6. The amount of drainage water from the field is equal to a water layer of 154 mm per crop. The amount of acidity leached into the canals is roughly 5000 mol soluble aluminum per ha per crop, an a total acidity of 23000 mol acidity per ha per crop.

Discussion

**Deep reduction**

The results from the 1991 trial indicate clear effects of the water management on the agronomic parameters, composition of the soil solution and the redoxpotential. The rice plants in the soil under continuous submergence showed symptoms of iron toxicity during the reproductive stage and, in a later stage, a large part of the root system died. Although the plant symptoms indicate iron toxicity, iron cannot be held directly responsible for the nutritional disorder observed. The estimated level of dissolved iron in the W\(_c\) treatment never exceeded 10 ppm. Soluble aluminum during the reproductive stage did not exceed 5 ppm. The soluble aluminum level in the W\(_i\) treatment showed much higher values. At the start of the reproductive stage a redox potential of +6 mV was measured in the root zone of the W\(_c\) plots. The redox potential in the regularly oxidized plots was significantly higher: +290 mV. Unfortunately the redoxmeasurement during flowering failed. In soil solution samples, taken during the reproduc-

Table 4 Quality of surface water and amount of toxic elements leached into the surrounding canals

<table>
<thead>
<tr>
<th>Days after sowing:</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-2</td>
<td>8</td>
<td>41</td>
<td>64</td>
<td>85</td>
</tr>
<tr>
<td>Irrigation canal:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-</td>
<td>6.3</td>
<td>6.8</td>
<td>6.3</td>
<td>6.8</td>
</tr>
<tr>
<td>soluble aluminum (ppm)</td>
<td>1.3</td>
<td>-</td>
<td>7.2</td>
<td>1.8</td>
<td>1.35</td>
</tr>
<tr>
<td>total acidity (mol/l)</td>
<td>0.29</td>
<td>-</td>
<td>0.56</td>
<td>0.23</td>
<td>0.15</td>
</tr>
<tr>
<td>Drainage canal:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-</td>
<td>3.4</td>
<td>2.9</td>
<td>2.9</td>
<td>2.6</td>
</tr>
<tr>
<td>soluble aluminum (ppm)</td>
<td>19.5</td>
<td>-</td>
<td>56.7</td>
<td>148</td>
<td>129</td>
</tr>
<tr>
<td>total acidity (mol/l)</td>
<td>0.29</td>
<td>-</td>
<td>10.7</td>
<td>26.2</td>
<td>23.3</td>
</tr>
</tbody>
</table>

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tive stage in the W e plots, a strong H₂S smell was detected. Large amounts of black decaying remnants of *Eleocarpus dulcis* roots were found. The roots were incorporated into the soil during the land preparation.

Based on these observations, the following mechanism is believed to be involved (Moorman and Van Breemen 1978, Van Breemen 1980), (see Figure 6). In order to survive in a predominantly reduced environment, the rice plant pumps oxygen downward through the root, creating an oxidized zone around it. In this oxidized zone around the root, iron III is precipitated as a brown crust of Fe³⁺ hydroxides, preventing the uptake of excess Fe²⁺ ions, usually present in reduced soils. Locally, in the presence of decomposing root remnants, very strong reduction takes place. In these reduced conditions, reduction of sulphates to sulphides can take place, which can be recognized by a black colour and strong H₂S smell. In the presence of a decomposing root remnant, the iron III hydroxides in the oxidized layer are reduced to Fe²⁺, as can be seen by the disappearing of the brown crust around the root. Now Fe²⁺ ions can freely enter the root and the rice plant, resulting in brown colouring of the plant. In a later stage, rice roots are covered by black FeS and die. The dead rice roots are added to the amount of fresh decomposing organic matter. The nutritional disorder asso-
ciated with deep reduction may therefore be described as H₂S-induced iron toxicity.

To prevent the deep reduction, in the \( W_t \) treatment, the topsoil was oxidized regularly by applying a long irrigation interval. This resulted in a nutritional disorder during the vegetative stage. Plants and roots were stunted. The estimated level of iron III during the vegetative stage was around 50 to 70 ppm. At this level no toxicity is to be expected, even at low nutrient levels. No clear leaf symptoms were observed. The concentration of soluble aluminum in the \( W_t \) treatment was significantly higher compared to the \( W_c \) treatment. During the vegetative stage the concentration increased from 5 to 40 ppm. In the \( W_c \) treatment soluble aluminum increased from 5 to 8 ppm. Concentrations of soluble aluminum considered toxic for rice roots mentioned in the literature vary widely (Van Mensvoort et al. 1985; Tanaka and Yoshida 1970; Tanaka and Navasero 1966; IRRI 1978). Since nutritional disorders other than aluminum toxicity are not expected, it may be concluded that the plants were suffering from a mild form of aluminum toxicity.

In the course of the reproductive stage, the plants in the \( W_t \) treatment recovered despite an increasing concentration of soluble aluminum. The key to recovery can probably be found in the physical soil condition. In the course of the reproductive stage, due to repeated drying of the soil in the \( W_t \) treatment, shallow cracks were formed. Root development was concentrated in the suitable environment along the cracks. In the soil matrix only some thick, stunted roots, typical for aluminum toxicity, were found.

**The leaching effect**

The lack of evidence supporting the 'leaching theory' may be explained by the physical characteristics of the soil. Before cracking, hardly any flow occurs due to the low permeability of topsoil and hardpan. After repeated drying of the topsoil, cracks occur between 20 to 30 cm large soil prisms, and the cracks penetrate down to the transition between the topsoil and hardpan. Water is able to move relatively fast through the large cracks without influencing the soil solution inside the soil matrix.

**The oxygen-flow effect**

No significant differences between redoxpotentials were found along the transects, and between the 15 and 30 m. drain distance. The redoxstatus seems to be fully controlled by the wetting or drying of the heavy clay soil, rather than by oxygen transported by water flow.

It must, however, be noted that the yields of fields having a drain spacing of 15 to 30 m, as in the 1991 winter-spring crop were 3.8 ton/ha, whereas the yield in the field having a drain spacing of 70 m (1990 winter-spring) yielded only 2 ton/ha. The large difference in yield between the fields may be explained by the bad leveling of the 70 m. field, while the 30 and 15 m fields were excellently levelled.

**Conclusions and recommendations**

1) The cultivation of an irrigated winter-spring crop on a severe acid sulphate soil in Hoa An station is economically and technically feasible.
2) There is strong evidence for the effect of strong reduction on plant performance. Plants growing under continuously submerged conditions were suffering from a nutritional disorder which can be described as H₂S-induced iron toxicity. The nutritional disorder occurred in the course of the reproductive and ripening stages and resulted in a significantly higher percentage of empty grains. Regular oxidation of the topsoil as a remedy to the nutritional disorder associated with deep reduction brings about another nutritional disorder: aluminum toxicity. Regular oxidation of the topsoil does not result in a significantly higher yield. An ideal water management strategy may be found by limiting the dry periods to one or two periods just before the flowering. This way, aluminum toxicity during the vegetative stage is prevented, as well as deep reduction during the flowering. It may be helpful to dry the soil intensively to induce cracking of the topsoil.

3) The redox status of the soil seems to be more important than the leaching rate in determining plant performance, occurrence of nutritional disorders and composition of the soil solution. The redox status of the soil can be controlled by managing the drainage. No evidence was found to support the role of the flow of oxygen-rich water through the topsoil into the drains in controlling the redox status of the soil.

4) Good leveling is essential to control the drainage. If equipment or labour are scarce, shallow drains can be used to drain surface water from the lowest parts of the field.

5) Pollution of surrounding canals by acid drainage water from a newly reclaimed field is a fact. Irrigation and drainage canals should be separated at tertiary level. At primary and secondary level, sufficient flow is needed to prevent undesirable high concentrations of acidity in the canal water.

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