An overview of water management of acid sulphate soils

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Abstract

The paper addresses the issue whether water management is the key and the only practical way to reclaim and ameliorate a large area of acid sulphate soils. It reviews recent developments in water management practices with special emphasis on leaching, flushing and deacidification measures. Their success and failure is related to the critical role of water and its movement in initiating chemical and physical processes in the soil. Therefore, the choice of suitable practices depends strongly on the surrounding hydrological conditions of the environment and the physical properties of the soil. Labour, the amount of water needed, and possible environmental consequences may pose severe limitations to the application of water management measures for reclamation on a large scale.

Introduction

In most cases, severe acidity and the large areas of land involved prohibit reclamation of acid sulphate soils by chemicals (e.g. liming) because of the high costs. Appropriate water management has been identified by several authors (Dent 1986, Sen 1988a) as the only practical way to manage these soils. Water management is imperative because most acid sulphate soils are in extreme and hostile hydrological conditions, such as waterlogging during the rainy season and lacking water in the dry season. It is not surprising that many water control measures have been tried out by farmers, governmental and private agencies as one of the first steps in the process of reclamation. Their efforts have met with both success and failure, and it is not uncommon that mistakes have been repeated. This is an indication of the poor distribution of available knowledge on the reclamation of acid sulphate soils.

The purpose of this paper is to give a review of recent developments in water management in Southeast Asia and elsewhere in the world with special emphasis on (i) watertable management, (ii) surface water management and (iii) leaching, and on the analysis of their interaction and adaptability to different hydrological, environmental conditions and the soil physical properties.

Watertable management

*Optimum watertable level*
Detrimental effects of pyrite oxidation by lowering the watertable in coastal potential
acid sulphate soils on crop yields were reported by Beye (1973), Kanapathy (1973), and Yin and Chin (1982). Such studies led to one of the general recommendations for management of potential acid sulphate soils: controlled high watertable to keep the sulphidic subsoil waterlogged (Dent 1986) and, hence, prevent acid formation.

This recommendation puts emphasis on the role of water in controlling the chemical processes in acid sulphate soils. Water is also a medium of transport of toxicities and nutrients in the soils. Watertable management should also be analyzed in its relation to evaporation by which toxins accumulate in the surface horizon through upward flux of solutes during a dry period. This is of particular importance in areas with a long dry season and with bad groundwater quality. Any attempt to check the oxidation of pyrite by keeping the watertable high is counteracted by an increased evaporation and transport of acidity to the surface horizon. Keeping the watertable high does not necessarily reduce the toxicities at the rootzone. Sen (1988b) reported that, regardless of the watertable levels, the average total acidity and pH over the upper 30 cm of potential acid sulphate soil columns did not show much variation (Table 1) though lower watertables enhanced the oxidation of pyritic materials.

Where the sulphidic horizon occurs near the surface, high watertable will impede leaching of the accumulated salts, the workability of the soils and reduce the aerated zone for root development of upland crops. This might be the reason for yield difference, as reported by Dent (1986), of about 8 t ha⁻¹ of oil palm on normal, non-acid soils and on acid sulphate soils with high watertable management at 0.6 m.

For actual acid sulphate soils, few data exist on the effects of keeping the watertable above the oxidized horizon. Theoretically, there can be no further deterioration of soil properties resulting from exposure of a completely oxidized sulphuric horizon to the air because oxidation of pyrite has been completed. Konsten et al. (1990a) in Kalimantan detected no signs of further acidification when the watertable dropped and exposed the sulphuric horizon of acid sulphate soils to the air during the dry period.

### Table 1

<table>
<thead>
<tr>
<th>Column number</th>
<th>Groundwater level (cm)</th>
<th>pH</th>
<th>EC (mS/cm⁻¹)</th>
<th>Average total acidity (mol m⁻³)</th>
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<td>6</td>
<td>65</td>
<td>3.49</td>
<td>1.16</td>
<td>1.19</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>3.54</td>
<td>1.08</td>
<td>1.13</td>
</tr>
<tr>
<td>8</td>
<td>65</td>
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<td>12*</td>
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<td>40</td>
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<td>1.14</td>
<td>0.83</td>
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<tr>
<td>14</td>
<td>65</td>
<td>3.62</td>
<td>1.08</td>
<td>1.04</td>
</tr>
</tbody>
</table>

* control column
Table 2 Changes in chemical properties of the top soil layer of an actual acid sulphate soil due to capillary rise from different watertable depths (Tuong et al. 1993)

<table>
<thead>
<tr>
<th>Water table depth (cm)</th>
<th>pH</th>
<th>Soluble acidity (cmol kg(^{-1}))(^a)</th>
<th>Soluble Al(^{3+}) (cmol kg(^{-1}))(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(1)</td>
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<tr>
<td>30</td>
<td>3.6</td>
<td>3.4</td>
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<td>60</td>
<td>3.1</td>
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<td>15</td>
</tr>
<tr>
<td>90</td>
<td>3.5</td>
<td>3.5</td>
<td>13</td>
</tr>
</tbody>
</table>

(1) initial value
(2) 90 days after start of the study
\(^a\) Soluble acidity and Al\(^{3+}\) measured in saturation extracts

season. Likewise, not much will be gained by keeping the watertable high in these ‘mature’ soils because submergence of the jarosite layer is not followed by a lowering of the redox potential or an increase in pH (van Breemen 1976, Danh 1991). This is due to low content of organic matter and the extremely acid conditions in which iron-reducing bacteria are absent. In these soils, a deep watertable is recommended because it reduces capillary rise from the groundwater and the accumulation of acid salts at the top soil horizon as illustrated in Table 2. In practice, tangerine farmers in Nakorn Nayok province, Thailand, keep watertable levels at more than 1.5 metres in an acid sulphate soil where the jarosite layers start at 60 cm (Charoen and Maneewon 1989). Keeping watertable low is particularly important to avoid the upward transport of acid water to the rootzone when there is bad quality groundwater influx from surrounding areas (Kselik 1990).

In recently-oxidized acid sulphate soils, pyrite may still exist in the inner cores of the soil peds of the sulphuric horizon and may be oxidized if the watertable drops for an appreciable time. This may be the reason for Xuan’s recommendation (1987) that both the sulphidic and sulphuric horizons should be kept in submerged conditions. The determination of optimum water level in these soils requires further research to find an optimum balance between the rate of acidification and rate of toxicity accumulation on the surface layers.

Practical difficulties in watertable management

The success of a high watertable strategy for potential acid sulphate soils has been demonstrated for oil palm by Yin and Chin (1982) and for grassland in North Western Europe and New Zealand (Dent 1986). It is, however, important to recognize the practical difficulties in maintaining the watertable at the desired depths on a large scale. One of them is the spatial variation in depths of the sulphidic and sulphuric horizons. Sometimes they vary greatly at distances less than 50 m (e.g. Burrough et al. 1988). To be effective in preventing oxidation of pyrite, the watertable has to be kept at different levels at different parts of a water management scheme. This may complicate the management of the system to an impracticable level on a large scale. It is imperative to have detailed maps of depths of these diagnostic horizons and to plan and operate the hydraulic components accordingly. In most cases of opening up new areas, these maps are not available.
Another difficulty is associated with the required density of canal networks to be compatible with the hydraulic conductivities (K), the transmissivity (T) of the soils and the climate. Watertable in areas with fairly high K and T can be controlled by manipulation of water level in the drainage canals spaced at reasonable distances. Such a situation prevails in South Kalimantan, Indonesia, where T is reported to be in order of hundreds of metres per day (Hamming et al. 1990) and as a consequence watertable varied only about 20 cm over a distance of few kilometres between the two main drainage canals (Figure 1a). Watertable cannot be controlled with the same ease in situations, like in Vietnam, where a long dry season exists and the hydraulic conductivity is in the order of 0.1 m day$^{-1}$ (Thuan 1989). Results from a simulation run by Thuan indicated that the general groundwater level in the Plain of Reeds, Vietnam, at the end of the dry season is not affected by the provision of drainage canals at 200 m intervals. Field measurements (Tuong et al. 1988) showed that the groundwater level at the end of the dry season dropped sharply at the first 10 metres away from the canal, and steadily decreased with the distance away from the canal (Figure 1b). Obviously, high evaporative demand over a long dry season created a loss of water through capillary rise which was not adequately compensated by recharge from...
the surrounding canals through slowly-permeable soil. In this situation, if the water-table is to be controlled by canals, very dense networks at distances less than 20 m will be needed. High labour requirements would discourage such a solution on a large scale.

**Surface water management**

The rate of reduction in acid sulphate surface soils is known to be slow (Ponnampet-uma et al. 1973, Van Breemen 1976). This is particularly true for ripe acid sulphate soils as further evidenced by recent experiments. Ritsema et al. (1991) indicated no spectacular pH effects for actual acid sulphate soils during prolonged submergence. Satawathananont et al. (1991) reported (Figure 2) no appreciable reduction in soluble aluminum after 6 months of submergence in two out of three ripe acid sulphate soils. Obviously, from the soil amelioration point of view, keeping these ripe soils under submergence is not a necessary measure, though the presence of the surface water will help suppress the capillary rise of toxicities to the rootzone.

In raw acid sulphate soils, surface layers are often rich in organic matter and iron. Reduction is much faster but prolonged submergence will not necessarily reduce water soluble Al concentration to a non-toxic level, even though the pH may have increased to higher than 4.4 (Satawathananont et al. 1991). It is commonly observed in raw acid sulphate soils that rice plants in the higher spots of waterlogged fields perform better than those in continuously-submerged locations. This may be attributed to 'side effects' of submergence: increase in dissolved iron II and/or H₂S and the acidification of the surface water (Van Breemen 1976). Hanhart and Ni (1991) proposed a compromise of intermittent drainage. They found that rice grown under intermittent drainage had healthier root systems, less empty grains, heavier weight per panicle. Rice in continuous submergence showed strong bronzing symptoms but had more tillers.

![Figure 2 Changes of water-soluble and extractable Al with time in stirred suspensions of four acid sulphate soils under incubation in a closed system. Ma, Rs, Rsa are raw acid sulphate soils. Bg is pre-oxidized potential acid sulphate soil (data from Satawathananont et al 1991)](image_url)
Table 3 Plant development and yield of rice grown on a severe acid sulphate soil in Hoa An, under continuous submergence (Ic) and with wet/dry cycles (Ii). (Data from Hanhart and Ni 1991).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plant height at day 48, cm</th>
<th>Tiller number at day 48 per 0.45 m²</th>
<th>Yield, ton ha⁻¹ per panicle</th>
<th>Weight per Empty grains, per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ii</td>
<td>34.4*</td>
<td>200*</td>
<td>3.8</td>
<td>0.532</td>
</tr>
<tr>
<td>Ic</td>
<td>39.5*</td>
<td>234*</td>
<td>3.6</td>
<td>0.453</td>
</tr>
</tbody>
</table>

(Note: The values indicated by * are significantly different at a 0.05% interval)

(Table 3). Further research is needed to arrive at an optimum surface water management strategy for these raw acid sulphate soils.

Leaching

Positive effects of leaching of acid sulphate soils have been reported Ponnamperuma et al. (1973), Kivinen (1950), van Breemen (1976). However, most early studies were carried out in small, homogenized samples or in small pots where the water flow pattern and soil physical properties were greatly modified as compared to the real field conditions. This is unfortunate, because the rate of leaching and therefore its field applicability depend on those properties.

Undisturbed soil core and field experiments indicate that leaching of acid sulphate soils is a slow and water-demanding process. Table 4 gives a summary of findings on leaching of aluminum in the top 25 cm of undisturbed soil samples. Aluminum is chosen because it is likely to be the principal hazard for agricultural crops and can become toxic at concentration as low as 2 ppm in the solution (Dent 1986). Leaching aluminum from undisturbed soils is particularly difficult. Even one metre of water was not adequate to bring the aluminum concentration of the rootzone to a safe level for plant growth.

Field evidence indicates that leaching of undisturbed soils is not only a slow process but is limited to a fringe of about 10 m along the drainage canals where there is inadequate exchange of water between the canal and the soil body (Figure 3). The limited

Table 4 Effects of leaching on aluminum concentration in soil solution at depths 20-25 cm of undisturbed severe acid sulphate soils by various authors

<table>
<thead>
<tr>
<th>Authors</th>
<th>Days of leaching</th>
<th>Water used cm</th>
<th>Al³⁺ in soil solution at depth 20-25 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Before leaching mmol(+) L⁻¹</td>
</tr>
<tr>
<td>Sen 1988a</td>
<td>30</td>
<td>100-450</td>
<td>33</td>
</tr>
<tr>
<td>Tuong et al. 1993</td>
<td>15</td>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>1300</td>
<td>10</td>
</tr>
<tr>
<td>SIWRR 1990</td>
<td>63</td>
<td>450</td>
<td>9.3</td>
</tr>
<tr>
<td>Konsten et al. 1991</td>
<td>200</td>
<td>&gt;1000</td>
<td>&gt;20</td>
</tr>
</tbody>
</table>

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Figure 3 Variation of Al and SO$_4^{2-}$ in soil solution at three different depths as function of distance from a drainage canal in the acid sulphate soil area of Cu Chi, Vietnam.

effects of leaching and flushing of undisturbed soil in the field are also shown in Figure 4, which presents pH of the surface water of a fish pond in acid sulphate soil area at Cu Chi, Ho Chi Minh City, after a six-month effort of leaching with nearly neutral water at a rate of 20 mm day$^{-1}$. A large area in the middle of the pond, with pH lower than 3.5, appeared not to be affected by the leaching process. The findings help explain why areas subjected to annual overland flooding, like the Plain of Reeds, remain acidic for years.

Konsten et al. (1990b) also reported slow leaching under natural conditions in Pulau Petak, Kalimantan where annual rainfall is about 2300 mm. They estimated that the annual leaching amounted to 1.3 per cent of the total acidity present in the upper 65 cm. At this rate it will take at least 80 years to get rid of the all acidity. In poorer drained areas it may take longer.

Some processes during leaching
One of the reasons for the persistence of aluminum in the soil solution during the leaching process is that a portion of the aluminum in the soil complex is slowly released into the solution (SIWRR 1990, Konsten et al. 1991, Van Mensvoort et al. 1991). The greater part of leached aluminum over the initially present soluble aluminum in layer 0-5 and 0-25 cm in Figure 5 must have come from this release.

The release can be interpreted as a reestablishment of equilibrium of the soil-water system, which was upset by the leaching process. It is impossible to determine which of the processes of cation exchange, dissolution or desorption is responsible for the release of aluminum and sulphate into the soil solution. Possibly, it is the dissolution of jurbanite, as indicated by Van Breemen (1976) and Danh (1991).

Another important aspect affecting the leaching rate in heavy clay acid sulphate soils is the distribution of flow in the soil profile. Water percolating through the soil mainly passes round, rather than through, the peds. Solutes held within the peds are, therefore, protected against leaching until they diffuse to the ped surface. ‘By pass’ flow is responsible for the removal of solutes from the soil body but, at a later
A Layout of the fishpond

B pH of surface water

Figure 4 Layout (A) of a 900 x 400 m fish pond being reclaimed in an acid sulphate soil, Cu Chi with continuous water flow of approximately 20 mm/day. pH of surface water after six months along 5 transects and at various distances from the right ring canal is shown in (B).

stage of leaching, it is the intra-ped diffusion which controls the rate of leaching. This diffusion may be responsible for the increase of Al in the soil solution during the submergence following the leaching process in Figure 6. In this case, the rate of release of $\text{Al}^{3+}$ into the solution appears to be very slow: after 90 days, the average concentration of $\text{Al}^{3+}$ in soil solution layer 25-50 cm increased about 1.5 meq/l (Figure 6), equivalent to only about 1 per cent of the KCl-extractable aluminum in the layer.

The arrangement and sizes of macro-pores and aggregates will have a strong influence on both 'by pass' flow and the extent to which diffusion proceeds towards equilibrium and, therefore, on the leaching process. The initial distribution of solutes within soil aggregates is also important.

Enhancement of leaching via land preparation
Proper land preparation and its timing to form suitable soil aggregates and to influence the initial solute distribution can enhance the leaching rate. Tuong et al. (1993) showed
that ploughing and drying the soil under the sun for two weeks before leaching improved the leaching rate and could reduce Al concentration in the soil solution considerably as compared to non-ploughed plots (Figure 7). It was postulated that, under the drying process, Al moved to the outside of the soil crumbs where it has better contact with the fast-moving water and, thereby, is removed more efficiently. The postulation was supported by consistently higher concentration of soluble ions in the outer 3 mm of the soil crumbs as compared to that of the inner cores (Figure 8).

Farmers in the Mekong Delta plough their land, then leave it fallow and submerged in flood water before taking advantage of the recession of the flood to flush the root zone of about 20 cm. The flushing process begins when the flood depth lowers to about 40 cm and is achieved in combination with land preparation: the field is harrowed and puddled before the water is drained out of the field. Flood water is readmitted and the cycle of flushing and puddling is repeated several times. Farmers claim

![Figure 5 Al³⁺ leached out of three soil layers as compared with soluble Al³⁺ originally in the soil solution within the layers before leaching. Total leaching time: 63 days at 7 mm day⁻¹ (SIWRR 1990)](image)

![Figure 6 Changes in Al³⁺ in soil solution at sampling depths 5, 25, 50 cm of an undisturbed acid sulphate soil column. Data from SIWRR (1990)](image)
that the harrowing and puddling processes ‘stir up’ and dissolve the toxic elements which then can be removed with the water.

Other remarks on leaching
To sum up, the leaching process of acid sulphate soils involves many complicated mechanisms which are not yet fully understood. Further research is needed to arrive at quantitative expressions for the amount of water needed for the leaching process. It appears, however, that severe acid sulphate soils need water in the order of 1 m for the initial leaching to remove the free acid which is accessible to moving water, creating initial conditions suitable for root growth in macropores. A considerable quantity of acid still remains in the soil peds and in the exchange complex. If not properly managed, its subsequent release into the soil solution presents a risk of aluminium and other toxicities at a later stage to plants grown on leached soils. It was noticed (Van Mensvoort et al. 1991, Sen 1988a) that during the first 15-30 days after transplanting, rice grew well on newly leached soils but, then, the growth was retarded. In some cases (Tuong et al. 1993), the rice plants performed very well in the vegetative stage but produced only empty panicles. It is, thus, important to realize that leaching is not a once and for all measure of soil amelioration. In order to maintain soluble acidities of the macropores at a safe level for root growth, leaching (or flushing) should be continued during the plant growth cycle. Leaching may have to be repeated for many years before the soil can be said to be free of acidity.
Leaching also removes valuable basic cations which further worsens the already low nutrient status of most acid sulphate soils. Chemical amendment is imperative in leached acid sulphate soils.

When adequate fresh water is available and properly managed, leaching can turn acid sulphate soils into productive soils, but the opportunity cost of water use should be analyzed critically when irrigation water is also in high demand for other areas. Techniques to enhance leaching efficiency by use of rainfall and flood water should be further investigated.

Environmental impact of leaching and drainage of acid sulphate soils

Reclamation, leaching and drainage of acid sulphate soils for agricultural cultivation affects the environment, especially the aquatic one. As an extreme example, Sterk (1991) calculated that a shower of 36.3 mm in 30 minutes could leach 143.6 mmol(+) m\(^{-2}\) of acidity from the topsoil of a new (three months) raised bed of acid sulphate soil. Figures calculated from changes in concentration of the soil and soil solution range from 1 to 3 mol(+) m\(^{-2}\) per cropping season (Konsten et al. 1990b, Hanhart and Ni 1991). It is not uncommon that the pH in tertiary canals and farm ditches of the reclaimed area remains less than 3, with aluminum concentration exceeding 3 mol(+) m\(^{-3}\) (Kham 1988, Chairuddin et al. 1990). The pollution is not confined to the reclaimed area. Through diffusion and mass transport, acidity concentration is diluted but contaminates a much larger surrounding area. Figure 9 illustrates such a contamination in the Plain of Reeds, Vietnam (Kham 1988) where pH of the surface water remained below 5 during the rainy season on almost all the 500,000 ha of the Plain. Higher pH values due to the mixing of the river water at high tides, was only possible along a belt of about 10 km from the Mekong river where pH is 7.5-8.0.
Similar contamination on a large area was reported by Chairuddin et al. (1990) for Pulau Petak, Indonesia. Acid water contamination may have profound effects on the aquatic population of the area. Grimas (1988) reported a chronic ‘depressed’ benthic situation (both regarding the abundance of the benthic animals and the number of species) in the centre of the Plain of Reeds, approximately coinciding with the most heavily polluted area with aluminum concentration higher than $0.3 \text{ mmol(+) m}^{-3}$ (Figure 9).

Fish production in the Plain of Reeds has not been studied quantitatively, but it is expected to be greatly affected by acid pollution of the water and/or by the decrease of food, for example the benthic communities. Elsewhere, strongly negative effects of flushes of severe acidity from reclamation of acid sulphate soils in coastal mangrove forests on shellfish, crustacea and fish was reported by Marius (1982) and from inland acid sulphate soils on fish population by Chairuddin et al. (1990). Both species diversity and abundance of fish population were approximately halved in the polluted area (Tabunganen) as compared to the surrounding, not-polluted areas of Pulau Petak, South Kalimantan. Somewhat paradoxically, the authors found that the amount earned by fishing was highest in the most acidified area. This was the result of a higher fishing effort and more time spent in selling the fish directly to the consumer rather than because of particularly good fishing grounds. This shows the importance of fisheries in providing extra income in areas where farming is less successful due to acidity problems.

The negative effects on the fish population of acidification of canal waters by leaching of acid sulphate soils, and the importance of fisheries for farmers’ income and diet, make careful management of these resources imperative. Simulation techniques may offer a predictive tool to study the degree and extent of pollution from develop-
ment plans and can, possibly, ensure that the negative effects are within the 'absorbing' capacity of the surroundings. Conservation of part of the swampy area is highly recommended. Another option in already-devastated areas is the restoration of swamp forests. This will not return the soil to its properties before acidification but will minimize the acid pollution to the surroundings. Such a method has been tried out in the Plain of Reeds by dikebuilding and tree planting for the establishment of more than 5,000 ha of wetland forest (Duc 1988, Rome 1990). After a few years, the wetland regained a resemblance of the original wetland forests in health and appearance and, once again, became a feeding ground for fish and suitable environment for the home-coming of once-driven-away red headed cranes (Rome 1990).

References


Rome 1990. Coming home. In Vietnam, a majestic bird rises from the ashes of war. Sirea, 75,2


Effect of land preparation on leaching of an acid sulphate soil at Cu Chi, Vietnam

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Abstract

A large part of the severe acid sulphate soil areas of the Mekong Delta, Vietnam is underlain at a depth of 15-30 cm, by a slowly-permeable layer which impedes water movement and reduces leaching. This paper reports an attempt to enhance the leaching in an aeric sulfaquept by breaking this layer. Three treatments are applied: (i) a control without preparation before leaching, (ii) hoeing to the depth of 10-15 cm followed by sun-drying for two weeks, and (iii) hoeing to the depth of 20-25 cm and sun-drying for two weeks before leaching. The effect of leaching was greatly enhanced by land preparation and sun-drying. Toxicities were removed faster and water was used more efficiently. In the non-hoed treatment, after four weeks and approximately 1300 mm leaching water, the toxicities remained high enough to inhibit rice growth while in other treatments they were reduced to a much lower level with less water and in a shorter period. The effects are explained by the movement of water through the soil profiles and the distribution of toxicities within the soil crumbs subjected to the drying process.

Introduction

The texture of most of the 1.6 million hectares of acid sulphate soils of the Mekong Delta is heavy clay (Mekong Delta Integrated Survey Program 1986). Its low permeability and structure impede water movement and inhibit leaching. Farmers invariably practice leaching in combination with various land preparation techniques. They claim that leaching can be greatly enhanced by ploughing and fallowing before leaching. This study aims at quantifying the effects and identifying possible mechanisms by which ploughing followed by fallowing modifies the leaching process.

Materials and methods

Soil and site of experiment

The experiment was carried out from March 6, 1989 and lasted for thirty days in an abandoned field of acid sulphate soil in Cu Chi district, 50 km Northeast of Ho Chi Minh City. This area is flooded from August to January, with a maximum flood depth up to 40 cm in September-November. Previously, the watertable in the dry season was more than 80 cm below surface. Seepage from an irrigation canal constructed in 1987, has raised the dry season watertable to about 40 cm and aggravated the waterlogging problem.
Table 1 Some chemical properties of soil in the experiment, Cu Chi

<table>
<thead>
<tr>
<th>Depth cm</th>
<th>pH H₂O</th>
<th>pH KCl</th>
<th>EC mS cm⁻¹</th>
<th>Acid* mmol c⁻¹ kg⁻¹</th>
<th>Al* %</th>
<th>Ca kg⁻¹</th>
<th>Na %</th>
<th>K %</th>
<th>N Tot %</th>
<th>OM %</th>
<th>Am. Fe** mg/100 g</th>
<th>Av. P*** %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
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<td>2.8</td>
<td>2.5</td>
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<td>183</td>
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</tr>
<tr>
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<td>0.8</td>
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<td>145</td>
<td>21</td>
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<td>0.36</td>
<td>11.7</td>
<td>0.22</td>
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<td>3.2</td>
<td>0.7</td>
<td>179</td>
<td>145</td>
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<td>153</td>
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<td>26</td>
<td>2</td>
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<td>135</td>
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<td>2</td>
<td>0.10</td>
<td>2.1</td>
<td>0.17</td>
<td>0.24</td>
</tr>
</tbody>
</table>

* in a 1 M KCl extract  
** iron extracted with ammonium oxalate  
*** in a 0.01 M sulphuric acid extract

The soil is a Typic sulfaquept, with sulfuric horizon extending from 40 cm depth to the sulfidic material at 135 cm. The whole soil profile is characterized by very low pH and high exchangeable aluminum (Table 1).

Some soil physical properties are presented in Table 2. The original, unploughed soil had by low permeability, especially at depth 20-40 cm.

Treatments and experiment layout

The treatments were three levels of land preparation before leaching:
P1: Land was not prepared  
P2: Land was hoed once to 10-15 cm and dried in the sun for two weeks  
P3: Land was hoed twice to 20-25 cm and dried in the sun for two weeks

The treatments were arranged in a complete randomized block with three replications. Each plot was a 1.5 m x 1.5 m (Figure 1), with sides of wooden planks driven into the soil 20 cm. The wooden sides were designed to reduce the lateral seepage from the plot, which was further minimized by 2.5 m x 2.5 m ‘buffer zones’ where the water level was kept at the same level as in the inner plot. Leaching water was applied to

Table 2 Some hydraulic characteristics of soil in the experiment, Cu Chi

<table>
<thead>
<tr>
<th>Depth cm</th>
<th>Vertical Saturated Hydraulic Conductivity (m day⁻¹)</th>
<th>Horizontal Saturated Hydraulic Conductivity (m day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1</td>
<td>P2</td>
</tr>
<tr>
<td>0-10</td>
<td>0.15</td>
<td>1.79</td>
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<tr>
<td>10-20</td>
<td>0.30</td>
<td>0.13</td>
</tr>
<tr>
<td>20-31</td>
<td>0.03</td>
<td>–</td>
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<tr>
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<td>0.16</td>
<td>0.16</td>
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<td>42-53</td>
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</tr>
<tr>
<td>53-65</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Note: P1 = control  
P2 = hoed to depth 10-15 cm  
P3 = hoed to depth 20-25 cm
the experimental plots from a calibrated tank, leachate was collected from drains surrounding the experimental plots.

**Sampling and chemical analyses**

Each experimental plot was equipped with a battery of six tubes to extract soil solutions at depth 0-5, 5-15, 15-25, 25-35, 35-45 and 55-65 cm. The construction of soil solution tubes was similar to that described by van Breemen (1976) with some modification to avoid vertical leakage along the tube side and to enhance free flow of soil solution at the sampling depths into the tubes. Samples were taken by pre-vacuumed bottles at the start of the leaching treatment and 0.5, 1, 2, 4, 7, 14, 21 and 30 days thereafter.

The pH and electrical conductivity (EC) of the solution were measured within one hour after sampling. Other constituents were analyzed as described in Begheijn (1980). To stop oxidation of Fe$^{2+}$ ions during the storage before the analysis, a small portion of soil solution was fixed with 0.1 M HCl.

**Results and discussion**

**Soil solution chemistry**

A significant positive correlation was found between EC, Al$^{3+}$, titratable acid and soluble SO$_4^{2-}$ for all sampling times and depths. A significant negative correlation existed between pH and the above constituents for the two depths 0-5 and 5-15 cm but not for greater depths. No significant correlation was found for Fe$^{2+}$ and other measurements.
The pH of the soil solution in the first two sampling depths (0-5 and 5-15 cm) was raised by the leaching process (Figure 2a), where the effects of land preparation were strongly felt at early sampling times. For deeper sampling depths, pH remained rather constant throughout the leaching period (Figure 2b) and no significant differences amongst treatments were found.

Figure 3 demonstrates that land preparation treatments significantly enhanced the leaching of $\text{Al}^{3+}$. Differences between the P2 and P3 treatments were noticeable even at greater depths at early sampling times but, as leaching proceeded, these effects diminished. After about one week, $\text{Al}^{3+}$ concentration remained almost constant. In the non-hoed treatment, $\text{Al}^{3+}$ concentration at all depths remained very high, far exceeding the tolerable level of rice, while in the hoed treatments it was brought down to less than 1 mmol(+)/liter. Variations in EC, titratable acid and soluble $\text{SO}_4^{2-}$ were similar to that of $\text{Al}^{3+}$.

The behaviour of $\text{Fe}^{2+}$ (Figure 4) was peculiar in that its concentration at the shallower depths increased within a few days after the start of leaching under the P1-treatment. This rise of $\text{Fe}^{2+}$ was too fast to be attributed to the reduction process in which $\text{Fe}^{2+}$ reaches its peak about 2 weeks after the soil submergence (Dent 1986, Ponnampuruma 1984). The phenomenon may be explained as the effect of a rising
Figure 4 Changes in Fe\(^{2+}\) of soil solution at sampling depths (a) 5-15 cm and (b) 55-65 cm during the leaching process as influenced by three land preparation treatments.

Wettable which brought the Fe\(^{2+}\)-rich groundwater to the surface layers. In the hoed treatments, this mixing effect of the wettable was suppressed by the fast downward movement of water.

In deeper horizons, Fe\(^{2+}\) concentration decreased as a result of the simultaneous actions of leaching and dilution from water of better quality from above and was greatly influenced by land preparation treatments.

Leaching efficiency and the importance of soil structure
The faster rate of leaching achieved by land preparation can be explained by the

Figure 5 Leaching efficiency expressed as (a) decrease in Al\(^{3+}\) concentration (compared to original concentration) per 100mm cumulative water applied and (b) incremental decrease in Al\(^{3+}\) concentration per each additional 100 mm (sampling depth 15-25 cm)
increase in infiltration rate of the profile and hydraulic conductivity of the most slowly permeable soil layers (Table 2). Land preparation causes more macropores between the soil crumbs. Despite of these ‘by passes’, leaching efficiency, in terms of its effect in removing $\text{Al}^{3+}$, of the hoed treatments was much higher than the non-hoed treatment (Figure 5). This is particularly clear when the amount of water applied was less than 1000 mm.

The higher leaching efficiency indicates the importance of land preparation in changing the structure of the clay soil into clods which have more surface contact with the fast-moving water through the macropores. Furthermore, under the drying process, toxic substances move to the outside of the soil crumbs where they are removed more efficiently. This explanation is supported by the consistently higher concentration of soluble ions in the outer 2 mm of the sun-dried soil clods as compared to that of the inner cores (Figure 6).

After the removal of the easily-accessible substances at the clod surface, leaching could only remove substances which move by diffusion from the inner cores to the clod surfaces. This is a slow process, so leaching efficiency decreased rapidly as more water is added. Beyond about 1500 mm, additional water does not further reduce the $\text{Al}^{3+}$ concentration of the soil solution. It should be noted that the infiltration rates in the experiment were very high, even after 30 days of submergence, those of P3 plots approximated 100 mm/day. This might be attributed to the proximity of the plots to the surrounding drainage canals. In actual farmers’ fields, the infiltration will probably be much lower and leaching would require more time.
Conclusions

Land preparation by hoeing and drying under the sun before leaching enhances leaching. Toxicities are removed faster and with less water. The enhanced leaching effects are attributed to the change from large structure elements to smaller clods and the movement of toxicities during the drying process to the sides of the clods where they are removed more efficiently by the fast-moving water through the macropores. Leaching effects decreased rapidly after the removal of these readily-soluble substances.

Acknowledgements

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References
