Reclamation of saline clay soils

A manual for the Horizontal Leaching Technique

Reclamation area, Clarendon, Jamaica (Head pond area in foreground)

University of Southampton
Institute of Irrigation Studies

in association with

HR Wallingford
Overseas Development Unit

ODA
Overseas Development Administration

The Leverhulme Trust

THE SUGAR COMPANY OF JAMAICA LTD.

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A manual of the Horizontal Leaching Technique

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1996

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HR Wallingford
Wallingford, UK

Published by: HR Wallingford
Wallingford, Oxon. OX10 8BA

and University of Southampton
Southampton, SO17 1BJ

British Library cataloging in publication data
A catalogue record for this publication is available from the British Library

ISBN 1 898485 03 8

Foreword

The recent development of the Horizontal Leaching Technique provides an opportunity for land reclamation agencies in arid and semi-arid countries to undertake the reclamation of saline clay soils. Clay soils are potentially very fertile, but the removal of excess salt in them has presented severe technical difficulties, and until now there has been no suitable approach for reclaiming heavy clays.

The Horizontal Leaching Technique presented in this manual is based on several years of research carried out jointly by the Institute of Irrigation Studies (IIS) of Southampton University and Overseas Development Unit (ODU) of HR Wallingford. The technique has been developed to a level that it can be recommended for widespread use. It is hoped, as well as enabling land reclamation agencies to identify whether saline clay lands can be reclaimed, that research teams will be able to utilise the Horizontal Leaching Technique and may be able to extend it.

Acknowledgements

The manual presents a land reclamation technique that has been developed as a result of research work supported by the Overseas Development Administration of the British Government and by the Leverhulme Trust. The work was carried by the Institute of Irrigation Studies, part of the Southampton University Department of Civil and Environmental Engineering under ODA Contract R4896, and by the Overseas Development Unit of HR Wallingford who were supported by ODA (Job no.TPS/107/22, ODA Ref. no. R5835). The work of the Institute of Irrigation Studies was also supported by a research grant award provided by the Leverhulme Trust (Ref no. F180/AA)

The authors wish to extend their gratitude to the Jamaica Ltd Monymusk Division of the Sugar Company of Lioneltown Jamaica, for the very extensive cooperation and use of facilities during the three year research programme based on their estate. This extends to staff at all levels from the Managing Director to the field staff, all of whom played a vital role in the success of the project. The authors are particularly grateful to the two field assistants Wesley Boothe and Alvin Gardon whose enthusiasm ensured that maximum benefit was gained from the field study. The contribution of the Jamaican Sugar Industries Research Institute at Mandeville, is gratefully acknowledged.

Previous contributions by the Institute of Village Affairs at Tarsus, Turkey, and by the Delta Sugar Company at Kafr el Sheik, Egypt, are gratefully acknowledged.

Acknowledgement is made of the permission granted by Longmans to reprint figures 5, A3, A4, and A5, from Rowell: Soil Science - Methods and Applications (1994).

Summary

The manual is intended for use by agricultural engineers, agronomists and/or soil scientists involved in the field operation, or technical management, of irrigated agriculture on clay soils.

The main use of the horizontal leaching technique is within a system of mechanized farming since it requires the use of heavy plant such as tractors and subsoilers. In common with most irrigation projects, fields need to be relatively large (minimum 0.5 hectare) and fairly flat i.e. less than 1% slope.

The horizontal leaching technique is a new procedure, and so this manual has been prepared to enable the reader to:-

- **Assess whether the technique is suitable for the particular salinity problems encountered.**
- **Provide sufficient technical information to implement the method.**

The practical application of the horizontal leaching technique involves 4 main activities :-

- **Assessment of site suitability and pilot testing of methodology.**
- **Site preparation.**
- **Water application procedures.**
- **Monitoring and assessment.**

Application of the technique should be preceded by a site assessment to determine the cause of the salinity problem, which is briefly outlined in Section 2 of the manual. The technique involves several basic field operations which should be followed in all cases. These are briefly outlined below and are described in detail in Sections 3 to 5. These describe the basic techniques, the soil types in which they can be applied, and include sub-sections which cover the following operations:-

- **Drainage system installation:** A series of perforated pipe drains (laterals) are installed in parallel lines and at the chosen spacing (usually 30-50m) across the field (aligned across the main slope). The laterals will receive the saline water draining from the reclamation plots and discharge to an outlet or to a collector drain which conveys the saline drainage water off site.

- **Harrowing and land smoothing:** The field to be reclaimed needs to be cleared of vegetation or surface trash by harrowing. Smoothing may be needed on rough uneven surfaces.

- **Layout for subsoiling:** It is recommended that the land is subdivided into plots, typically 20-30m wide separated from each other by undisturbed soil barriers of 1-2m width. The barriers minimise lateral seepage and ensure that the main direction of flow is between the head pond and the lateral drain.

- **Subsoiling:** The subsoiling procedures must follow a chosen pattern of spacing, direction and number of passes.

- **Bunding:** Water control within the field is assisted by constructing a framework of earthen bunds to contain or hinder overland flow. Compacted earthen bunds are constructed around the perimeter of the field to minimise wastage of water by leakage. Cross-plot bunds help to minimise surface flow between the head pond and the drain. The first set of cross-plot bunds enclose the head pond which serves as the main infiltrating basin. Longitudinal bunds are also placed above the unsubsoiled barriers between each plot to help ensure that flow occurs longitudinally.

- **Water application:** At the outset, water is supplied to the head pond, usually about 5m wide, located either in the middle or at the top of the plot. The position depends on the drain spacing and the land slope. Water is then allowed to infiltrate until it begins to pond on the surface. During this period water begins to advance down the field through the restructured soil towards the drain. Application is subsequently reduced to maintain an almost constant ponded water level within the head pond (in practise about 50-100mm deep). The infiltration rate in the head pond continues to decrease and ultimately it becomes necessary to break the first bund and allow ponding to extend down to the next cross-plot bund.

- **Monitoring:** Monitoring provides data to determine the success of reclamation, to identify areas of improvement, and aid the making of operational decisions.

- **Appendices:** To allow non-specialists to use this manual, detailed appendices have been included.

Contents

Contents continued

Tables

Figures

Contents continued

Plates

Appendices

Contents continued

Appendix figures

Contents *continued*

1 *Introduction*

1.1 The need for saline soil reclamation

One of the major causes for the loss of productive land in the world, particularly in irrigated lands, is the build up of salinity in the soil. At the present time it is estimated that this rate of loss is so great that it is nullifying the rate at which new land is being introduced. Furthermore the amount of remaining land suitable for irrigation is finite and dwindling rapidly - all the best land has already been developed.

The problem is particularly acute in clay lands because of the inherent difficulty of getting water to pass through these heavy soils and to remove salt from the root zone. However, clay lands are still very attractive for the development of irrigated agriculture because of their good potential for crop production. This is now increasingly the case in developing countries because of their increasing demands for food production.

There is thus a profound need for techniques that will aid development authorities and agencies to prevent salinity levels from building up in the lands for which they are responsible and to reclaim those areas in which excess salinity has built up, or was already existing. It is in response to the second need that a series of development studies have been carried out by the Institute of Irrigation Studies at Southampton University with collaboration from the Overseas Development Unit of HR Wallingford. The technique that they have developed is a significant contribution to this difficulty and provides, for the first time, a practical means for land reclamation that can be undertaken by suitably equipped land development agencies.

1.2 The horizontal leaching technique

This manual describes a new procedure for reclaiming saline heavy clay soils, called the "Horizontal Leaching Technique", and is illustrated schematically in Figure 1.

The procedure is a rapid and practical method that enables land reclamation engineers to restructure clay soils, and then to leach out a large proportion of the soil salts. The applied water and the removed salts are then conveyed away from the area by buried pipes installed at spacings that are wide (30-50m) and thus economical.

The methodology has only been used to date on saline soils. Development work that would make the Horizontal Leaching Technique applicable to saline-sodic soils is discussed in Appendix 8.

The procedure comprises 3 stages:-

1. Land preparation
Mechanical subsoiling is firstly carried out. This shatters the large peds of clay into smaller sized aggregates. But as well as increasing the soil's hydraulic conductivity, it has a second function, that is to bring the salt that is held deep inside the massive blocks much closer to the surface of the newly formed aggregates, from where it can be more easily removed.

2. Water application
Water is applied to one edge of the reclamation area in order to saturate the area's soil profile, and to begin the extraction of salt out of the newly formed aggregates.

3. Horizontal drainage
The water is induced to flow horizontally through the restructured soil profile, and as it does so it leaches the excess salt away from the aggregates and delivers it to the pipe drainage system.

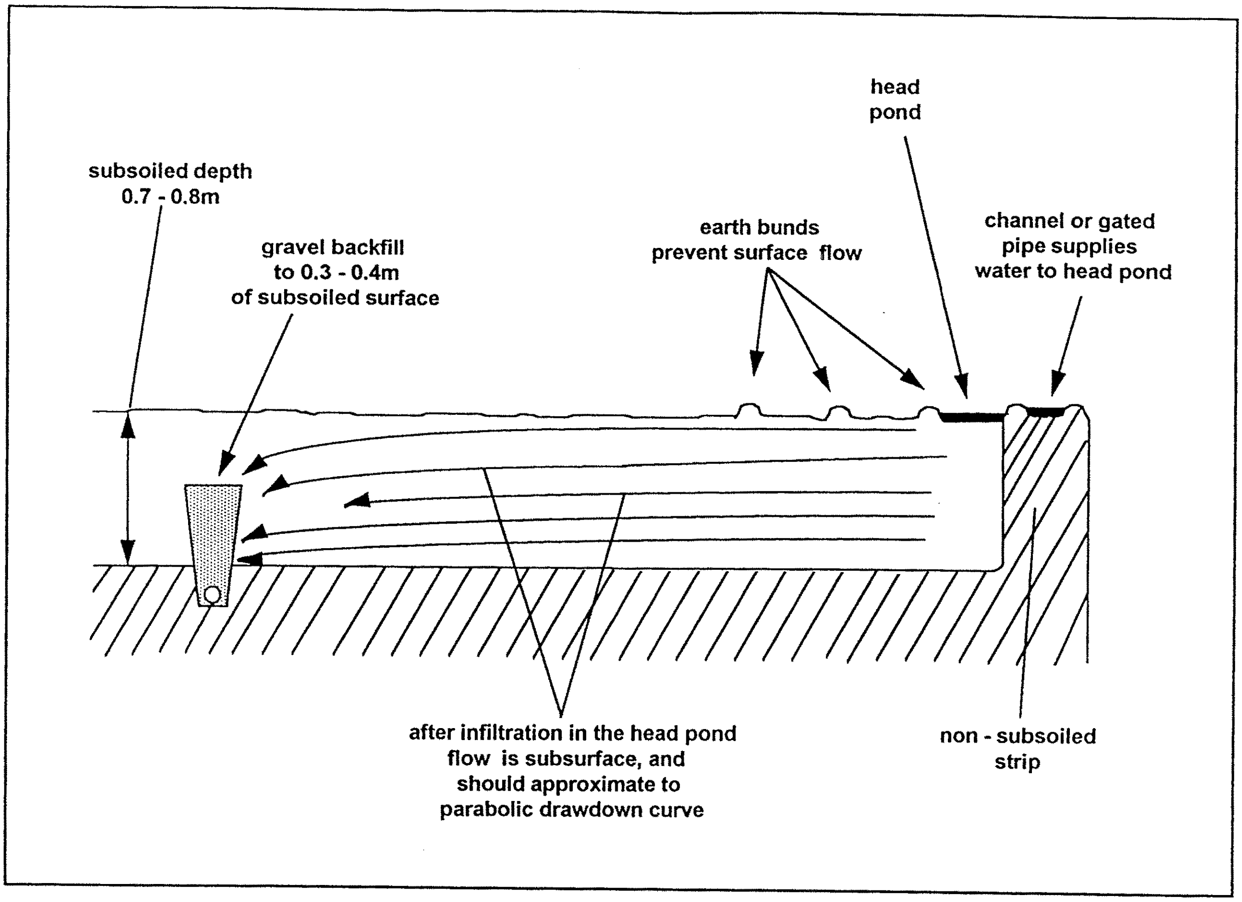

Figure 1 Horizontal Leaching Technique

1.3 Aim of the new reclamation method

Economically successful reclamation of saline clays is dependent on both enough water passing through the soil profile and that salts locked in the clay are made more accessible to the leaching water. The process needs to be completed in a matter of weeks, rather than in months or years.

The objectives are to:-

- Increase the number of large, freely draining macropores and ensure that they provide a stable continuous network (at least until their role in leaching has been completed).
- Reduce the size of aggregates in the soil profile. This is to minimise the distance through the clay matrix for salt to diffuse to the macropores.
- Impose a situation whereby applied water is forced to pass horizontally, and relatively uniformly, through the profile that has been restructured.

The horizontal leaching technique has been designed to satisfy each of the above objectives using:-

- **Intensive mechanical subsoiling** - The soil is broken up (restructured) by intensive subsoiling (sometimes called ripping) to the maximum depth possible. This enhances the volume and continuity of the macropores, improves permeability and decreases aggregate size (see Figure 2). The maximum depth is usually 0.7-0.8m.

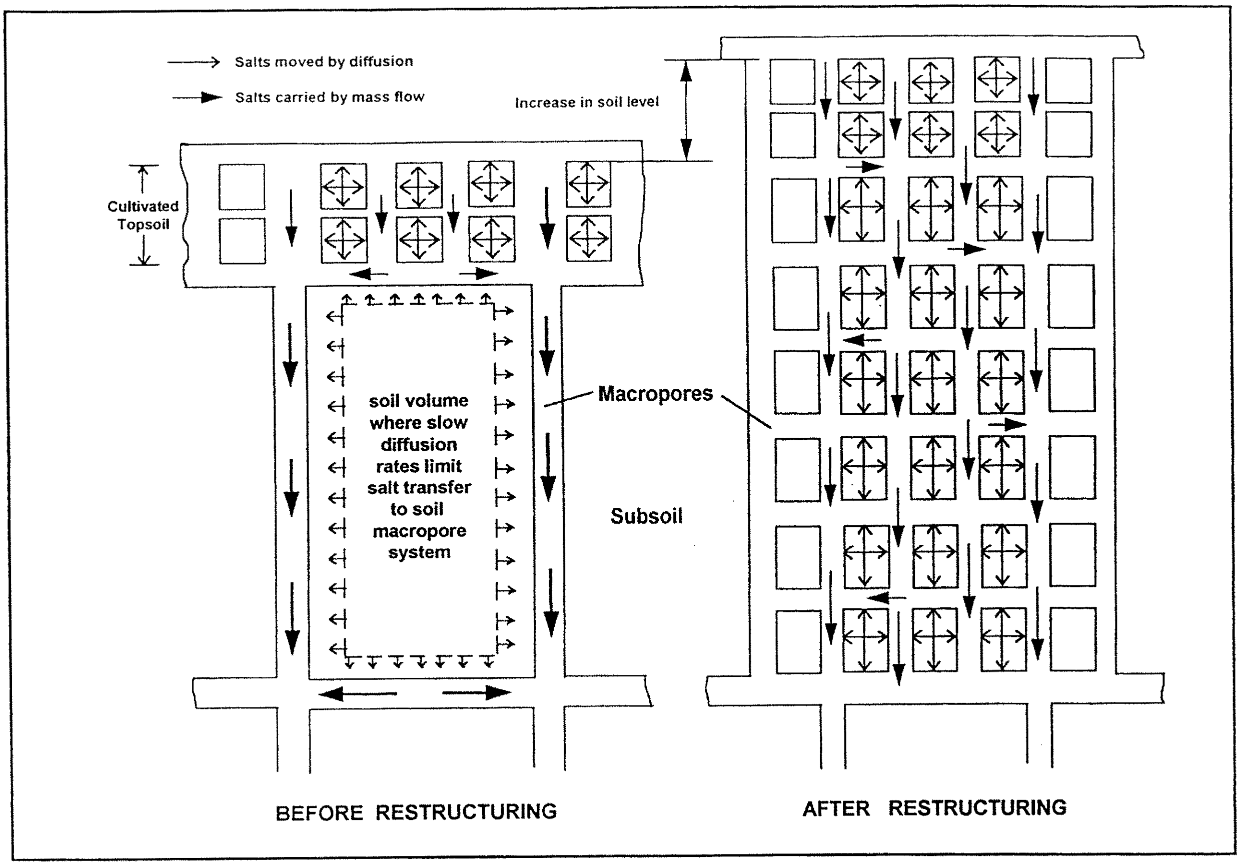

Figure 2 **Schematic representation of the effect of restructuring on the distribution of small and great peds and on improving the capability of leaching water to interact with diffusive movement of salt within those peds**

- **Irrigation** - Water is applied and held on the surface within a narrow strip of land (the head pond) parallel to an installed system of lateral field drains. The location and distance separating the head pond and the drains is determined primarily by field slope. Direct overland flow is minimised by constructing earthen bunds across the plot at regular intervals. The difference in levels between the water ponded in the head pond and the drain generates flow through the entire restructured soil profile towards the drain (see Figure 3).

- **Preventing desaturation -** Once water application has begun, the reclamation area is not allowed to desaturate or drain down. As long as the restructured soil aggregates are immersed in water they have a 'buoyancy' which reduces the overburden weight. If the macropores do become drained, the full wetted overburden weight is transmitted down to the underlying wet soil causing more deformation and consolidation. Consolidation reduces porosity and hydraulic conductivity especially in the lower part of the restructured soil profile and is to be avoided (see Figure 4).

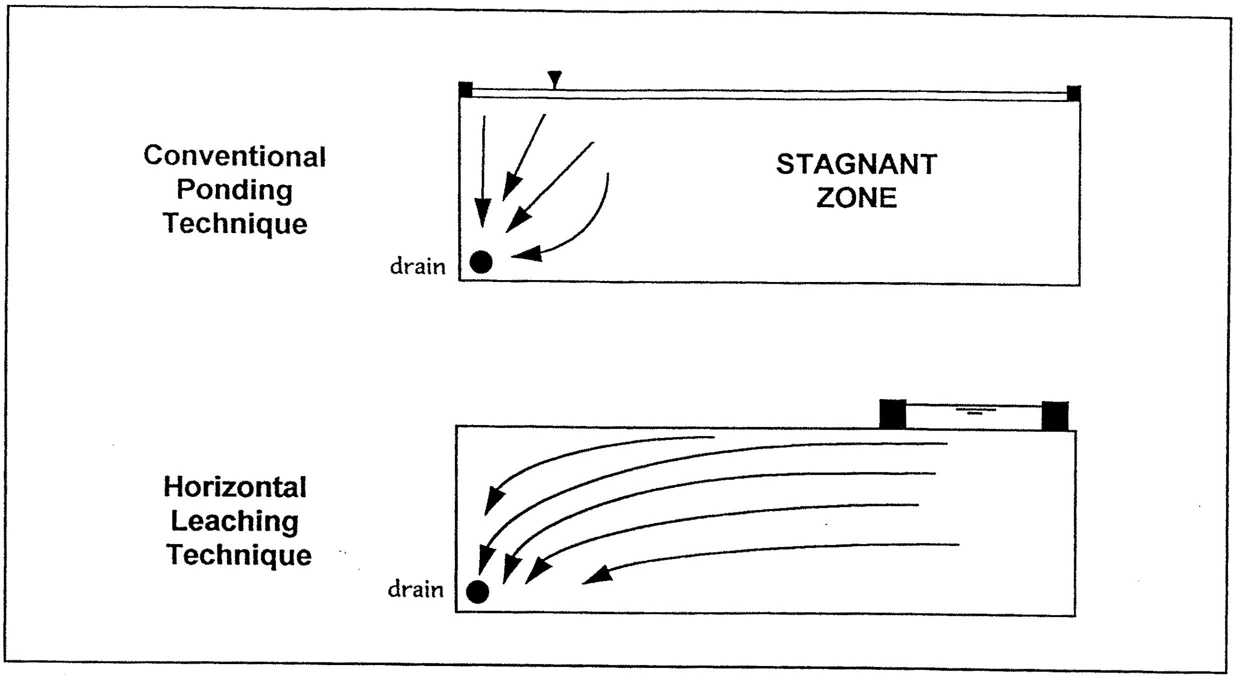

Figure 3 Comparison of long leaching flow lines under the horizontal leaching technique with the ineffective leaching that occurs under the ponding technique

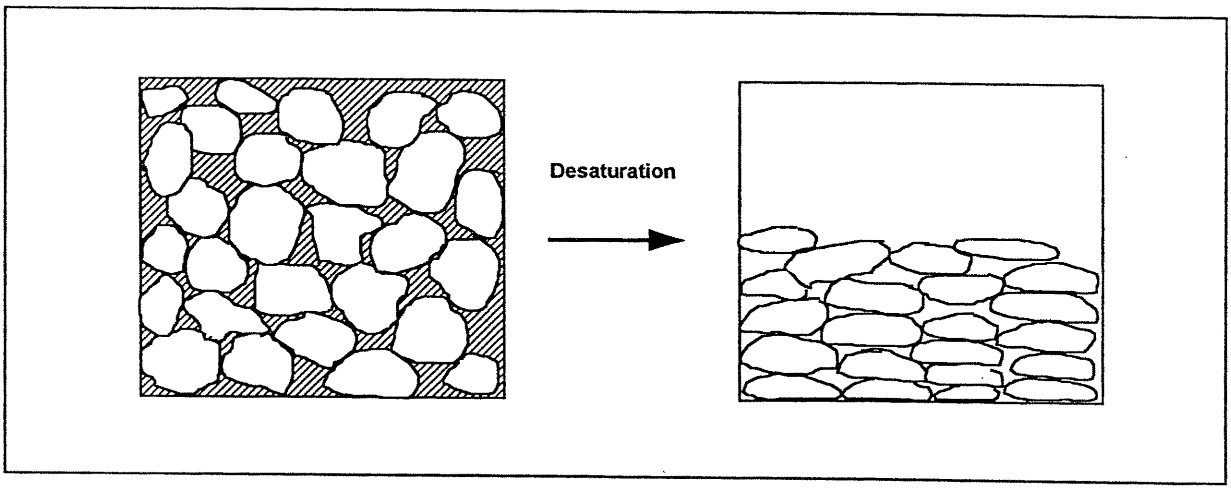

Figure 4 Comparison of schematic soil particle distribution under the buoyancy - supported conditions that occur during horizontal leaching, with the slumping that occurs during desaturation of the soil profile

2 *Site Suitability*

2.1 Introduction

The horizontal leaching technique can be used as a remedial procedure for salinity in clay soils only if the primary cause of salinization has been identified as one of low soil permeability. In general, the technique is suitable for heavy clay soils (normally greater than 1m depth) with saturated hydraulic conductivities (K values) less than 0.1m d^{-1}. There is scope for reclamation by conventional techniques if hydraulic conductivities exceed 0.2m d^{-1}, such techniques being described in Appendix 4.

It is strongly recommended that pilot studies be carried out before employing the horizontal leaching technique on a large scale. This is particularly important since the recommendations on drain spacing outlined in Section 4 are considered conservative. Any increase in drain spacing that can be achieved will result in significant savings in cost.

2.2 Site assessment

Three assessments need to be carried out to identify whether the technique is suitable for use at a certain location:-

- Determine local soil properties - these include physical and hydraulic characteristics such as hydraulic conductivity, infiltration rate and soil texture.
- Establish the cause of salinity.
- Quantify the degree of salinity and sodicity (if present).

If these show that the soil complies with suitability criterion stated in Section 2.1, the horizontal leaching technique may be used. But there are some further practical requirements which define whether the location of the site is suitable. These comprise:-

- A suitable sink for the safe disposal of saline discharge.
- Land slopes < 1%.
- Minimum field size of 0.5 hectares.

A monitoring programme can be established to identify the cause of the salinity build-up, e.g. impermeable soil, non-uniform in-field water application, inadequate supply. The programme can be extended to include the amount of salt and water entering (and being removed from) the soil profile during irrigation. The measurements can be made over a single irrigation interval but preferably over an annual cycle.

If such a monitoring system is not already established, it will involve considerable cost, difficulty, and time to obtain sufficient reliable data to identify salt build up. It therefore may be more practical to make an assessment based on local experience and soil survey information combined with direct measurement, and then pilot testing the methodology.

For example, the infiltration rate of the soil can be assessed by ponding water over a 10-20m^2 area. Observations from such a test can provide an indication of the amount of salt moving downwards in the situation prior to reclamation.

If it is not possible to take a systematic set of site measurements, an approximate assessment of suitability for reclamation can be made based on soil core sampling and soil pit investigation. The soil cores are used to identify the extent of suitable areas based on soil texture, structure and mineralogy. Figure 5 shows the soil texture class triangles used in the USA and the UK to assess soil type from the particle size distribution. The areas need to have uniform deep clay of thickness greater than 1m, and of clay content greater than

45%. Soil pits enable the soil profile to be examined for indicators of poor permeability, such as gleying/mottling and restricted root development. Accumulations of salt crystals, found at the surface or within the profile, indicate poor leaching due to low permeability. If these are seen even when the leaching requirement is being supplied, and/or when there is no shallow water table, the effectiveness of leaching can be deduced to be especially poor. In all such situations, infiltrometer ring tests in the soil pits can be carried out to provide a quantitative assessment of permeability.

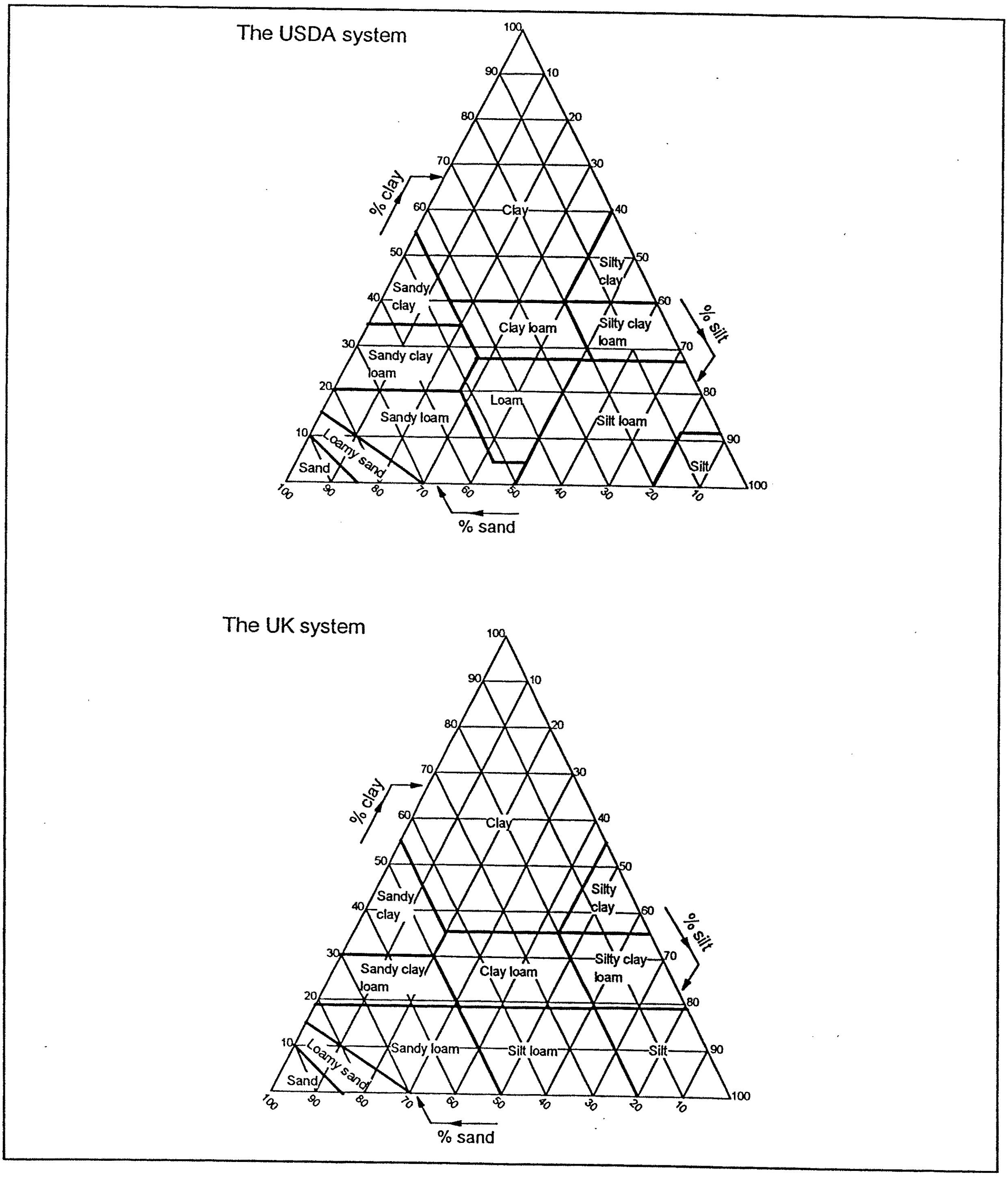

Figure 5 **Soil textural classes and their particle size distribution (USDA and UK Systems)(Reprinted, with permission, from Rowell:- Soil Science - methods and applications, Longman Group, 1993)**

2.3 Subsoiling strategy

The effectiveness of subsoiling is dependent on:-

- The soil characteristics - particularly moisture status, soil texture and bulk density.

- The type of subsoiler and the available tractor power.

Subsoiling operations should be designed to provide adequate restructuring of the soil profile with minimum costs in machinery time and fuel consumption.

Tests to determine optimum subsoiling procedures should be made on a suitable area containing the same soil type. These tests will determine the effect of soil moisture on subsoiling performance. The methodology for the trial is given in Appendix 7.

2.4 Pilot testing

Before considerable effort and investment goes in applying the horizontal leaching technique to a new area, it is strongly recommended that a series of pilot tests be carried out to help the instigating agency to plan exactly what sort of reclamation procedure should be recommended locally. Results from these tests will indicate the effectiveness of the horizontal leaching technique and whether any particular local problems are apparent.

Polythene-lined trenches containing hand-dug restructured soil can be set up and used for preliminary investigations of soil behaviour under the horizontal leaching technique. Trench trials provide important information on:-

- The stability of the soil relative to wetting and to leaching of salt.

- Rate of salt release from the restructured clay.

- Estimation of the improvement to soil hydraulic conductivity that could be achieved by restructuring.

- Estimation of the length of reclamation plot down which water will be sent, and thus the spacing between drains.

The information gained from trench trials and from subsoiling evaluations (Appendix 7) can be used to estimate approximately the optimum size of reclamation unit. Based on these dimensions, a plot trial should be carried out to help finalise the size of the basic unit that will be reclaimed. These will provide confirmation that the chosen plot dimensions are effective before large-scale investment is made in terms of capital cost and labour and machinery hire. The measurements required are described in Section 5, and a schematic representation of a trench trial is given in Appendix 9.

3 Site preparation

3.1 Introduction

The techniques described in this section are based on experience gained from field trials on saline clay soils in Turkey and Jamaica. This work has provided a basic design procedure that should enable most saline heavy clay soils to be reclaimed successfully. Figure 6 illustrates the basic field layout for the one-way flow method and the two-way flow method that can be used with the horizontal leaching technique. The figure indicates recommended plot sizes of 30m by 30m, and 50m by 30m, which correspond to drain spacings of 30m and 50m respectively. On many sites it is anticipated that these recommended drain spacings will be conservative underestimates, and that the plot sizes can be enlarged with obvious economic benefits.

It is strongly recommended that before any widescale application, the technique should be tested locally to determine optimum operating conditions (see Section 2.4). This is particularly important with respect to drain spacing but also for soil conditions and operations to achieve maximum subsoiling efficiency. The extent of restructuring largely determines the rate of salt release, the soil's hydraulic conductivity, and thus the drain spacing, and time of reclamation.

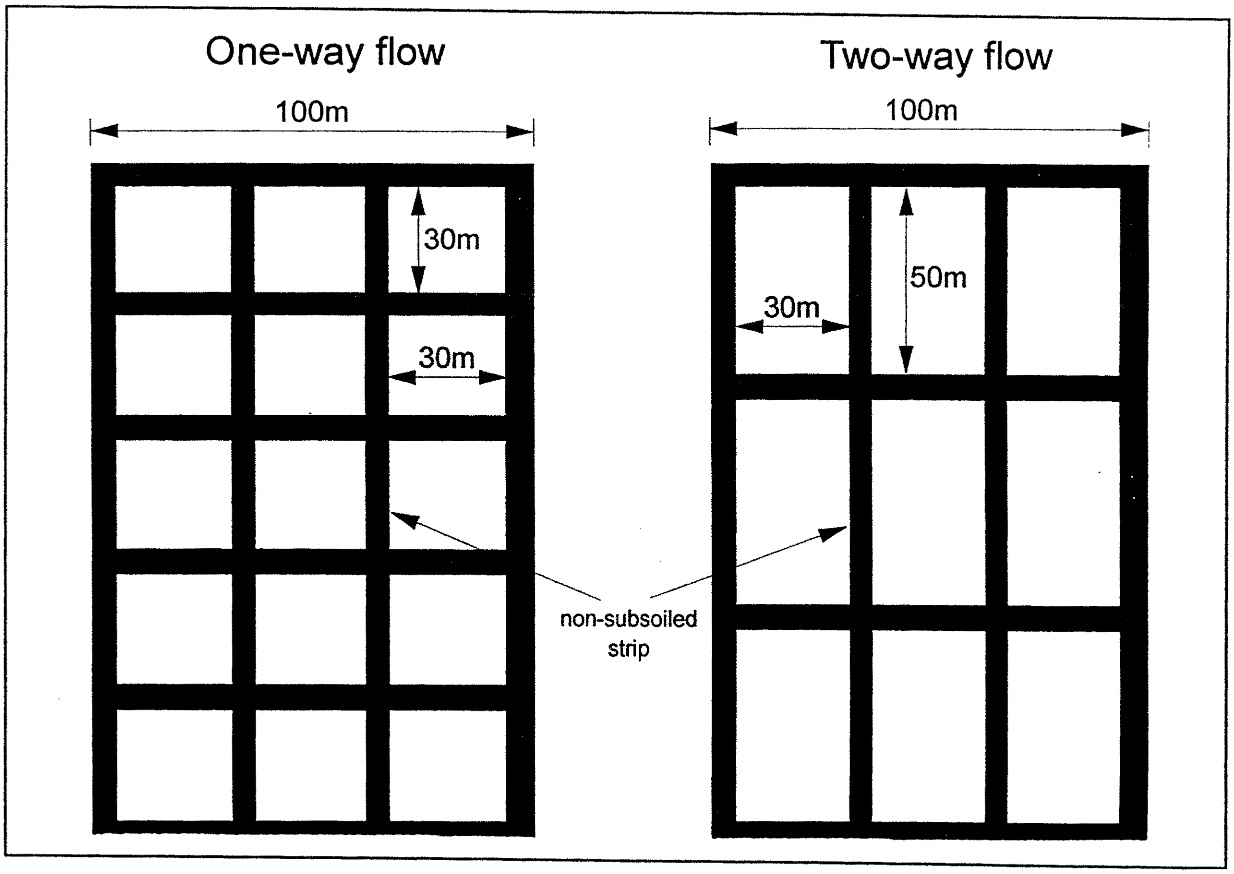

Figure 6 **Dimensions of plots for one-way and two-way flow situations, showing position of 5m wide non-cultivated separation strips**

3.2 Field design and layout

The following description of applying the methodology is illustrated for a field of 100m width. There are two basic field layouts for the Horizontal Leaching Technique, depending on whether one-way or two-way flow is adopted. In both cases, the field should be sub-divided into a number of independent and separate plots, 30m wide and of length 25-30m to the laterals. The drain forms one boundary, whilst the other three boundaries are created by non-subsoiled strips of land, 2m wide.

One-way flow - for relatively sloping land
On sloping land (slopes > 0.5%) only one-way flow is possible, and a drain spacing of 30m is recommended. Figures 7 and 8 indicate the field layout, and show the positions of the plots, the non-subsoiled strips between them, the position of the supply and drainage channels and the direction of the leaching water as it passes one way from the head pond, through the subsoiled plot and out into the lateral drain placed at the end of the plot. Figure 9 indicates how leaching water is prevented from flowing over the surface of the plot by the bunds of the head pond. It also shows how subsurface flow is encouraged to pass into the newly subsoiled zone, from where it can begin to flow through the plot to be reclaimed.

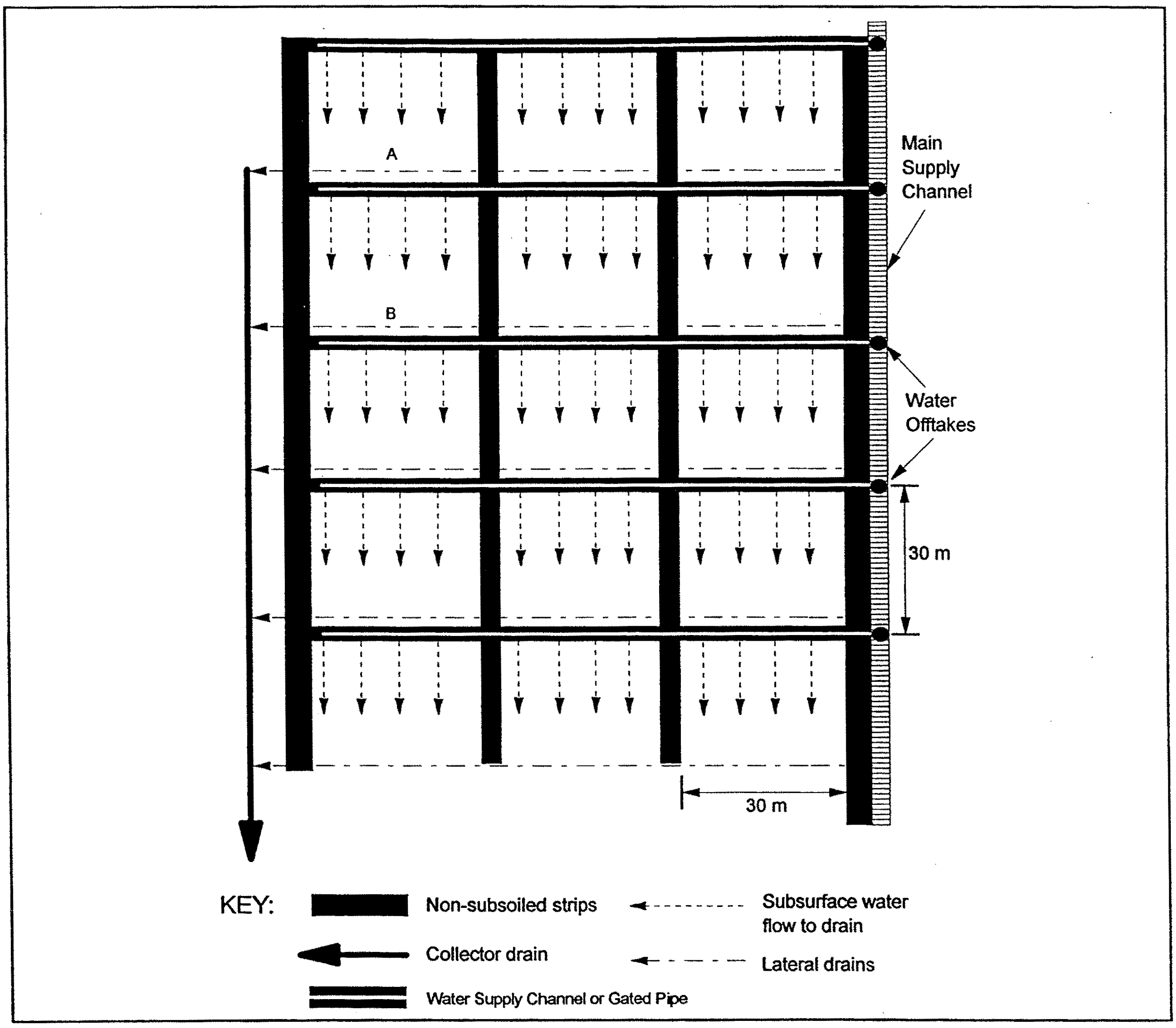

Figure 7 **Plan diagram of 30m square plots under one-way flow, showing water flow pattern from main supply channel to collector drain**

Two-way flow - for relatively flat land
On relatively flat land (slopes < 0.5%) two way flow is possible and enables the recommended drain spacing to be extended to 50m. Figure 10 gives the field layout and shows the direction of the applied water, this time travelling in two opposing directions away from the head ponds towards two lateral drains.

When installing either of these procedures the layouts shown in Figures 7 and 10 should be marked out on the ground using wooden pegs or similar before subsoiling.

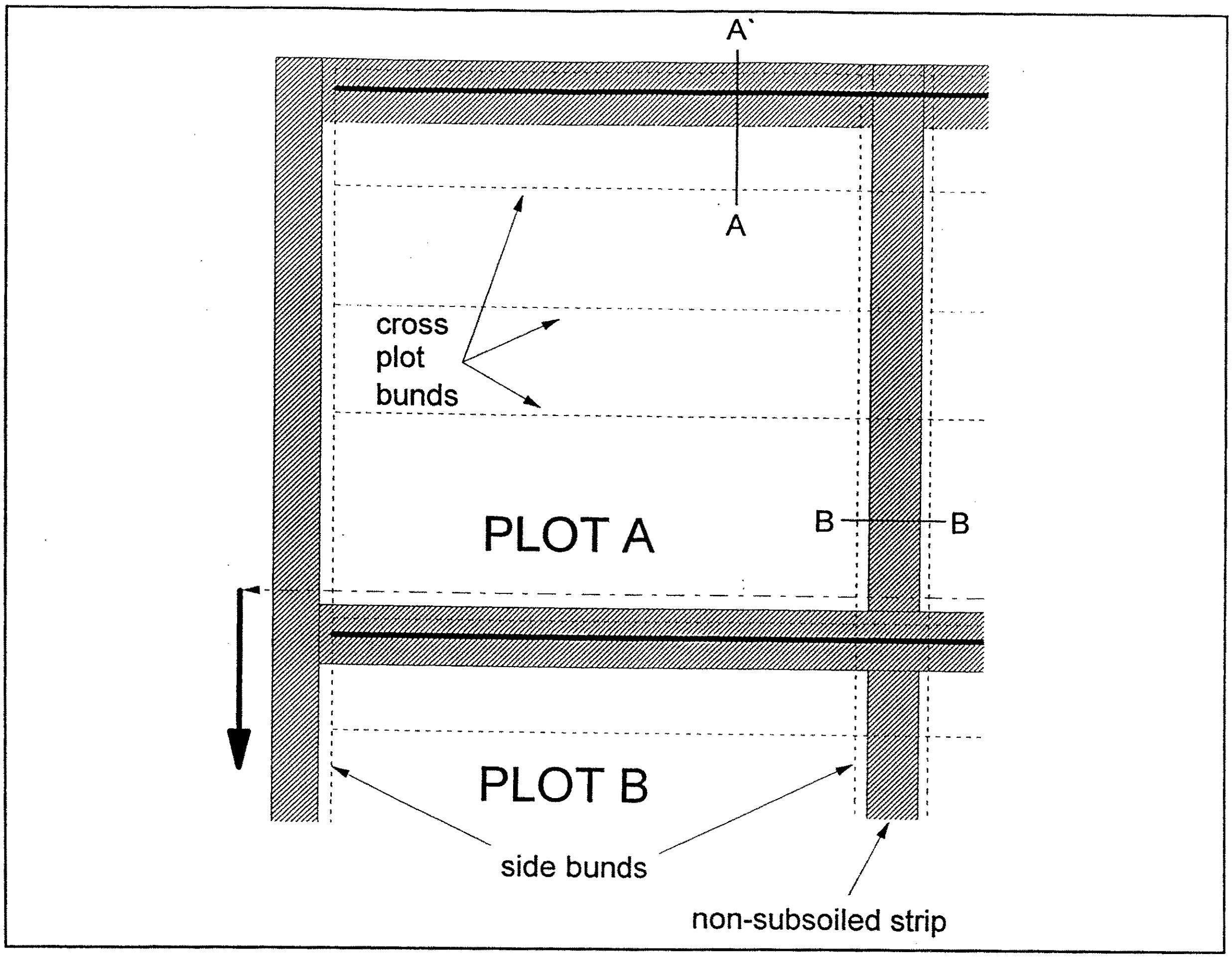

Figure 8 Plan diagram of single 30m square plot (see fig 7) showing positions of cross-plot bunds, side bunds and non-subsoiled strip separating adjacent plots

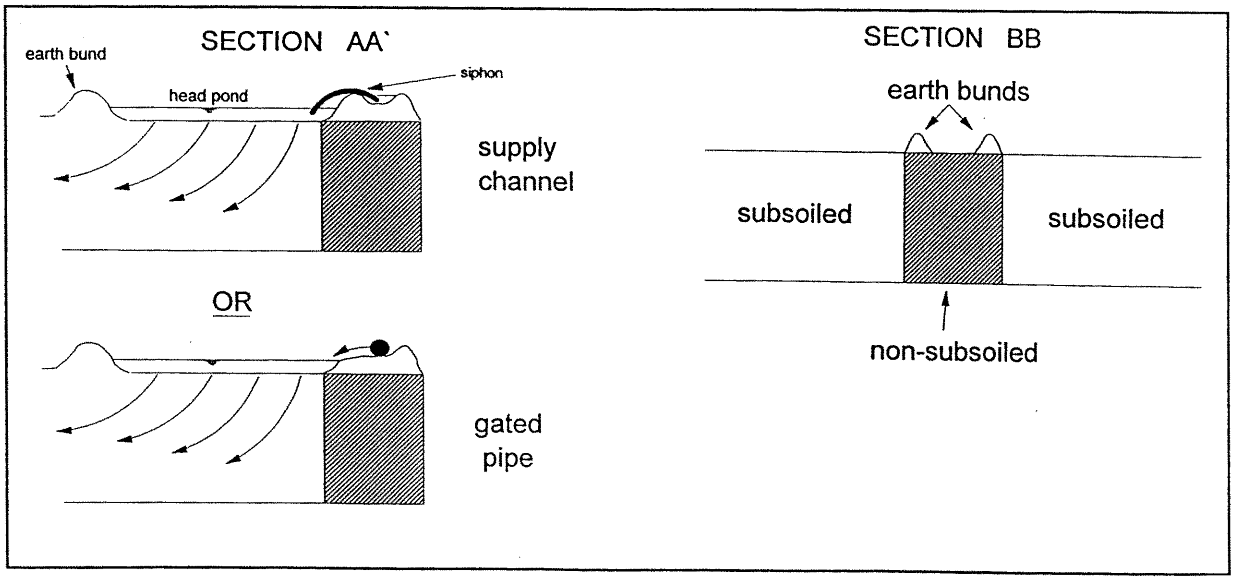

Figure 9 Sectional diagrams showing sub-surface flow from head pond (supplied by open channel or gated pipe), and physical arrangements around perimeter of plot (see figure 8)

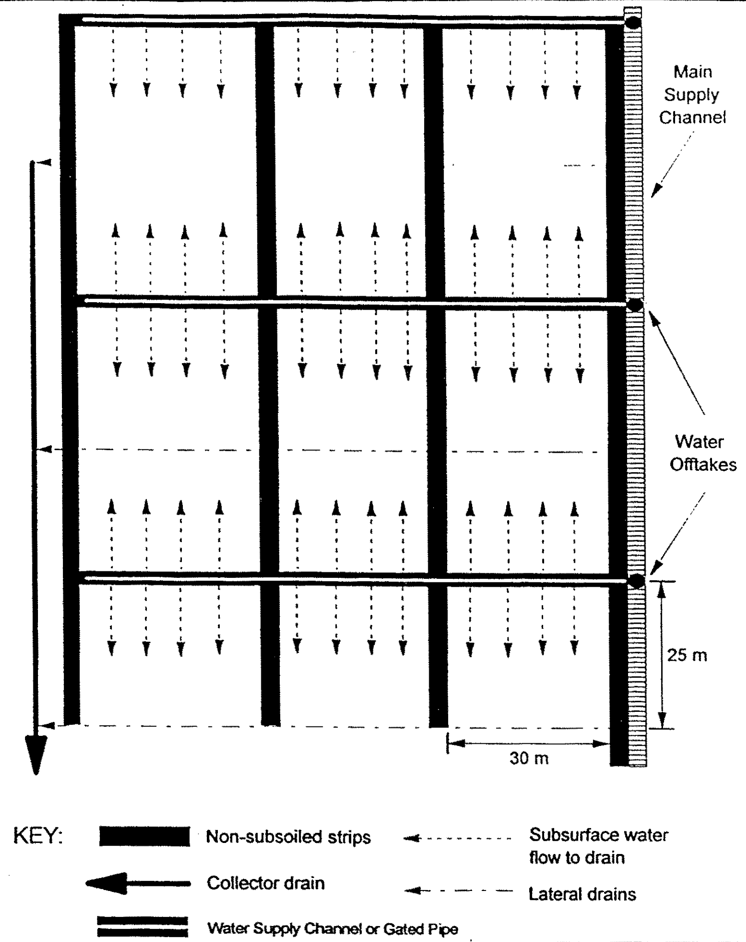

Figure 10 **Plan diagram of 50m x 30m plots under two-way flow, showing water flow pattern from main supply channel to collector drain**

3.3 Drainage installation

The lateral field drainage system required for the horizontal leaching technique can be installed using the following procedures.

The laterals are perforated plastic pipes, or similar, laid at a minimum depth of 0.9m (or 0.2m below the maximum depth of subsoiling which is 0.7m) on the bed of a narrow trench (see Figure 11). The trench is then backfilled with coarse stone or gravel to within 0.4m of the surface. The pipe should have a slight slope (minimum 0.15m per 100m) to ensure that water flows to the outlet point. The lateral discharges into an open ditch or buried collector pipe.

The trench should be as narrow as possible. A width of 0.2m is a realistic minimum. Because its depth is relatively shallow, the trench should remain stable until it has been backfilled with gravel, provided that the soil remains dry. A slight side-slope is desirable on the trench wall but not essential, provided the trench is backfilled on day of excavation.

The stone or gravel backfill must be clean with a minimum size of 10-15mm. Its purpose is to collect water draining through the restructured soil profile and allow it to flow easily to the drain pipe.

The guideline spacing between laterals is 50m when two-way flow is possible, and 30m when only one-way flow is possible, as shown in Figures 7 and 10.

3.3.1 *Equipment*
Conventional drain installation plant may be used to install the lateral drains, but a simple alternative is to use a backacter to dig the trench. A tractor and hydraulically-operated gravel trailer can then be used to place the gravel backfill.

3.3.2 *Pipe size*
The lateral needs to have sufficient capacity to convey the saline drain discharge away. In practice, reclamation is likely to be achieved in stages, with only one or two plots contributing water to the drain at any one time so flows in the laterals are likely to be relatively small.

Formulae used to determine pipe sizes are:-

Smooth pipes	$Q = 89\ d^{2.71}\ i^{0.57}$
Corrugated pipes	$Q = 38\ d^{2.67}\ i^{0.5}$

Where Q is the required discharge in $m^3\ s^{-1}$, d is the pipe diameter in metres, and i is the pipe slope in $m.m^{-1}$.

The maximum flow to lateral drains observed during field investigations for single-way flow was $37.5m^3\ d^{-1}$ over a distance of 25m. Taking laterals of length 60 m, spaced at 50 m, and receiving water from both directions (two plot widths) as an example, the maximum discharge will be $180m^3\ d^{-1}$ (or $0.002m^3\ s^{-1}$). Using $Q = 38\ d^{2.67}\ i^{0.5}$, with a pipe slope of 0.15m per 100m (0.0015), the pipe-diameter required will be 0.084m (84mm).

In practice, a pipe diameter of 80mm should suffice for most situations.

The consequences of slight underdesign of the pipe are also not serious, since water will simply back up, increasing discharge in the pipe and causing water-table levels to rise within the plots.

The collector drain which receives the discharge from the laterals may be either an open ditch or pipe.

The total discharge to the collector from the laterals will depend upon the proportion of the field being reclaimed at any one time, which in turn is dictated by the availability of water.

3.4 Subsoiling
Achieving a standard of subsoiling that will impart adequate restructuring to the soil profile will depend on local conditions and on the availability of tractors and equipment. The soil's moisture content during the subsoiling operations plays a critical role in the success of the restructuring process. In the Horizontal Leaching Technique the soil has to be restructured by intensive mechanical subsoiling to a depth of 0.7-0.8m. This enhances the volume and continuity of the macropores, improves permeability and decreases aggregate size - as previously shown in Figure 2.

Prior to subsoiling, the land must be cleared of vegetation (e.g. by burning), and smoothed to remove obvious depressions. Bushes and trees must be removed. Harrowing prior to subsoiling opens up the soil surface, which reduces draught and improves restructuring efficiency.

The effectiveness of subsoiling in restructuring the soil is determined by:-

- How intensively the soil is disturbed (this is dependent on the subsoiling depth, spacing and numbers of passes).
- The direction of the operations.
- The soil moisture content.

- The characteristics of the subsoiling implement used.

Ideally, operating procedures for subsoiling should be based on local testing (Appendix 7). The procedures described here are those that have been found to work effectively during the development of the technique.

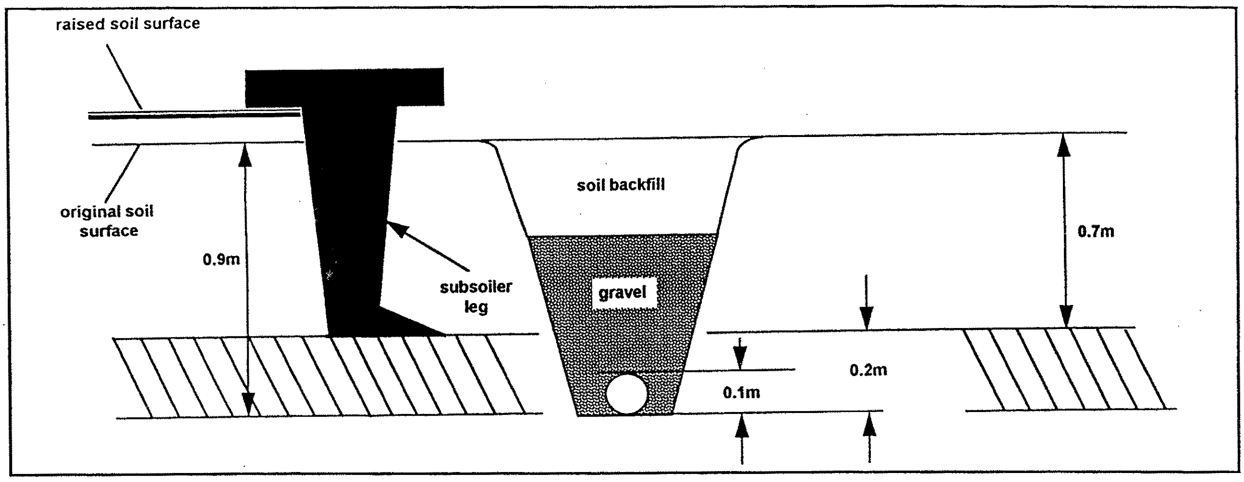

Figure 11 Comparison of set depth of subsoiler before and after passing through drain backfill

3.4.1 Equipment

A high-powered (250-300 h.p.), wheeled tractor can be used to draw a tool frame with a set of leading shallow tines followed by two winged subsoiler tines. The shallow tines disturb the soil but do not increase total draught.

Alternatively, a lower powered (150-170 h.p.) crawler tractor (i.e. tractor fitted with tracks instead of wheels) is preferable for subsoiling. Crawler tractors have two major advantages over wheeled tractors. Firstly, their weight is spread over the much larger contact area of the tracks, so they do not cause excessive re-compaction, and consequently give better restructuring of the soil profile. Secondly, they have lower traction losses as they move along, so they can complete the subsoiling operations quicker.

A typical set up is illustrated in Plate 1, comprising the crawler tractor with the subsoiler legs attached to a tool frame and mounted directly behind the crawler tracks.

The subsoiler foot **should be fitted with wings** (see Figure 12). Although the wings increase draught forces by 15-20%, the extra soil disturbance developed at depth between the tines is essential. For a subsoiler without wings, this deep disturbance can only be achieved by a substantial increase in the number of passes, which involves considerably more work in the long run.

The specifications for the tractor and subsoiler used in the completed experimental trials is provided in Appendix 7 as a guideline to tractor type and power inputs that will be required elsewhere. It also includes machinery work rates so that costings can be estimated.

3.4.2 Moisture limits on subsoiling operations

Assessment of soil moisture content before subsoiling should be carried out by taking samples using an auger in increments of 0.25m to a depth of 1m. The gravimetric moisture content of the samples should be determined. At least 5 auger holes per hectare should be taken.

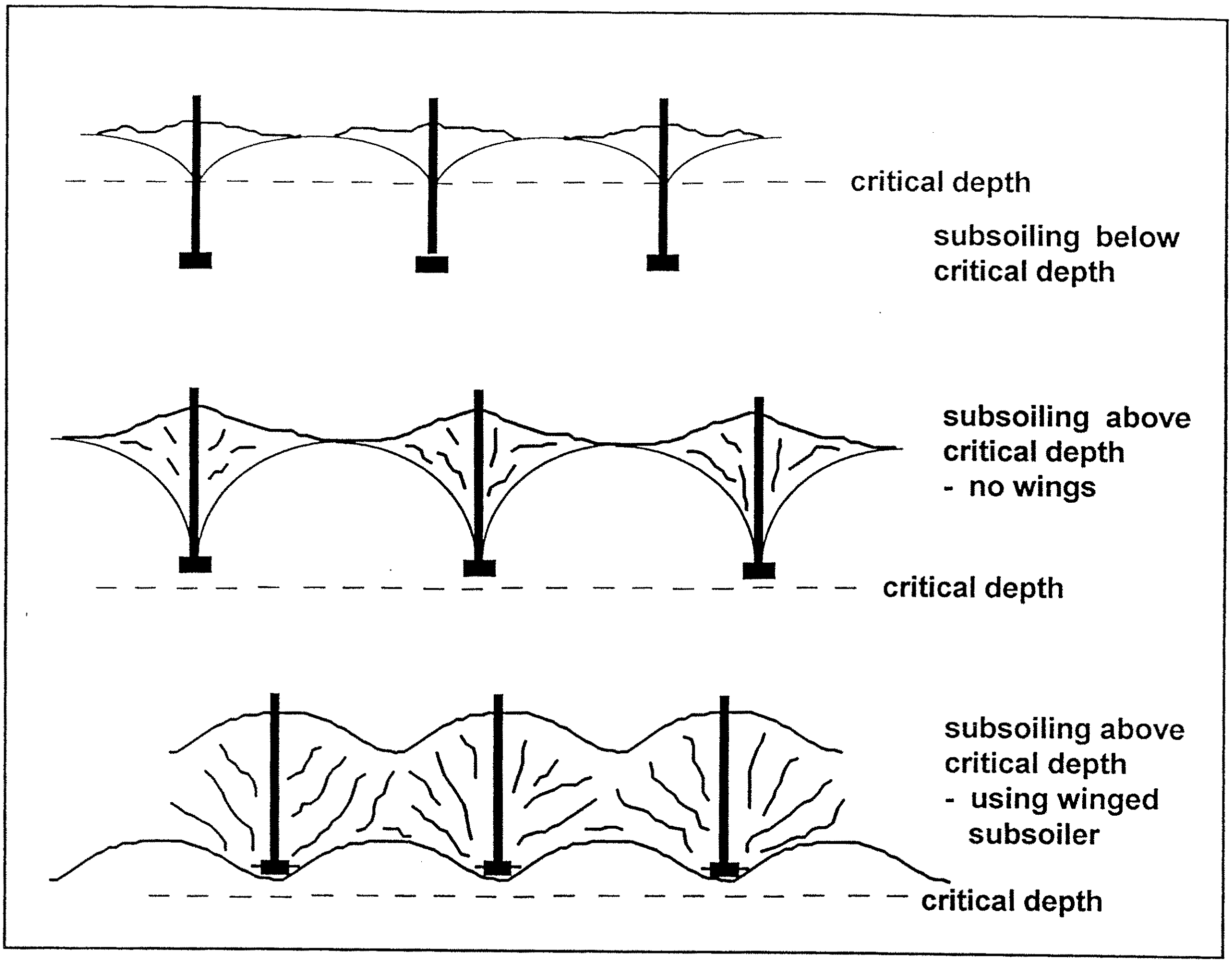

Figure 12 **Comparison of soil shatter zones for subsoiler set above and below the critical depth, and fitted with and without wings**

Lower Limit
The minimum desirable moisture content is determined by the soil becoming so dry that its hardness increases the draught power requirement. When the soil moisture content is too low (say below 16-18%), the draught forces needed to pull the subsoiler become very high. Furthermore, the soil breaks down into very large clods. In certain cases, it may be more important to make sure that the soil is not so dry that it will breakdown as soon as it is irrigated. When a clay soil is too dry, the aggregates break down violently (slake) on wetting and in extreme cases form an impermeable sludge. Water stability tests (Yoder, 1936) indicate that for a given clay soil there is a sharp decrease in soil stability to wetting over a well defined, though narrow, range of moisture contents (see Figure 13). Even allowing for soil variability, severe slaking is likely to occur at moisture contents below 20%.

In practice, if there is any vegetation on the land (e.g. crops or weeds), the moisture content of soil below 0.2m is unlikely to fall below permanent wilting point. In a heavy clay soil this will be in the range 22-30% (gravimetric).

For most clays, the safe lower limit for subsoiling is a soil moisture content of about 20% (gravimetric).

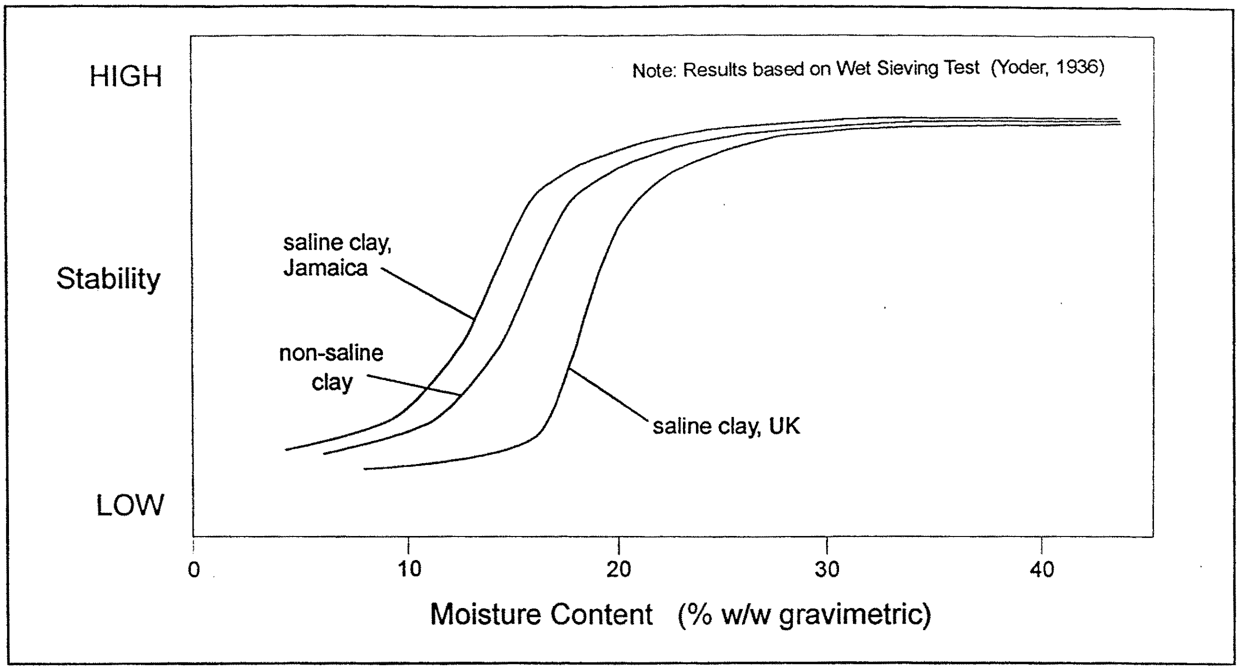

Figure 13 **Relationship between moisture content of clays, and the stability of aggregates to sudden wetting**

Upper limit
The upper limit of moisture content for subsoiling is the **lower plastic limit.** At this moisture content the soil changes from being friable to plastic. The lower plastic limit is defined using a simple procedure (Sowers, 1965), and correlates well with actual moisture contents measured during observed changeovers from plastic failure to shear failure and shattering.

A soil moisture content 2-3% below lower plastic limit is recommended as the upper moisture limit for the subsoiling operation. Lower plastic limits in clays tend to be in the range 28-36%, so the upper limit for subsoiling will normally be in the range 25-33%.

Summary
Minimum = 20%
Maximum = 25-33% (or 2-3% below lower plastic limit)

3.4.3 Depth of subsoiling

The maximum working depth to achieve efficient restructuring of a clay soil is known as the **critical depth.** During subsoiling, this is the depth below which the soil fails, or is displaced by plastic deformation, rather than by the desired lifting and shattering (see Figure 12). Subsoiling below the critical depth tends to produce pipes or channels in the soil instead of the desired fracturing.

The critical depth is defined as the point below the surface where the vertical resistance of the soil to movement by the subsoilers tines exceeds the force needed to force the soil to flow around the sides of the advancing tine. Critical depth depends upon the power that can be applied by the tractor, the shape and arrangement of the subsoiling tool as well as the soil's mechanical properties.

For the Horizontal Leaching Technique the critical depth must be greater than 0.7m. In order to achieve restructuring to at least 0.7m, it is necessary reduce the strength of the overlying soil by first loosening the upper part of the soil profile. This is done by shallow subsoiling which loosens the soil to a depth of at least 0.4m before the full depth is attempted. The disadvantage, however, of such separate operations is the difficulty of obtaining traction on the loosened topsoil. Alternatively, the tool frame of the subsoiler can be fitted with shallow leading tines.

3.4.4 *Spacing*

Spacings between the lines of subsoiling are best achieved by fixing two tines to the tool frame and making sequential passes across the field, as shown in Figure 14. An alternative approach is to fix the tines in a line on the tool frame at the selected spacings.

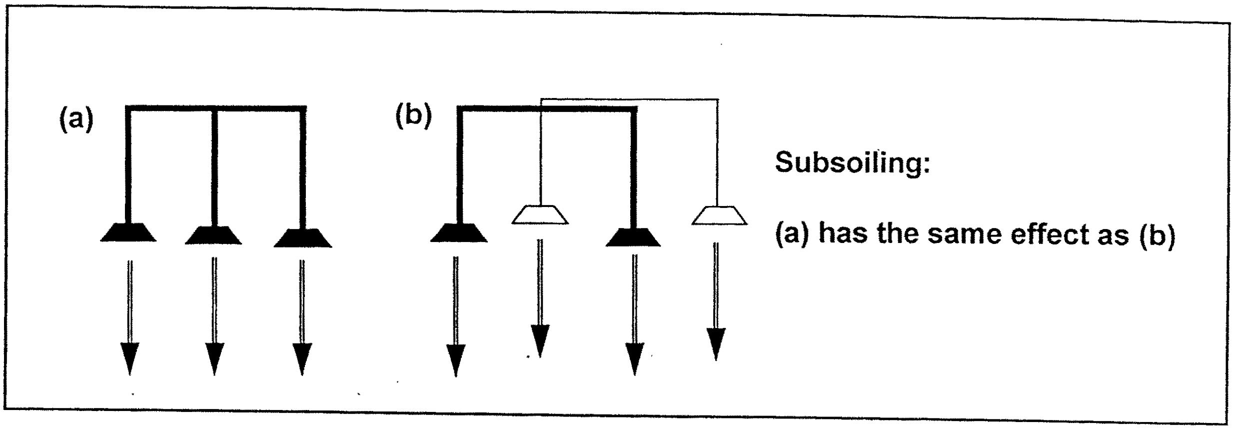

Figure 14 **Comparison of single pass of a triple subsoiler with two passes of double subsoiler**

The minimum spacing between subsoiler lines, typically 0.5-0.6m, is governed by the width between the tractor's track-lines, since re-compaction of loosened soil must be avoided (see Figure 15). In practice the maximum distance between subsoiled channels should not exceed 0.9m. This can be achieved either by using 3 tines mounted on the toolbar at spacings of 0.9m or by using two tines spaced 1.8m apart and then carrying out the next pass at half tractor spacing.

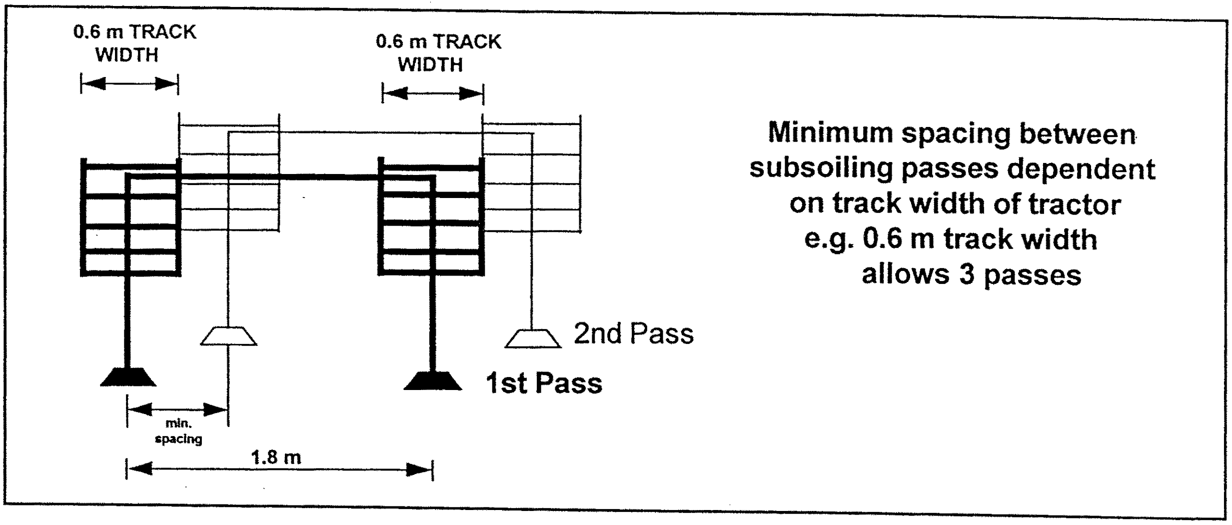

Figure 15 **Schematic plan diagram showing how the minimum spacing between subsoiler passes is dependent upon the width of the tractor's wheel or caterpillar tracks**

3.4.5 *Direction of passes*

The direction of the final subsoiling pass can have a major influence on how the water flows through the plot to the drain. Earlier studies have shown that water tends to move preferentially in the direction of the final pass. Because of this, the final pass at the full working depth (0.7-0.8m) should be longitudinally up and down the plot, between the head pond and the lateral drain.

Making the final subsoiling pass across the plot (cross-ripping) introduces unacceptable resistance to flow. In effect, it greatly reduces the soils effective hydraulic conductivity. This also happens if subsoiling is carried out when the deeper soil is too wet. Despite this handicap, one cross-ripping at full depth is desirable at one of the earlier stages since it provides extra disturbance at depth.

The following sequence for soil restructuring was found to work in field trials, and comprises three subsoiling operations:-

- Subsoil longitudinally at shallow depth (0.3-0.4m).
- Subsoil across the plot (cross-rip) at full depth (0.6-0.8m).
- Subsoil longitudinally at full depth (0.7-0.8m).

Both the initial and final passes are carried out at the minimum 0.6m spacing. Plates 2 & 3 illustrate the subsoiler working at the two operating depths.

3.4.6 Subsoiling procedures

The sequence of operations described in the following sub-sections has been found to provide adequate restructuring to 0.7m depth. They are applied for illustration to a field of width 100m and length 150m. In the case of two-way flow (see Figures 16 and 17), water flows from a central head pond to laterals displaced longitudinally 25 metres in both directions. In the case of one way flow, water flows from the head pond to a lateral located 30m downslope (see Figures 18 and 19).

The fields should first be divided up into a number of plots to be subsoiled, separated by non-subsoiled strips. The main differences between the two layouts relates to the positions of the undisturbed strips, and the positions at which the subsoiler is lifted (see Figures 16 and 18).

The equipment used for this comprises a crawler tractor with two subsoiler legs fixed on the toolbar directly behind the tracks (i.e. with no leading shallow tines), as illustrated in Plates 1-3.

Procedure 1 : Two-way flow layout with 50m drain spacing

The procedure is summarised schematically in Figure 16.

The first pass should be at right angles to the lateral drain, at a depth of 0.4m, using two sub-soiler legs fixed directly behind the tracks to give a 1.8m subsoiler spacing.

- The tractor should enter the field in the lower right-hand corner at A, the subsoiler lowered to the working depth before reaching the lateral and pulled through the drain backfill.
- The tractor then moves up the field and lifts the tines out of work at B. The tractor advances 2m and then lowers the implement back into work at C. This procedure leaves an undisturbed barrier 2m wide mid-way between the laterals.
- The subsoiler is then pulled up the field at working depth until it passes through the next lateral drain backfill at D. The operation progresses in this way up the field, leaving an undisturbed barrier of width 2m between plots and always pulling the subsoiler through the backfill of the laterals.
- At E, the end of the field, the tractor turns (i.e. half way across the plot) and re-enters at F. From here it pulls in the opposite direction down the field, following the same sequence of operations.
- After passing through the lateral at the lower end of the field (G) the tractor turns and re-enters the soil 0.9m (half the subsoiler spacing) across the field from the initial pass.
- These operations are then repeated working sequentially across the full width of the field.

Plate 1 Tractor and subsoiler configuration

Plate 2 Tractor and subsoiler working at shallow depth

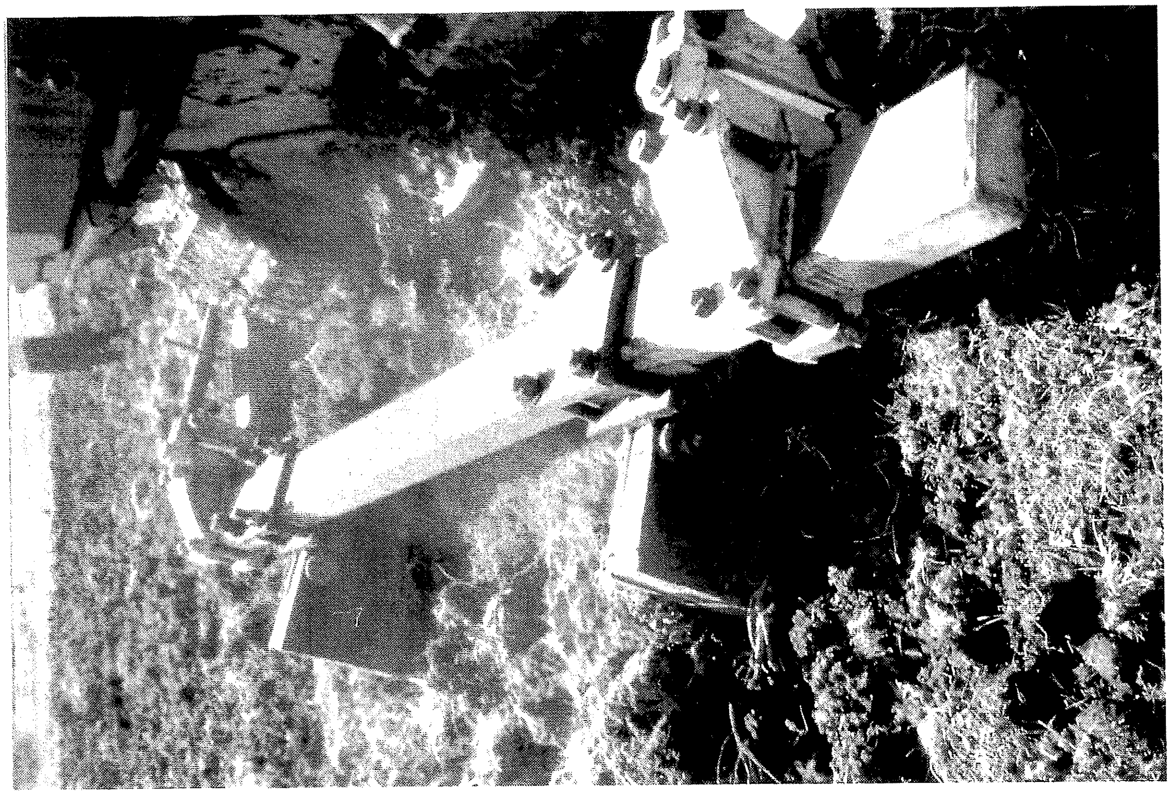

Plate 3 Tractor and subsoiler working at full depth

Plate 4 Tipping bucket drain discharge recorder

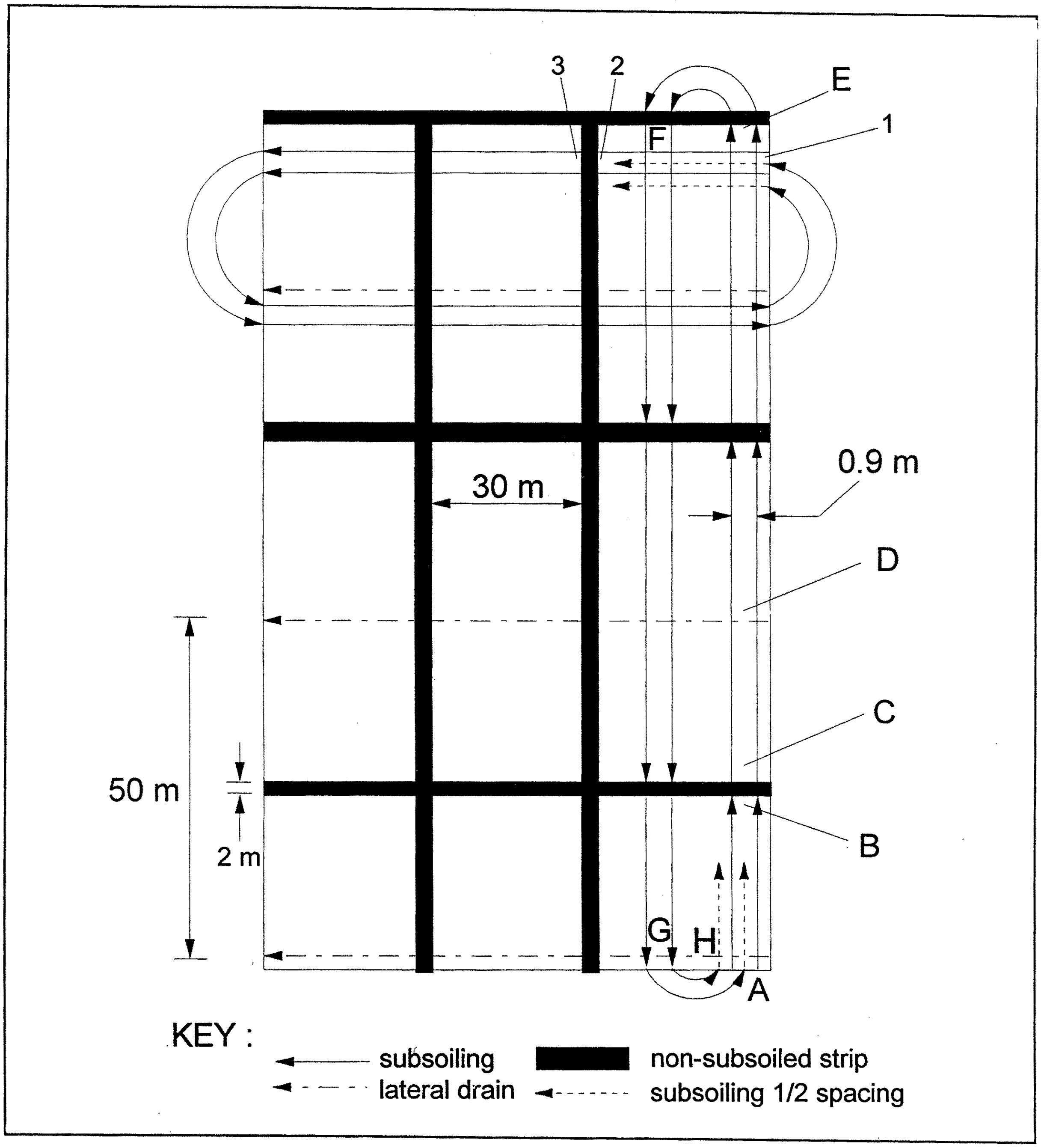

Figure 16 **Schematic plan diagram showing the routing of subsoiler passes to achieve a spacing between passes of half a tractor width (0.9m) for two-way flow system. (NB in the non-subsoiled strips the tractor operator has to raise the subsoiler)**

The second pass is across the field (cross-ripping) at full depth (0.7m) at a spacing of 0.9m (½ subsoiler spacing) between the subsoiling lines. At the edges of the 30m wide plot the subsoiler is inserted (1) and lifted (2). This process is repeated across the field starting with the reinsertion at (3) which leaves a consistent 2m wide undisturbed strip.

The third, and final, pass is again made at a right angle to the lateral drain up and down the field, but now working at full depth (0.7-0.8m) and at a minimum of half subsoiler spacing (this could be reduced to one-third spacing in certain situations). The same operations to raise and lower the subsoiler are still required in order to maintain the undisturbed strip between the plots.

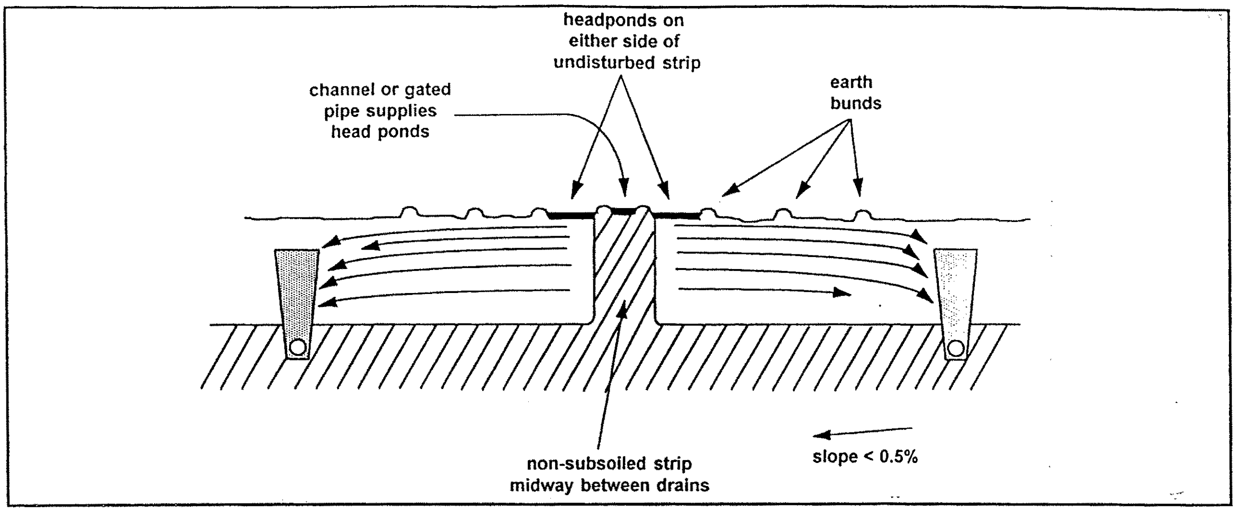

Figure 17 **Schematic diagram of two-way implementation of horizontal leaching technique**

Procedure 2 : One-way flow layout with 30m drain spacing

The procedure is summarised schematically in Figure 18.

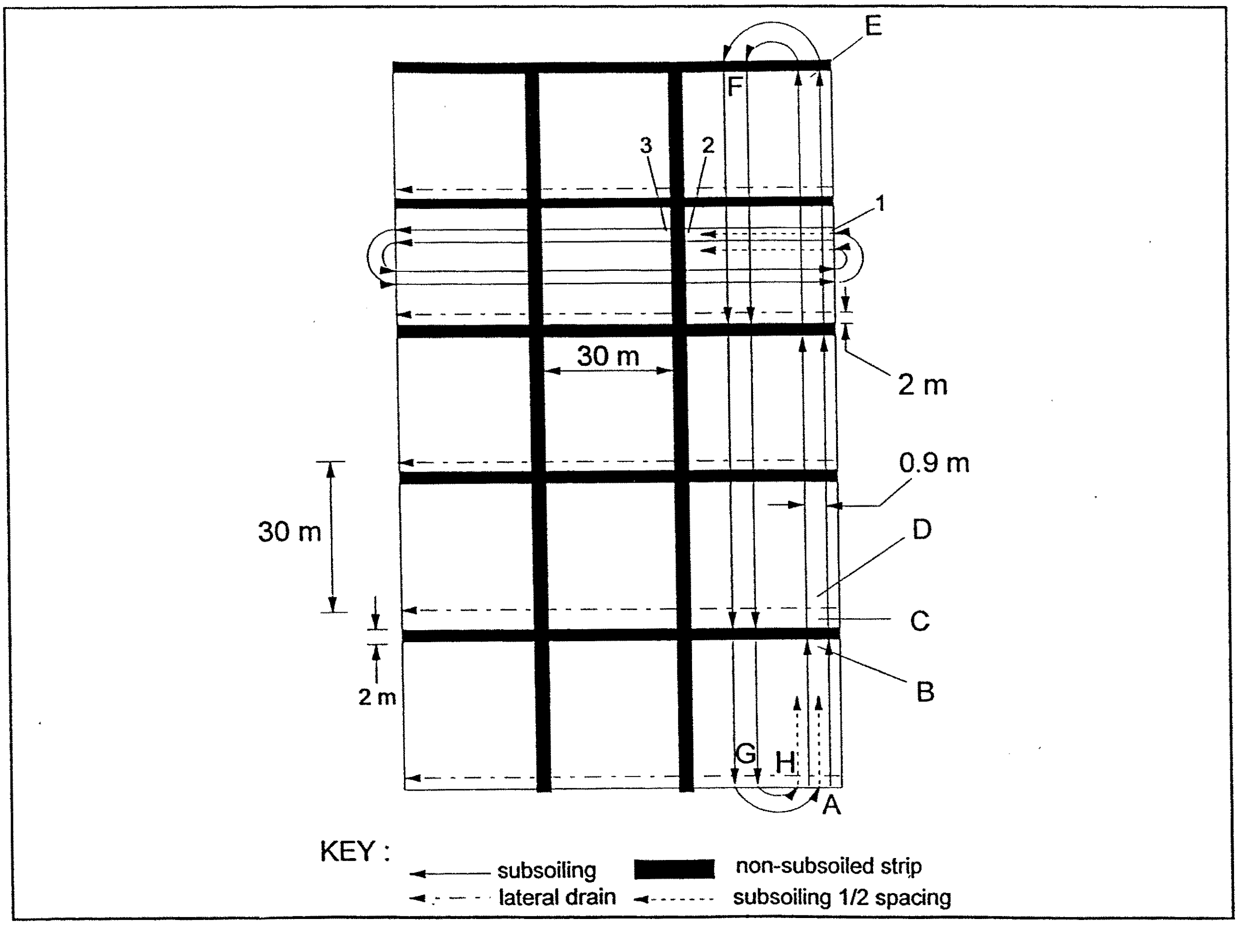

Figure 18 **Schematic plan diagram showing the routing of subsoiler passes to achieve a spacing between passes of half a tractor width (0.9m) -for one-way flow system, (NB in the non-subsoiled strips the tractor operator has to raise the subsoiler)**

When subsoiling for one-way flow, the procedures are similar except that a 2m wide undisturbed strip now has to be left on the downslope side of each lateral drain. This is needed to prevent water seeping backwards into the upslope lateral when the plot downslope is being reclaimed. The undisturbed strip should be about 3m downslope of the drain, so that the tine can be lifted out of work after passing across the lateral.

The first pass should be at right angles to the drain lateral, at a depth of 0.4m, using two subsoiler legs fixed directly behind the tracks to give a 1.8m subsoiler spacing.

- During longitudinal subsoiling, the tractor enters the field at the bottom left hand corner at A and is pulled through the drain backfill.
- At a distance of 25m into the field (B), the subsoiler is pulled out and advanced 2m to leave an undisturbed strip.
- The subsoiler is lowered again at C, still 3m downslope from the drain and pulls through the drain backfill as before.
- This sequence of operations continues up the field, but in all other aspects the operations are similar to those for the two-way layout.

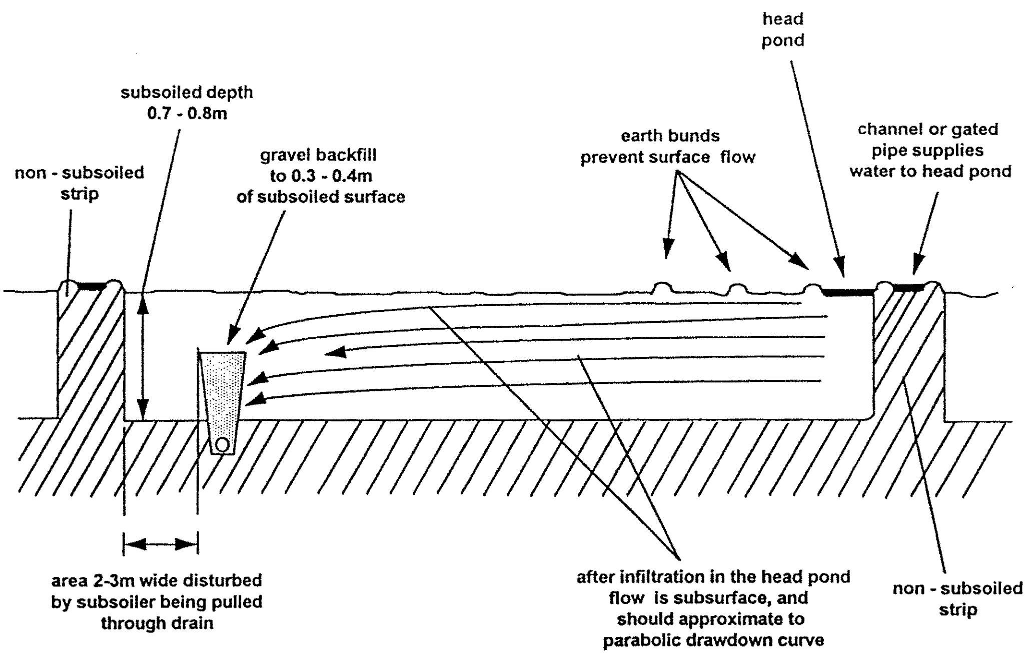

Figure 19 Schematic diagram of one-way implementation of horizontal leaching technique

3.5 Bunding

3.5.1 Purpose

Several lines of earthen bunds need to be constructed both to control the level of water in the head pond and to limit unwanted surface flow. These bunds are typically 0.2-0.3m high and 0.6m wide across their base (see Figure 20), and are constructed either by hand or by a mechanical ridger. They have to be carefully constructed since it is virtually impossible to obviate leakage. Their purpose is to restrict, delay or minimise surface flow, and to maximise infiltration. There are two types of bunds:-

- Cross-plot bunds (across the field) that are installed to minimise surface flow between the head pond and the lateral drain.
- Boundary bunds around the perimeter of each plot to minimise leakage and allow water control to be exercised independently.

When constructing bunds, it is important to ensure that excavated soil does not leave a deep channel into which water will run. Any apparent excavations should be smoothed over by moving soil across over a width of several metres on either side of the bund.

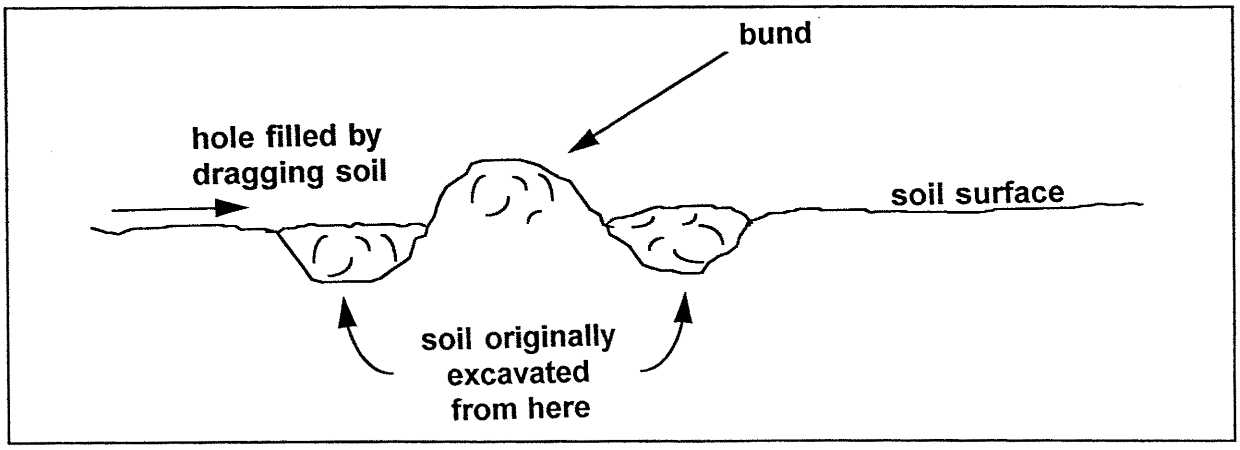

Figure 20 Arrangement for raising bund and for refilling borrow trencher

3.5.2 Boundary bunds
The bunds which prevent surface flow leaking sideways between adjacent leaching plots are constructed on top of the undisturbed 2m wide strips. Their construction and purpose is demonstrated in Figure 9, Section BB'. Wherever possible these bunds should be compacted by running tractor wheels along them, but without entering the newly subsoiled area. This is possible for the bunds around the outer perimeter of the field.

3.5.3 Rear bund
Each plot must have a water supply (in the form of a channel or a pipe) located at the upper edge of the plot, which is used to supply water into the head pond (see Figure 9, Section AA'). The bund may include a water supply channel constructed from compacted earth on top of the non -subsoiled strip. Its main function is to prevent water in the head pond from flowing backwards into the plot immediately upslope. For two-way flow a rear bund is not required.

3.5.4 Cross-plot bunds
The head pond is enclosed by the rear bund, the first cross-plot bund, and the side bunds. The remaining cross-plot bunds are positioned parallel to the first at regular intervals down the field (see Figure 8).

As the first bund is the most important, in conditions where inflow rate is difficult to control, a more rigid barrier is desirable. The damming effect of the earth bunds can be improved by means such as short corrugated metal sheets or plastic sheeting driven into the soil to a depth of about 0.2m. The sheets can be overlapped and packed with earth between the joints to provide an impermeable metal core within the earthen bund.

3.5.5 Head pond
For two-way flow the head pond is located mid-way between the drains which are spaced 50m apart (see Figure 17). The head pond in the 30m one-way flow plot is located adjacent to the upper boundary (see Figure 19). The bunds need to be arranged around the head pond, and its supply channel, to ensure that

a water surface of at least 150mm above the soil surface is possible. Water supply to the head pond can be arranged by means of a lined or unlined channel, but previous studies have shown that the flow rates to the head pond, and the distribution of that flow, can be more finely adjusted and more easily controlled if gated irrigation pipe (see manual back cover) is used. Pipe of 150mm diameter has been found to work well.

4 Water application and management

4.1 Introduction

There are two possible ways of applying water. Choice is dependent on the slope of the field.

- On moderate slopes (0.5-1.0%), water can only flow in one direction between the head pond and the lateral (i.e. in the direction of land slope). In this case an undisturbed strip has to be left on the downslope side of the lateral. The head pond is then established between the boundary bund formed on top of the upper undisturbed strip and the first cross-plot bund - see Figure 17.

- On flat land, and or on low slopes (<0.5%), water can be applied mid-way between the two laterals, generating infiltration and flow in both directions simultaneously. A central undisturbed strip mid-way between the laterals forms the boundary between the two plots. Water is supplied initially to the head ponds formed between the first cross-plot bunds in each plot - see Figure 19.

4.2 Water delivery methods

In-field water distribution is provided by delivery systems that control water flows from field gate to the plots. Water entering the field should flow down a main supply channel following the edge of the field and running down the direction of greatest slope.

Flow is diverted from this channel into a series of lateral field channels running across the field and parallel to the lateral field drains. These field channels are located either at the upper end of the plots (for the one-way flow layout at 30m drain spacing) or midway between the lateral drains (for the two-way flow layout at 50m drain spacing). They should be constructed on top of the undisturbed (non-subsoiled) barriers prepared during subsoiling operations.

The following methods can be used to deliver water from the lateral field supply channel to the head pond:-

- Water is diverted from the field channel into the head pond by making small cuts in the field channel.

- If gated pipe is available it may be laid directly in the head pond and its flow regulated by adjusting the gated valves.

- When a pump is available, water can be pumped directly from the main supply channel to the head pond, obviating the need for a lateral channel. The water can, for instance, be pumped through a 75-100mm diameter flexible layflat hose (needs 3.5 h.p. pump or similar).

- Layflat hose (say 150mm diameter) can also be used to feed water by pumping or by gravity. A minimum head of 0.5m will be needed at the head pond, or about 1.0-1.5m at the point of diversion if gravity flow is to be relied upon.

4.3 Water control : Principles and procedures during leaching

The following considerations need to be made in order to control water application during the reclamation procedure, but more particularly at the commencement of the process:-

- Water is firstly diverted from the lateral field channel or gated pipe into the head pond. This infiltrating zone is located either at the top of the plot (30m drain spacing) or mid-way between the drains (50m spacing), see Figures 17 and 19.

- Water supply is controlled to a rate sufficient to just maintain a shallow depth of water on the surface in the head pond, enough to cover most of the restructured aggregates (see Figure 21).

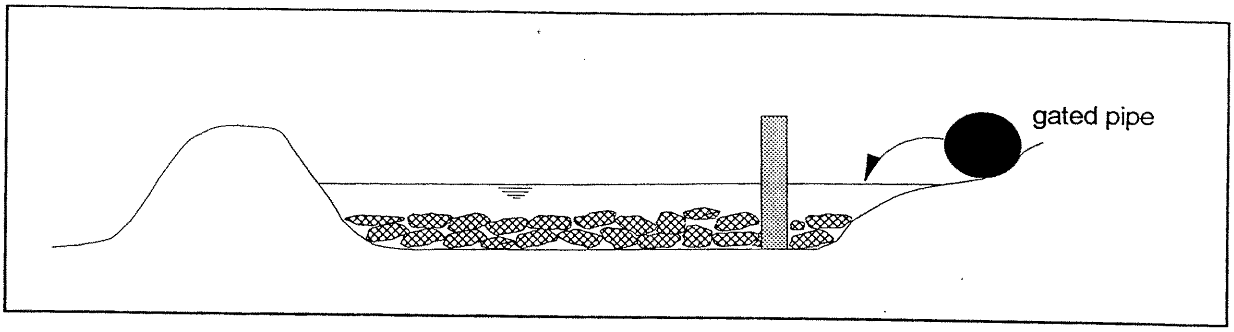

Figure 21 Water level in head pond (and showing soil aggregate submersion)

- It is important to maintain the water level in the head pond at approximately the same height throughout reclamation, so that a consistent flow pattern is established through the plot.
- Initially the plot accepts water rapidly because the soil is unsaturated. At this time a high application rate is required.
- As water infiltrates into the head pond, the wetting front begins to advance down the plot through the subsoil (see Figure 22). The rate of infiltration decreases and the supply can be cut back accordingly.

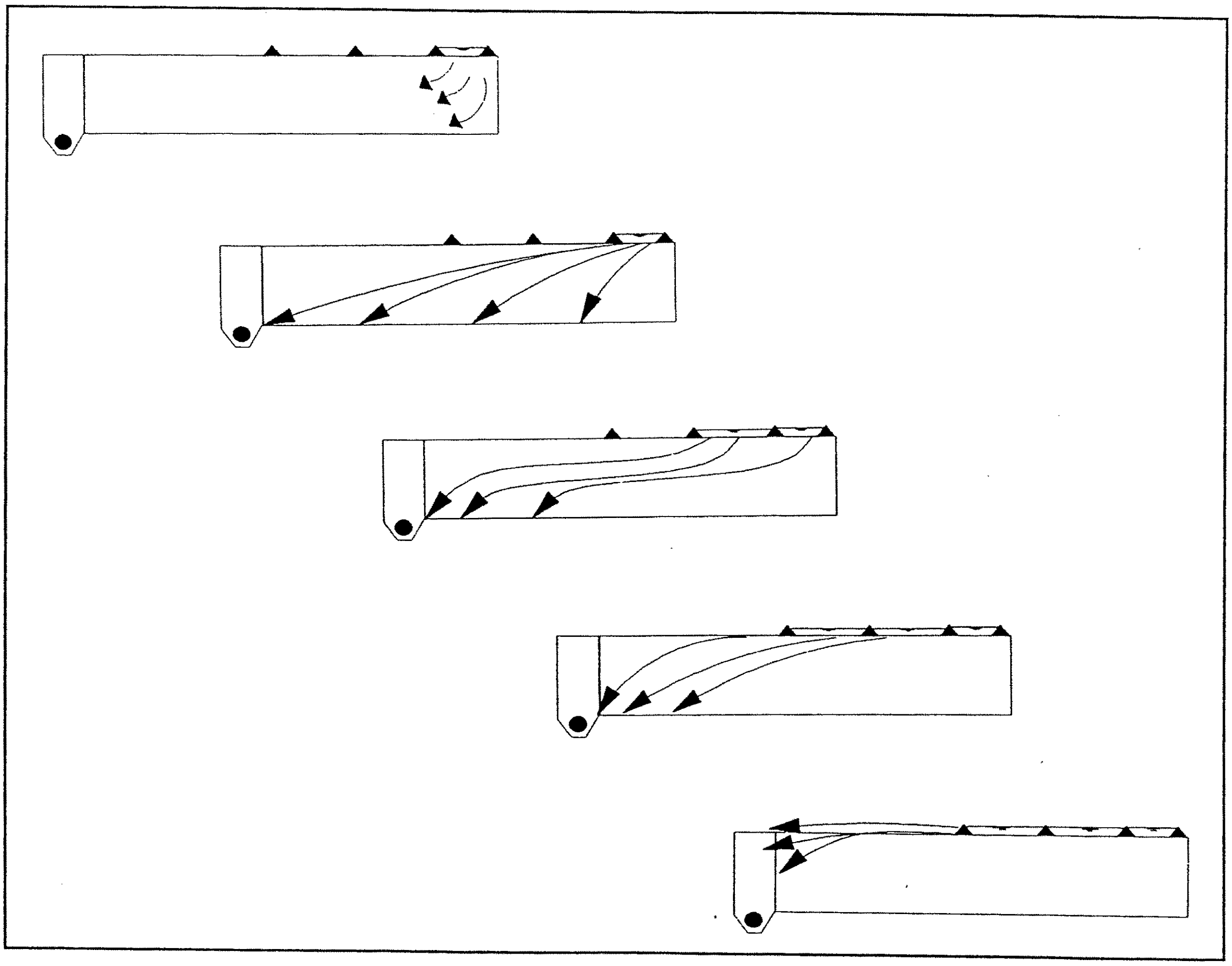

Figure 22 Pattern of subsurface water flow through plot at various stages during the reclamation process

- After some time, usually 1-2 days, the water-table develops a parabolic drawdown curve between the head pond and the lateral drain, as shown in Figures 22 and 25. At this point, water is flowing through the subsoil and carrying saline water to the drain.

- Water demand is greatest at the start of reclamation. Supply should be adjusted to maintain a constant ponded level in the head pond, but the demand will fall off as initial saturation is completed, and then become relatively stable a day or two after the wetting front has reached the drain and a steady flow pattern has become established.

- The steady-state situation will occur when the rate of water application approximately matches the rate of drainage. During this period, the watertable drawdown within the plot will remain approximately constant.

- After several days the soil in the upper part of the plot will have had most of its salt leached out. Further leaching in this area is not necessary, and is inefficient. The next stage can then be started which is to allow the head pond to advance down the plot to the next bund, and to commence leaching in the upper soil in this next area.

- In due course, this process will be repeated in respect of the third bund and then the fourth bund, etc, (see Figure 22).

- After approximately three weeks, the plot should be allowed to pond on the surface, close to the lateral drain, in order to pick up salts in the shallower layers of the soil profile, see Figure 22.

4.3.1 Water control : Operational decisions

During reclamation, the timing of three key decisions needs to be addressed:-

- Cutting back the initial high water application rate.

- Breaking down the cross-plot bunds to allow ponding to advance further down the plot.

- Stopping water application

These decisions can be made more easily if a monitoring programme for water-table levels within the plot is carried out. The way to do this is ideally using a series of dipwells (Appendix 6) that have been installed in at least one plot (see Figure 23). As an approximate alternative, the depth of the watertable within the plot can be estimated by inserting a narrow rod into the top-soil to expose the watertable.

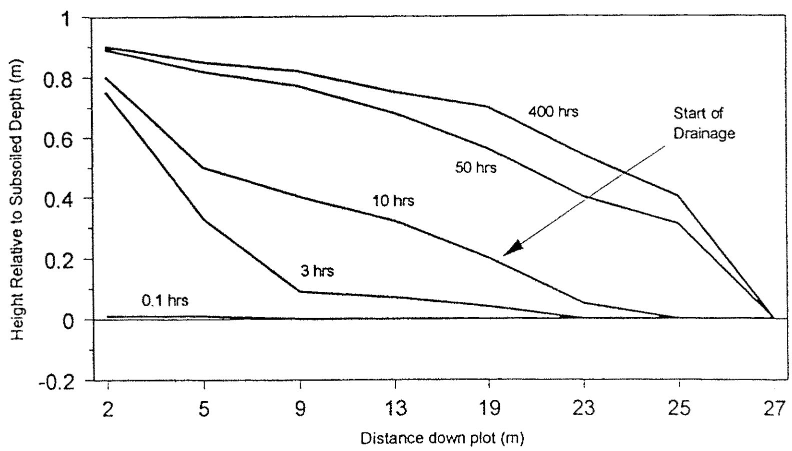

Figure 23 **Variation of longitudinal water level profiles during the 27m Plot Trial (Jamaica)**

Operational decision 1 : Cutting back the application rate
After the soil has wetted up and will no longer accept water readily, a decision has to be made about when to cut back the application rate in order to prevent flow shortcutting across the surface to the lateral drain. From the outset of the reclamation process, a reference level should be established coinciding with the water level in the head pond. This should be sufficient to cover the soil aggregates (see Figure 21). Water should then be supplied at a rate to just maintain the water level in the head pond at the reference level.

Supply should be reduced if either the water level in the head pond rises above this reference level or water begins to pond on the plot surface further than 10m down the plot.

Operational decision 2 : Removing the cross-plot bunds
As the soil in the plot wets up and salts are leached, the restructured clay swells and causes the hydraulic conductivity and infiltration rate in the head pond to fall. This process usually occurs over an interval of 3-6 days. Additionally leakage will inevitably occur both through and beneath the cross-plot bunds. Thus, the judgement as to when exactly to break down the cross-plot bunds and allow ponding to advance further down the field, is not an easy one. In practice, the first bund may be broken when the salinity of the drain discharge has fallen to a more or less constant value from the maximum attained soon after the drain begins to flow. Alternatively, the decision can be made if surface water begins to appear further than ⅓ down the plot, or the drain discharge decreases by say 50 %, despite there being a constant rate of water application.

Operational decision 3 : Stopping water application
Water application should be stopped if either the salinity of the drain discharge falls to the value of the salinity of the irrigation water, or if drain discharge stops. A maximum water application period of 6 weeks should be adequate to reclaim each plot.

The salinity of the drain discharge can be easily measured using a portable EC (Electrical Conductivity) probe.

4.4 Water requirements

4.4.1 Plot water requirements

The water intake rate of an individual plot during reclamation, e.g. the typical 30m by 30m plot shown in Figure 7, depends on the effectiveness of subsoiling. Water requirements are site specific and it is clearly advisable to carry out some preliminary tests to provide information on the intake rate (see Section 2.3). Results obtained so far indicate that:-

- Maximum water requirements occur at the start of reclamation and are expected to be in the range 5-10 litres sec^{-1}.
- The duration of maximum water application rate lasts between 6-12 hours, and during this period drain discharge should begin.
- After 2-3 days the intake rate usually reaches a fairly stable rate of 0.5-1 litres sec^{-1}.

A typical example is given in Table 1 which shows the water application rates for two different plot sizes based on the experimental work carried out on a heavy soil (> 60% clay, dominated by montmorillonite) in Jamaica.

Table 1 **Water application rates**

Water Application Rates (litres sec^{-1})		
	Plot Size (Width x Length)	
Time of Wetting	27m x 27m	30m x 45m
0-6 hrs Drain Discharge Starts approx. 6 hrs after	5.3	5.8
6-12 hrs	1.5	3.00
12-18 hrs	1.25	2.50
18-24 hrs	0.9	1.6
24-36 hrs	0.8	1.5
36-48 hrs	0.9	0.9
2-3 days	0.6	1.2
3-4 days	0.6	0.7
4-5 days	0.6	0.95
5-6 days	0.6	1.05
6-7 days	0.65	1.0
7-9 days	0.65	0.9

An approximate method to estimate the maximum water requirements at the start of reclamation is as follows:-

- Assume that over a period of 6-12 hours enough water must be added to completely fill the air-filled pore-space within the soil.
- As an example consider a 30m x 30m plot subsoiled to 0.8m depth.
- Soil dry bulk density (after subsoiling) = 1.1 tonnes m^{-3}.
- Density of soil solids = 2.65 tonnes m^{-3}.
- Initial moisture content = 25% (gravimetric).
- Total plot volume = 720 m^3.
- Total soil mass = 720 x 1.1 = 792 tonnes.
- Initial soil moisture in plot = 792 x 0.25 = 198 m^3.

- Volume of soil solids $= \frac{792}{2.65} = 299\ m^3$.

- Air filled pores in plot = 720 - 198 - 299 = 223 m^3.

Filling 223 m^3 pore volume in 12 hours corresponds to a water application rate of 5 litres sec^{-1}, whereas filling it in 6 hours corresponds to an application rate of 10 litres sec^{-1}.

4.4.2 Field water requirements

When calculating the water requirements, the fields shown in Figures 16 and 18 can be regarded as being divided into a number of reclamation plots each of which is an independent unit.

The number and sequence of plots being watered, and the timing of water applications can be managed by knowing the required supply needed for an individual plot and the total flow available in the field.

If several plots are to be reclaimed simultaneously, the flow rates have to be aggregated on a pro-rata basis. In practice, labour requirements are likely to result in some form of scheduling, reducing the overall peak water demands. A flow of 20-30 litres sec^{-1} will suffice for most circumstances.

5 Monitoring the reclamation process

5.1 Introduction

Monitoring is required to provide enough data to determine the success of reclamation, to identify areas of improvement, and to provide data for making operational decisions (e.g. when to break bunds).

Time and resources may not be available to carry out an intensive monitoring system, so on a rough scale of priority the measurements to be made are:-

- Salt in soil before and after reclamation.
- Water use during leaching.
- Salinity of the irrigation and drainage water.
- Drain discharge and amount of salt removed via the drains.
- Amounts of salt and water moving vertically and laterally from the plot.
- Soil hydraulic conductivity and water levels in the plot.

The first four measurements are basic and should be made if possible in all cases. Procedures are outlined in Section 5.2 below. The fifth and sixth measurements are only applicable in more detailed investigations which may be carried out during pre-testing, and are outlined in Appendices 5 and 6 respectively.

5.2 Salts in soil

5.2.1 Measurement

The impact of the Horizontal Leaching Technique can be assessed by measuring the salinity levels in the field plots before and after leaching.

At least 10 auger borings should be made for a typical 30m x 30m plot. If necessary these may be bulked together to reduce the amount of analysis. Each auger boring should be split into 3 depth intervals, e.g., 0-0.25m, 0.25-0.5m, and 0.5-0.75m, down to subsoiling depth.

When a more detailed investigation of the salt balance is being conducted auger samples will need to be taken below the depth of subsoiling in order to measure the amount of vertical salt movement. The principles of measuring salt and water changes are outlined in Appendix 5. Samples taken to 1.5-2 metres depth should be adequate. The auger holes should be backfilled with clay and be re-compacted.

Lateral seepage can be estimated by taking auger borings in transects outwards from the plot perimeter after reclamation. The distance of wetting by seepage can be established from the increase in soil moisture content, and changes in soil salinity within the seepage affected area, measured by the methods in Appendix 5.

The type of analysis is dictated by soil condition being reclaimed. The reclamation of **saline non-sodic clay** is concerned solely with a reduction in soluble salts levels, the samples should be analyzed for:-

- Electrical conductivity of saturation extract.
- Chloride concentration of saturation extract.

- Gravimetric soil moisture content (%).

- Soil bulk density.

Further details are given in Appendix 1. An alternative to using the extract from a saturation paste, is to use a 1 part soil to 2 parts water extract.

Important considerations when estimating the efficiency of salt removal are:-

- Removal of salts must be expressed in terms of the **Leachable Salts** present in the soil before and after leaching rather than the total amount of soluble salts. This is necessary because salinity levels cannot be reduced to zero, only to the level of the irrigation water (see Appendix 5 for methods of calculation).

- It is obviously desirable to maximise the proportion of the salt in the soil removed by the drainage system. Nevertheless it is recognised that if the soil is dry enough at 0.7-0.8 m for subsoiling operations then some deep percolation into the non-subsoiled clay below is inevitable, carrying salt with it. The quantity of salt percolating downwards depends on the initial salinity distribution in the soil profile (being higher when salinity increases with depth), the moisture content below subsoiling depth, the efficiency of subsoiling, and the duration of leaching.

- Where gypsum is naturally present in the soil, the salinity cannot be reduced below a level governed by the solubility of gypsum. This typically maintains the measured EC value at a minimum of 2-3.0 dS m^{-1}, and must be allowed for in both initial and final soil samples (see Appendix 5).

5.2.2 Calculation

Overall effectiveness of soluble salt removal is expressed as:-

$$\textbf{Effectiveness (E)} = \frac{\textbf{Leachable salts in plot after reclamation (equivalents)}}{\textbf{Leachable salts in plot before reclamation (equivalents)}} \times 100(\%)$$

$$\textbf{Leachable salt in plot (equivalents)} = \frac{(TLS \times BD \times A \times D)}{1000}$$

where:-

TLS	=	Total leachable salt of soil samples (meq kg^{-1})
BD	=	Soil dry bulk density to subsoiling depth (kg m^{-3})
A	=	Plot area (m^2)
D	=	Depth of subsoiling (m)

5.3 Water application measurement

If a gated pipe or pump is used to feed water to the plots a water meter in the supply pipeline may be used to measure the amount of water applied, and the flow rate.

Where water application is from a channel, suitable measurement structures, e.g. Parshall flumes, may be used. Typically the meter or open channel structure may be expected to deal with flows in the range 1-20 litres sec^{-1}.

5.4 Water salinity measurement

The EC of both the irrigation and drainage water can be measured easily on-site using hand held portable EC probes. For more detailed and accurate analyses (temperature in the field is often outside the recommended range for portable EC probes) samples should be collected in bottles and analysed in the laboratory.

5.5 Drain discharge and salt removal via the drainage system

5.5.1 Measurement

Drain discharge may be measured by a device such as a tipping bucket recorder (see Plate 4), placed below the drain outfall.

Such a system usually requires a drop of 0.5m below the drain outfall. A bucket and stopwatch provides a much simpler alternative.

5.5.2 Calculation

If regular measurements of drain discharge rate and corresponding salinity are made, then the total amount of leachable salts removed in the drains can be calculated from:-

$$\textbf{Leachable salt drained} = \left(\left(\frac{Cd_i + Cd_{i-1}}{2} \right) - Ca \right) \times Vd_i$$

where:-

Cd_i = Salinity of drainage sample (meq l^{-1})

Ca = Salinity of irrigation water (meq l^{-1})

Vd_i = Drainage volume of samples (m^3)

Drainage samples i = 1,2,3....n

Cd_{i-1} at i = 1 is the initial salinity at start of drain discharge

These measurements may be made on the basis of EC (dS m^{-1}) or concentration of a soluble anion e.g. chloride (see Appendix 1).

Results can be compared to the total salt removal from the soil during reclamation (Section 5.2) to ascertain what fraction of the salts have been removed via the installed drainage.

5.6 Performance assessment

Experience of using the Horizontal Leaching Technique on heavy saline clays has shown that the following performance in reclaiming clay soils should be achievable:-

Total leachable salt removal from soil: 60-80 %

Time: 3-4 weeks of water application.

Water use: 7500-10000 m^3 per hectare of land.

Soil hydraulic conductivity: 25-1000 m d^{-1}.

Salt removed in drainage water: 30-65% of total leachable salts.

5.7 Management of reclaimed land

Transfer of the reclaimed land back to agricultural production will require the soil to dry before allowing cultivations (including land levelling) to be carried out.

Salts displaced vertically downwards are potentially available to re-enter the soil rooting zone by upward capillary flow. However, resalinization is unlikely to occur if the soil is irrigated regularly to maintain a net downward flow of water.

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Appendix 1 Soil salinity

A1.1 Types of Salt

Salts within soils exist in the following three forms:-

i) **Soluble salts**: these are salts dissolved in the water contained within soil pores (soil solution) and are mostly dissociated (split up) into ions. The positively charged ions include Sodium (Na), Calcium (Ca), Magnesium (Mg). These "Cations" are balanced in solution by negatively charged "Anions" which include Chlorides (Cl), Sulphates (SO_{4}), Bicarbonates (HCO_{3}) and Carbonates (CO_{3}).[1]

The effects of excess soluble salts include:-

- Reduction of the water available to plants. The presence of salts in solution increases the amount of work that needs to be done to extract the water from the soil pores.
- Direct toxicities of ions such as Sodium, Chloride, Boron.
- Ionic imbalance in the plant.

ii) **Exchangeable Cations:** The colloidal solid material in soils which includes the clay particles and the organic matter usually has a negative electrical charge. This is neutralised by the adsorption of positively charged cations on the colloid surfaces (see Figure A.1). These so called "Exchangeable Cations" are able to exchange with Cations in the soil solution. However, although the composition of the exchangeable cations may change, the total amount must always balance the net negative charge of the soil colloids - Cation Exchange Capacity (CEC).

---

[1]**UNITS**

The total concentration of dissolved salts in solution (i.e. the sum of cation concentrations **or** anions) is expressed in units of **milliequivalents per litre (meq l^{-1})**, although recent soil salinity studies have used the unit of millimoles charge per litre.

1 mole of an element or compound, "the molar mass", is the mass in grams which contains the same number of atoms as 12 grams of Carbon12.
1 mole of charge is the charge associated with 1 mole of hydrogen (H^{+}) ions.
1 milliequivalent (meq) = 1 millimole of charge ($mmol_{c}$) = 1 millimole/ion valence.

The concentration of individual ions (e.g. Cl) may be expressed in millimoles per litre, or milliequivalents per litre.

Other units may be encountered such as milligrams per litre, % salt, or ppm, but will not be used here. Conversions are available in standard texts (ASCE, 1990).

A much more convenient indirect measurement of the total salt concentration in a solution is provided by the Electrical Conductivity (EC) of the solution. The EC value is directly related to salt concentration and is reported in units of deci-Siemens per metre (dS m^{-1}).

Generally, calcium is the most common cation adsorbed on a soils exchange complex, and it helps the clay particles to remain stable. In contrast, high levels of adsorbed sodium tend to make the clay particles unstable, and above a certain level the clay will become prone to instability and dispersion on leaching.

Soil stability is particularly important during reclamation. In cases where stability is in doubt it is usual to add calcium to the soil in the form of either gypsum or lime to counter the effects of the high sodium levels.[2]

iii) **Slightly Soluble Minerals:** The existence in the soil of gypsum ($CaSO_4.2H_2O$) and to a lesser extent calcium carbonate ($CaCO_3$) can provide a source of calcium ions to dissolve in the soil solution during leaching. The solubilities of gypsum and calcium carbonate are typically 30 meq l^{-1} and 5-10 meq l^{-1} respectively in `pure' water but may increase in more saline solutions.

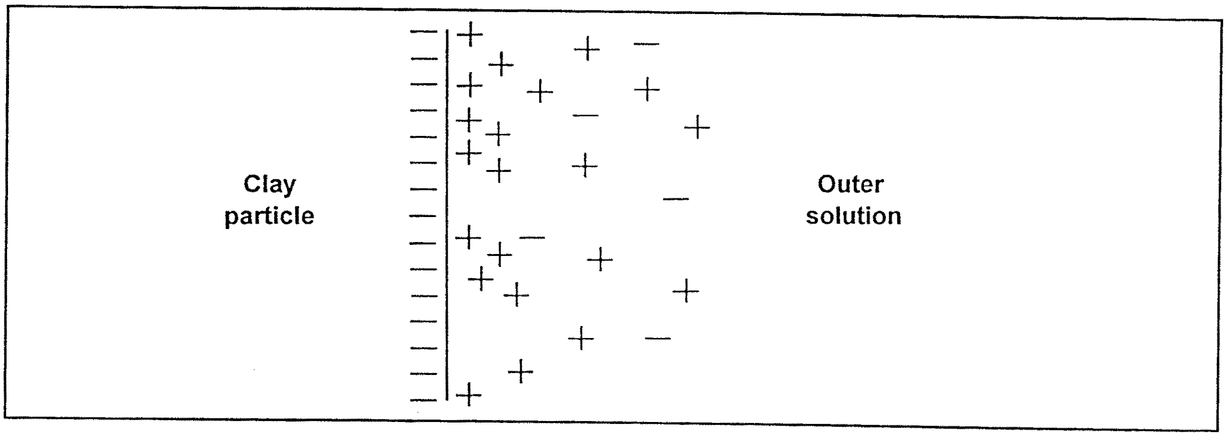

Figure A.1 Distribution of ions in double layer at surface of a clay particle

A1.2 Measuring and classifying soil salinity

Each of the three forms of salts discussed above in Section A1.1 are measured, represented, and classified in different ways. Detailed information on the analytical methods are provided in standard texts (ASCE, 1990).

A1.2.1 Measuring soluble salts

The most widely adopted measurement of soil salinity is the "Electrical Conductivity" (EC_e) of the soil saturation extract. An extract of the soil solution is obtained, usually by vacuum extraction, from a soil paste made up to a particular reproducible moisture content (the saturation paste).

The electrical conductivity is an indirect measure of the Total Soluble Salt concentration (TSS) of the extract (see Figure A.2). The relationship between the electrical conductivity of a solution and its total salt concentration can be approximated as:-

$$\underset{(\text{meq } l^{-1})}{\text{TSS}} = \underset{(\text{dS } m^{-1})}{\text{EC}} \times 10$$

---

[2]UNITS

The quantity of an exchangeable ion and the sum of all the negative exchange sites on the soil (CEC) is expressed in millequivalents per kilogram of soil (meq kg^{-1}).

For detailed studies the individual component ions of the solution should be determined. Indeed, the chloride ion is often used for quantifying soluble salt movement in soils because it is so soluble.

In heavy clay soils the moisture content of the saturation paste is typically in the range 75-100 % gravimetric.

A simpler procedure is to use 1:1, 1:2, or even 1:5 soil to water dilutions. These, however, suffer from greater inaccuracies because slightly soluble salts such as Gypsum and Calcium Carbonate, may dissolve and enter these weak solutions, interfering with the result.

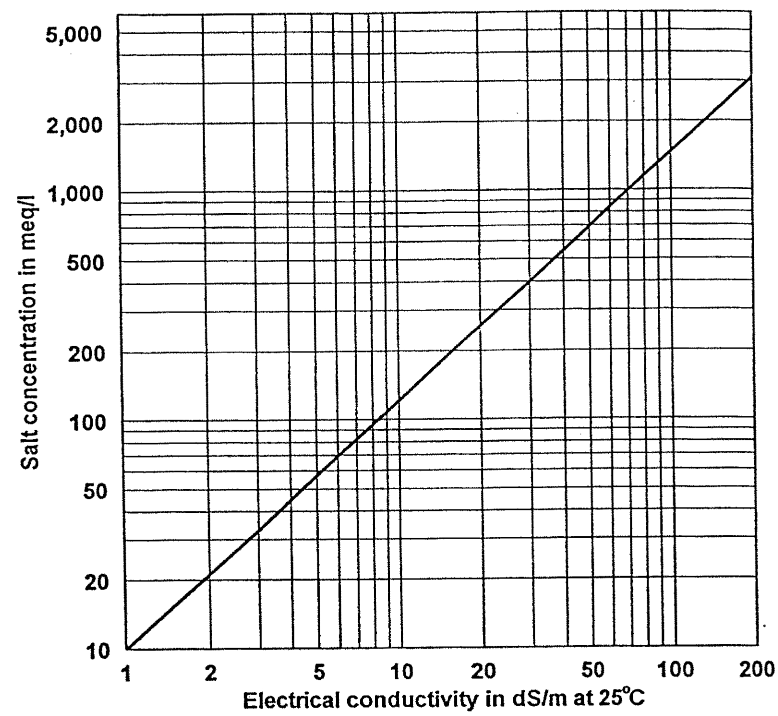

Figure A.2 **Relationship between electrical conductivity and salt concentration (after Richards 1954)**

A1.2.2 Measuring sodicity

The sodium levels within soils or `Sodicity' can be represented by the soils Exchangeable Sodium Percentage (ESP):-

$$\textbf{ESP (\%)} = \frac{\textbf{Exchangeable Sodium}}{\textbf{Cation Exchange Capacity}} \times 100$$

Standard methods for measuring ESP are laborious. For routine purposes, use is often made of the "Sodium Adsorption Ratio" (SAR) instead. The SAR is based on the concentrations of sodium, calcium and magnesium in the **solution** extracted from the saturated soil paste.

The SAR can be expressed as:-

$$SAR\ (meq\ l^{-1}) = \frac{Na\ Concentration}{\sqrt{\frac{Ca + Mg\ Concentrations}{2}}}$$

FAO now recommend using an adjustment of this parameter (FAO Water Quality for Agriculture, 1985) for detailed studies, particularly when using waters rich in Calcium, Bicarbonate, Carbonate, or Sulphate.

The ESP of the **soil** and the SAR of the **solution** are related in the following way:-

$$\frac{ESP}{(100-ESP)} = K_g . SAR$$

where K_g is a constant known as the Gapon Constant. Typical values of K_g are 0.015 although these are best determined for each soil.

A1.2.3 Measuring sparingly soluble salts

Gypsum (calcium sulphate) and carbonates (calcite, magnesian calcite, dolomite), are usually represented by their mass in the soil.

A1.3 Classification of soil salinity

There are several systems used to classify saline soils, the most widely used being the US Salinity Laboratory classification which sets:-

EC = 4 dS m^{-1} and ESP = 15 as the limits for salinity and sodicity respectively.

The ESP value is now widely recognised as being a rather arbitrary figure. There is no generally accepted single definition, and structural stability problems, particularly in soils dominated by montmorillonite, occur when ESP values are is the range 5-10, sometimes even lower.

Appendix 2 Water and salt movement in clay soils

A2.1 Introduction

In most cases, there is no satisfactory way of preventing salts from accumulating in irrigated heavy clays. Their near impermeability when wet prevents salts from being flushed away out of the soil profile. An understanding of the hydraulic properties of heavy clay soils is obviously of importance in assessing their potential for reclamation since the lack of flow of water through them is the fundamental constraint preventing reclamation.

A2.2 Structure of clay soils

In the field heavy clay soils usually have a clearly visible structure which consists of large blocks of soil, the peds, separated by well-defined cracks (see Figure A.3). In the subsoil the peds are usually prismatic or columnar (prisms with rounded tops), but topsoil peds are often composed of smaller blocky or angular-blocky units. This visible structural pattern can be regarded as being the **Macrostructure** and the pore system the **Macropores**. There are two distinct types of macropore; planar cracks which form by swelling and shrinkage during wetting/drying cycles, and tubular shaped 'bio-pores' formed by faunal activity or by the channels left when roots decay. Both cracks and bio-pores are predominantly vertical in orientation and often terminate at about rooting depth.

Figure A.3 **Diagram of a typical macrostructure profile in a clay soil (Reprinted, with permission, from Rowell:- Soil Science - methods and applications, Longman Group, 1993)**

Macropores (also called transmission pores) which range in size from 50 microns (1 micron = 10^{-6} m) up to several centimetres in width are distinguished not just by visibility (to the naked eye or a x10 hand lens) but by their function. They allow rapid drainage of water through the profile to occur under gravity after rainfall or irrigation.

Within the peds the microscopic arrangement of particles and pores forms the **Microstructure** and the **Micropores**. The structure within the peds is formed out of the sand, silt, and clay particles. In clay soils the sand and silt particles are usually seen as being embedded in a matrix of clay (see Figure A.4). The clay is arranged into structural units which have a major influence on the behaviour of the soil (see Figure A.5). The microstructure can be regarded as being similar to a bookshelf in which aluminosilicate layers are built into clay crystals (< 2 microns) and groups of crystals are themselves arranged into structural units called domains (< 10 microns). The major significance of this microstructure for the clay mineral montmorillonite is that water and exchangeable ions are able to move in and out of the microstructure, even the individual alumino-silicate layers, in response to osmotic forces. This greatly increases its active surface area and its potential for swelling (see Section A2.6). The micropores within the peds are formed from :-

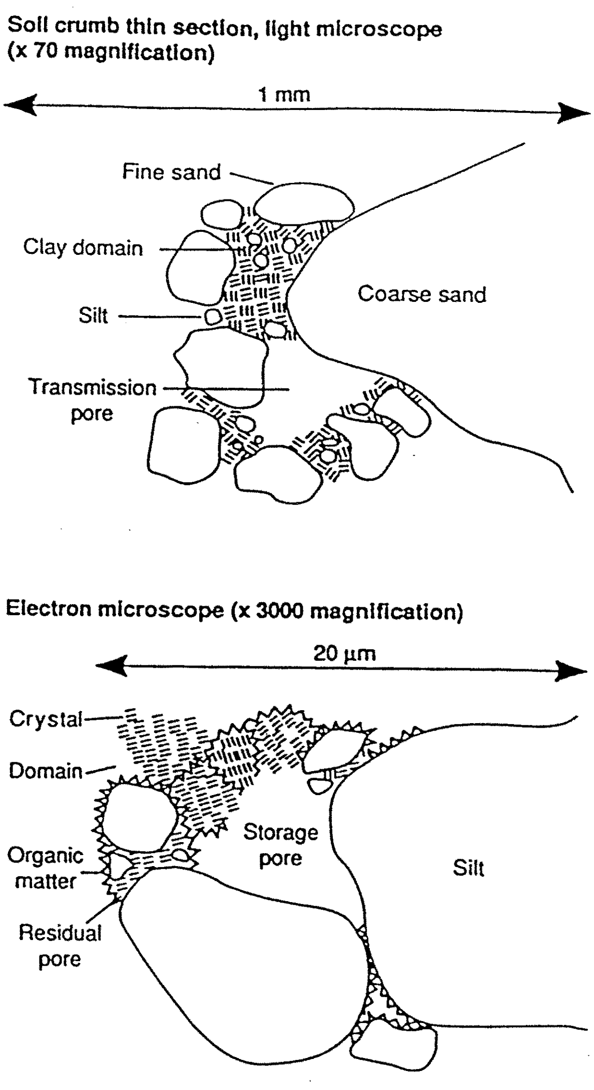

Figure A.4 **Diagram of a typical microstructure profile in a clay soil (Reprinted, with permission, from Rowell:- Soil Science - methods and applications, Longman Group, 1993)**

Storage Pores (50 - 0.2 microns): These contain water which is held after gravity drainage ceases, but is available for plants to extract.

Residual Pores (< 0.2 microns): Contain water held between domains, clay crystals and clay layers which is not available to plants.

In heavy clays, the micropores are dominated by smaller storage pores and residual pores. These are not rigid but may collapse as water is withdrawn during drying. Over a wide range of moisture contents the volume of water lost during drying causes an almost equal shrinkage in the volume of the peds. This mechanism is referred to as normal shrinkage.

Water movement at this scale also occurs in response to differences in salt concentration between the water stored in larger storage pores surrounding the clay particles and water held in the residual micropores within the clay domains or clay crystals.

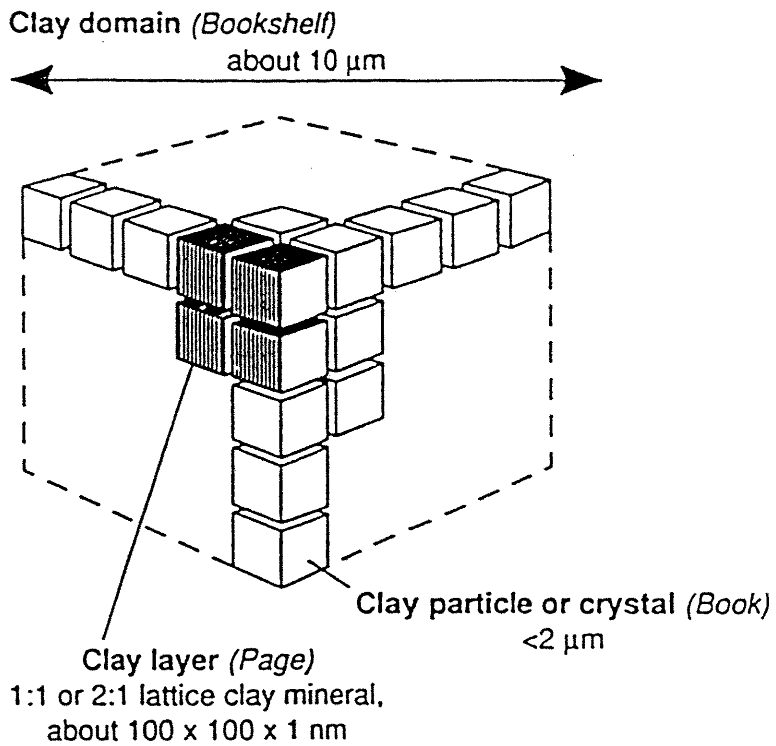

Figure A.5 **Size and arrangement of minerals in a clay soil (Reprinted, with permission, from Rowell:- Soil Science - methods and applications, Longman Group, 1993)**

A2.3 Wetting and drying

Clays, especially those dominated by montmorillonite, shrink on drying and form the system of macropores described above.

During irrigation, water infiltrates into the clay at the surface and spills from micro-depressions down into any open vertical crack (or any other similar continuous pore). These fill up from their base causing water to be absorbed by the peds in between (see Figure A.6).

The pronounced swelling on wetting generates stresses which result in the formation of secondary cracks; these expose a much larger surface area to wetting. Wetting tends to close up most of the cracks and some of the biopores. The fully wetted soil is likely to be very poorly permeable.

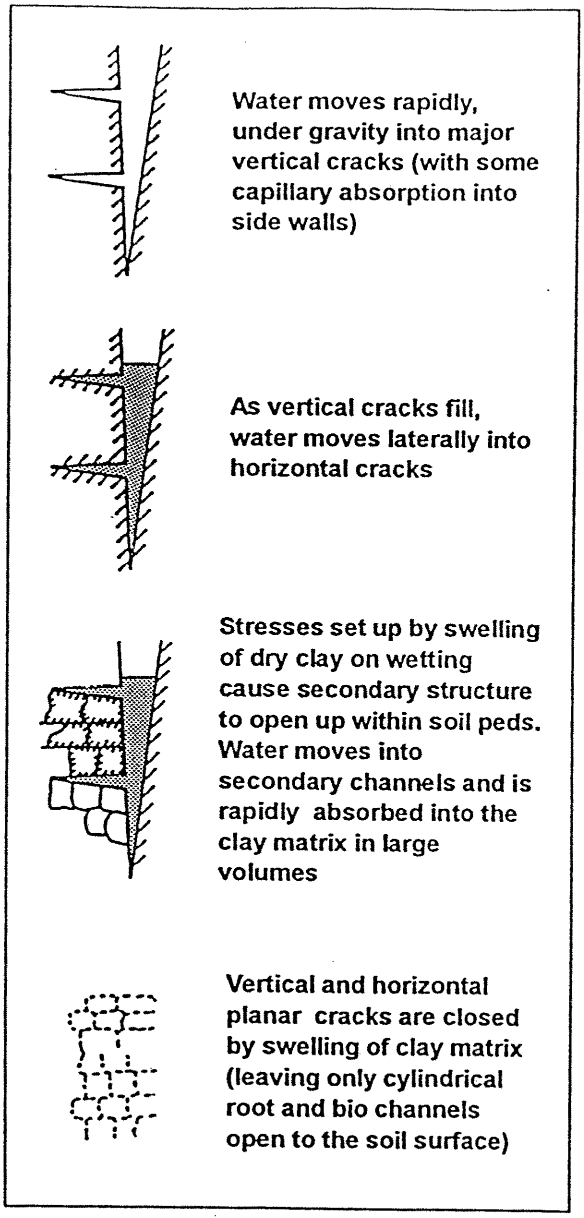

Figure A.6 **Four stages of wetting up and swelling during water flow and absorption in a cracking clay soil**

A2.4 Water movement in clays

Drainage through clay soils occurs mainly through the macropores, including the cracks and the biopores. The quantity of drainage is however, ultimately controlled by the continuity (or lack of it) along the macropores.

The saturated hydraulic conductivity of a fully wetted clay is generally very low, with an upper limit typically of perhaps 0.1m d^{-1}. Even this is solely attributable to the very limited number of macropores which remain open and part of a continuous system. When these are absent (e.g. due to compaction) the hydraulic conductivity reverts to a value reflecting the hydraulic conductivity of the peds, typically about 10^{-4}m d^{-1} (0.1mm d^{-1}). Changes in the soils properties, e.g. due to changes in soil chemistry or by compaction, can result in profound and often adverse changes in the soil structure and hydraulic conductivity.

A2.5 Salt movement

Salts move through the soil with the mass flow of water and also by diffusion.

- Diffusion is the random motion of ions in the soil solution. The process redistributes salts from areas of high salt concentration to areas of low concentration, irrespective of whether the soil water is moving or is static. Diffusion through clay soils is a slow process.

- Water entering or moving through the soil contains salts in solution. During wetting up, water (containing the dissolved salts) is drawn into the mass of the clay by the very strong suction forces which prevail when the soil is dry. Once a clay soil becomes saturated, water movement is confined to the macropores. Percolation downwards or seepage to drainage systems occurs in response to gravitational forces which are very much weaker than the above suction forces.

Flow through clay peds is negligible. Salt movement through the soil profile occurs initially by diffusion along a concentration gradient from:-

Ped Interior → Ped surface → Solution Flowing in Macropores

As long as water in the macropores is able to move freely it will be replenished by `fresh' water and salts will continue to be drawn along the concentration gradient out of the peds.

Diffusion within the peds is a key process governing the removal rate of salts from within the clay soils. Although it is a slow process in comparison to salt movement in lighter textured soils, it is not however the limiting factor, which is instead the lack of water movement through the network of macropores.

A2.6 Structural stability in clay soils

The structure in clay soils, in particular the configuration and continuity of the pore system, is a highly dynamic property. Changes in structure can result from wetting and drying and removal of salts by leaching. Both processes can cause blockage of water conducting pores which are vital for drainage.

In the context of reclamation of saline and/or sodic clays there are two effects:-

- **Swelling of the soil clay**

- **Dispersion of the clay**

When a clay soil dries, the micropores within the peds may contract rather than empty because the matrix of the clay is non-rigid. This causes peds to shrink. Cracks open firstly in the vertical plane between peds, and subsequently in a horizontal direction (see Figure A.7). When re-wetted the water enters these macropores, but is drawn rapidly by capillary suction into the micropores which re-expand, causing the peds to swell and the cracks to close.

In saline soils swelling also occurs when water moves between microscopic clay platelets in response to an osmotic potential difference. This occurs when the salt concentration in the larger pores bathing the clay is reduced by irrigation or leaching. The microscopic effect is magnified throughout the mass of the clay, causing macroscopic swelling of the entire matrix. As the solids swell, pores are closed off causing a reduction in the hydraulic conductivity.

Swelling is a partially reversible process, with the clay mass expanding or contracting as water moves in or out between the groups of clay platelets.

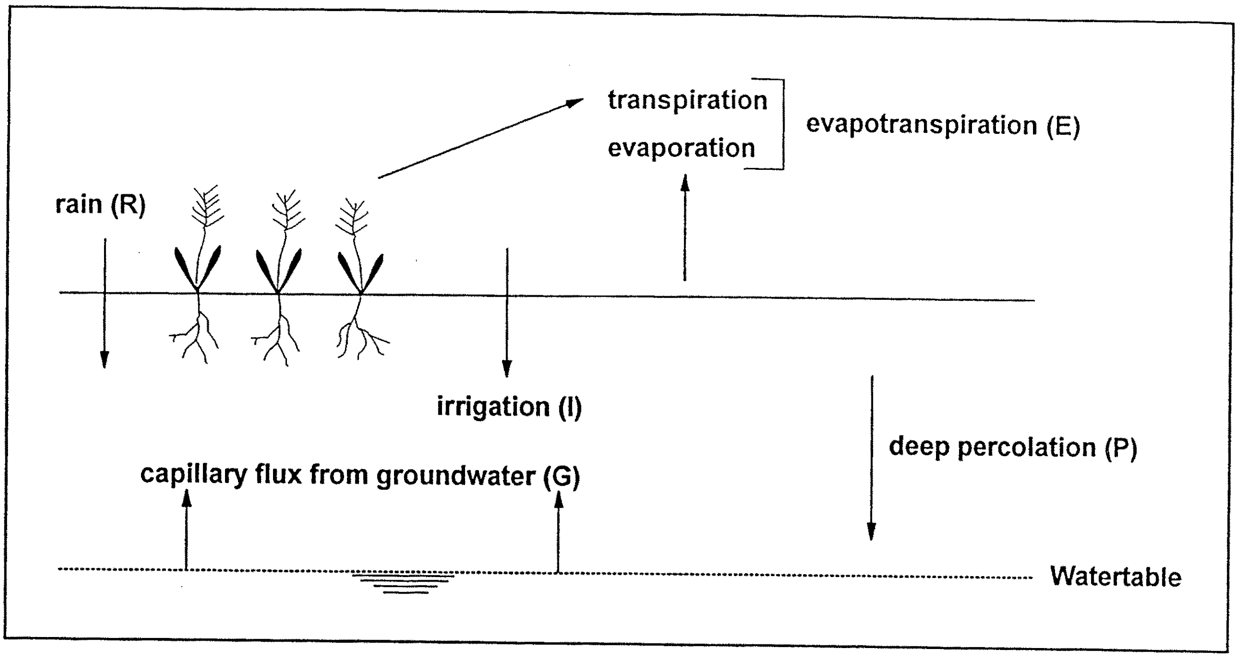

Figure A.7 **Flow lines (solid) and equipotential lines (dotted) for flow from surface ponding to a tube drain**

Dispersion is in effect swelling taken a stage further when separation of the clay particles (or groups of particles) continues until the attractive forces holding them together are completely overcome, causing the clay particles to break apart and disperse into the soil solution. Since the clay is the agent which binds the soil aggregates together this has a `knock on' effect at the macroscopic level, disrupting and breaking the attractive bonds between soil aggregates. Dispersed material is often washed into the larger macropores causing a concurrent loss of soil permeability. Unlike swelling this process is irreversible.

A2.6.1 Factors affecting soil stability during wetting

The degree of swelling and dispersion experienced during wetting is influenced by:-

i) Clay content

It is obvious that the greater the proportion of clay in the soil the greater the potential for swelling. Dispersion of the clay fraction however will disrupt the aggregate bonding in any soil type. In clay soils there is a much greater proportion of fine soil particles entering suspension and undergoing transport and deposition in the soil macropore system.

ii) Clay mineral type

The degree of swelling of the clay increases with the proportion of:-

Smectite > Vermiculite > Illite > Kaolinite

The principle smectitic mineral is montmorillonite and its large swelling potential is directly related to the large surface area (700-900 $m^2\ g^{-1}$) of the clay platelets.

Montmorillonite is usually the dominant clay mineral in vertisols and in alluvial clay soils formed in low lying or flat landscapes, particularly in semi-arid and arid areas.

It is the swelling properties imparted by montmorillonite which make these soils so prone to accumulating salts and so difficult to reclaim.

iii) Exchangeable sodium content

When the Exchangeable Sodium Percentage (ESP) exceeds 15, clay minerals become particularly prone to swelling during leaching.

Almost paradoxically dispersion can be a problem at lower ESP values, in the range 5-10, particularly in montmorillonitic soils. This phenomena occurs because the exchangeable sodium and calcium ions are not distributed uniformly across the charged clay surfaces in proportion to their overall amounts. Rather the calcium is `over-represented' between the clay layers and the sodium concentrated on the outer surfaces of small groups of layers (tactoids) or crystals. The explanation of this `ion de-mixing' phenomena is beyond the scope of this manual (see Shainberg and Letey, 1984), but it is important to recognise that structural breakdown can occur during leaching even at relatively low ESP values.

iv) Soil salinity

Salts in the macropores and storage pores are in equilibrium with the solution held between the clay layers. The higher the concentration of soluble salts in the pore solution, the more tightly packed the clay layers will be. As the solution in the macropores becomes diluted by normal irrigation or, by leaching, part of the `fresh solution' has to move into the spaces between the clay layers to re-establish equilibrium. This pushes the clay layers apart to cause swelling.

In contrast, with high salt concentrations in the water used for leaching or irrigation, dilution of the existing soil pore solution is less, and swelling is reduced.

Summarising:-

Increasing Soil Salinity	→	**Swelling and Dispersion**
Increasing Exchangeable Sodium	→	
Decreasing Salinity of Added Water	→	
Increasing Clay Content	→	
Increasing Montmorillonite in Clay Fraction	→	

Appendix 3 Causes of salinity

A3.1 Introduction

Selection of the most appropriate reclamation procedure depends on identifying the correct cause of the salinity problem.

Soil salinity is associated primarily with semi-arid and arid zones and with low lying or relatively flat lands. In these areas, whenever water accumulates at, or close to, the soil surface it evaporates or is transpired by vegetation, leaving the salts behind in the soil. In wetter regions salts tend to be leached away during the rainy season.

There are several causes of soil salinity problems including the use of saline irrigation water, inadequate leaching of salts, and inadequate drainage to transport leached salts away (see Figure A.8). The following expression is given for the salt balance:-

$$(G \times Cg) + (Vi \times Ci) = (Vd \times Cd)$$

where:-

G	=	Upward flow from groundwater into the soil profile
Cg	=	Concentration of salts in the groundwater
Vi	=	Quantity of Irrigation water entering the soil profile
Ci	=	Salt concentration of the irrigation water
Vd	=	Quantity of drainage leaving the soil profile
Cd	=	Concentration of salts in the drainage water

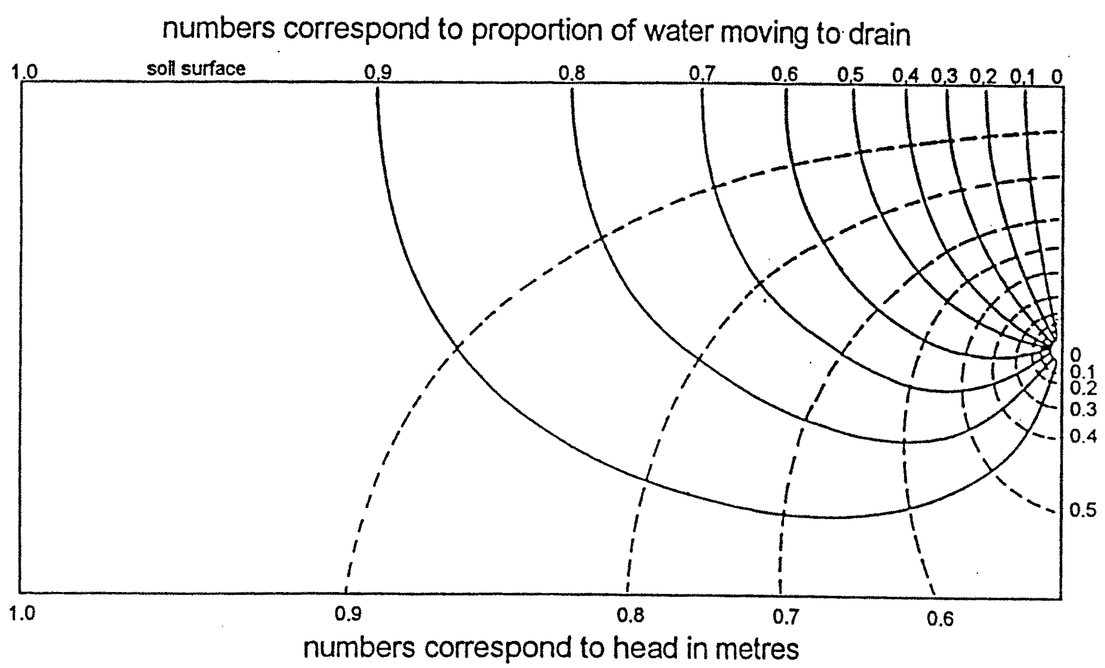

Figure A.8 Water balance in irrigated land

A3.1.1 Poorly permeable soils

In poorly permeable soils, insufficient water drains out of the soil profile to maintain a salt balance i.e. (Vd x Cd) is too small. A continuous build up of salts occurs in the soil profile, ultimately leading to abandonment of the land.

Inadequate drainage may also be caused by the existence of naturally occurring dense layers in an otherwise freely draining light textured soil, or by "plough pans" created by compaction below the depth of cultivations.

Most heavy clays, especially those dominated by the swelling mineral smectite (montmorillonite) have very low hydraulic conductivities when fully wetted. In such cases very little of the applied irrigation water (or the salts) percolates down below the root zone.

A3.1.2 Capillary salinization

When shallow water tables exist (e.g. less than 3m from of the surface) there is a risk that water will creep upwards because of the strong drying which takes place at the surface. As the water evaporates it leaves behind salts in the soil profile. Capillary salinization is usually associated with semi-arid and arid regions. Sustained high water tables in such regions are usually associated with the general rise of groundwater levels following the introduction of irrigation.

The increase in percolation associated with the introduction of irrigation occurs because of the unavoidable loss of water which occurs on irrigated land. Generally capillary salinization only causes a problem when the groundwater is saline and/or the raised level of the water table is sustained by seepage into the area. When the water table is very deep (e.g. greater than 4m) upward capillary flow is slow. In situations where there is no inflow, the water table will continue to fall, leading to a progressive decline in the rate of capillary flow.

A3.1.3 Water scarcity

Shortage of irrigation water often means that applied water may only meet crop water requirements or even cause a deficit to occur. In this situation there will be no excess water available to percolate beyond the root zone to control salinity. This will inevitably lead to a progressive rise in the salinity levels in the soil and a temporary rise in the salinity of the reducing amount of water remaining within the soil.

A3.1.4 Use of saline irrigation water

When irrigation water is saline, soil salinity is determined by the amount of leaching, and the quantity of irrigation water:-

$$EC_e = n \times EC_i$$

where:-

EC_e = Soil Salinity (EC of the Saturation Extract)
EC_i = EC of the irrigation water
n = Concentration factor, dependent on the amount of leaching

In the absence of restrictions on leaching (water shortage, permeability problems) the minimum achievable soil salinity is a function of the irrigation water salinity.[3]

A3.2 Remedial measures

Techniques are available to solve most salinity problems but these are not always economic, particularly in clay soils.

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[3]See Water Quality for Agriculture, FAO Irrigation and Drainage Paper 29 Rev.1 for current classification of irrigation waters.

Subsurface drainage (i.e. buried pipe drains) is specifically designed to minimise salinization by ensuring that a minimum quantity of water, "the leaching fraction", drains through the soil profile, keeping soil salinity permanently in check. Design is aimed at ensuring that the water table is maintained deep enough to prevent significant upward movement of salt by capillary flow. Generally, the feasibility of using a subsurface drainage system is based on economic considerations rather than technical ones.

Shortage of irrigation and the associated build up of soil salinity can be addressed by the occasional application of heavy waterings which flush accumulated salts down below the rooting zone.

Where irrigation water is saline, it can sometimes be mixed with good quality water or the two sources may be used alternately. With careful management different crop sensitivities can be matched to availablity and quality of water to produce a viable cropping pattern.

When impeding layers exist in an otherwise permeable upper soil profile, shallow subsoiling to just below the restrictive layer should be carried out. This will allow water applied for reclamation or for normal irrigation to wash the accumulated salts down out of the topsoil. In the case of poorly permeable soils the salts are likely to remain in the subsoil below the root zone and there is a danger that they will creep back towards the surface when the soil dries out.

Appendix 4 Review of clay soil reclamation techniques

A4.1 The importance of clay soils

Clay soils are some of the most productive in the world. They have a moderate to high fertility, and a high water holding capacity. They are often found in densely populated low lying alluvial or coastal plains, making them particularly attractive for irrigated agriculture in arid and semi-arid regions.

The risks of soil salinisation are high and are particularly acute in clay soils, because, unlike lighter textured soils, there is no economically viable method of draining them and of controlling salinity.

The types of clay soil which are most at risk from salinisation include:-

- **Vertisols** - known locally by a wide variety of names, e.g. Black Cotton Soils. The dominant mineral in these clay soils is montmorillonite which makes them very prone to swelling. Deep cracks formed during drying result in an exceptionally high initial infiltration rate but as the cracks close the soil becomes virtually impermeable. Because of this, very little of the applied irrigation (and salt) penetrates beyond the drying depth.

- **Alluvial clay soils** - encountered in river basins, deltas, old lake beds and coastal plains. Although they are often deposited in layers of varying texture, many areas have deep clay extending to more than 2 metres. These deep clays impede drainage and hinder the leaching of salts.

- **Marine clays** - inundated at some point by seawater and having a high salinity and sodicity (high sodium level).

Soil physical properties are influenced by the amount of clay up to about 30 % clay content, but at higher proportions the type of clay dominates the soil's physical properties. Heavy clays are those with a clay content in excess of 50%.

A4.2 Reclamation of saline clay soils

Soil reclamation in poorly permeable saline clays is made extremely difficult by two factors in particular:-

- **Inaccessible salts** - Most of the soluble salts are held in very small "micropores" (< 50 microns) within the mass of the clay (termed peds or aggregates). When the soil is wetted, it swells and the clay becomes virtually impermeable to flow. Salt can no longer be leached out effectively. The only mechanism left by which salt can still be removed is diffusion, but this process is very slow over the scale of a large soil ped. The amount of salts that can migrate through the clay matrix and eventually arrive at a larger "Macropore" (> 50 microns) in time to contact with the added water is very small. All the salt held in the micropores throughout the main body of the ped is effectively locked there.

- **Poor water conducting systems** - As a clay profile is wetted up, the cracks between peds close up and prevent water from flowing through. The only holes that remain open are biopores (such as root-tracks) and these do not provide any significant contribution to drainage. This is because they tend to be vertically orientated and terminate at or around rooting depth. With or without subsurface drainage, low permeability prevents enough water moving to leach salts unless many months of water application have been carried out.

A4.2.1 Conventional methods of reclamation : Applicability to clay soils

The most common method of flushing accumulated salts from permeable soils is to divide the field into small basins and pond water on the surface. The infiltrating water carries the salt down with it through the soil profile.

Conventional "rule of thumb" criteria indicate that in this process about 80% of the soluble salts will be removed by 1m of water passing through 1m depth of soil. In practice, before reclamation is undertaken preliminary ponding tests should be carried out to develop a leaching efficiency curve specific to the soil type.

The destination of the water that does manage to percolate down may either be the natural water table, a subsurface drainage system or simply the underlying soil.

Ponding - in clays without subsurface drainage
The swelling of heavy clays during ponding can seal the soil profile, resulting in little or no effective leaching below rooting depth (see Appendix 2).

However, during the wetting/drying cycle, some internal redistribution of salts may occur within the soil profile. This can be used to improve leaching efficiency and to encourage some downward movement of soil salinity. This is done using intermittent ponding. As the soil cracks during drying, some of the salts migrate to the crack surfaces. Here they are deposited as the water evaporates. During the next ponding, a fraction of the residual salt is washed to the bottom of the cracks. This is a much quicker transport mechanism than flow through the clay matrix.

Excessively long periods between pondings, however, can be counterproductive as they allow the salts to be drawn back up into the drying zone by capillary action.

Reclamation in conjunction with drainage systems
Removal of salt via an installed drainage system is preferred because:-

- The salt is transported out of the area and cannot move back into the soil profile.
- If a water table is present, the installed drainage system can be used to control capillary salinization.

Figure A.7 shows the flow lines that occur when water is ponded on the surface. It is clear that most of the infiltration, and thus the leaching, occurs close to the drain. Because of the very low horizontal hydraulic conductivity of the clay, drain spacings need to be very close to be effective and this is not economic.

In reality, the movement of water through drained clays can be very different from the ideal case outlined above, but with the same consequences (see Figure A.9). The topsoils of heavy clays are often permeable because biological activity creates a fine block surface structure or because tillage improves the structure. Applied water tends to build up a saturated layer on top of the impermeable subsoil and flow then moves horizontally by interflow through the topsoil. The water then either flows directly into open drains or moves down through the trench backfill to the pipe drain. In both cases the subsoil remains poorly leached.

A4.2.2 Conditions for drainage systems to work in clay soils
Many clay soils, particularly alluvial ones, are layered and contain permeable strata within the subsoil. If drains can be placed within the permeable layer, the resistance to flow will be greatly reduced. Most of the hydraulic head can then be used to promote downward flow through the poorly permeable layers. Flow to the drains will take place horizontally through the underlying permeable layer.

A4.2.3 Choice of reclamation technique
The disadvantages associated with using ponding for reclamation can be offset to some extent if it can be combined with a production activity such as fish farming or rice cultivation. In these cases the expense involved with the length of time required for reduction of soil salinity levels can be offset by the value of the associated production.

Rice production requires a surface drainage system to remove surface water at certain stages of crop growth, particularly before harvest in order to allow full maturation. As salinity decreases the rice may be grown in rotation with a dryland crop. In this case sub-surface drainage systems may be required for salinity control.

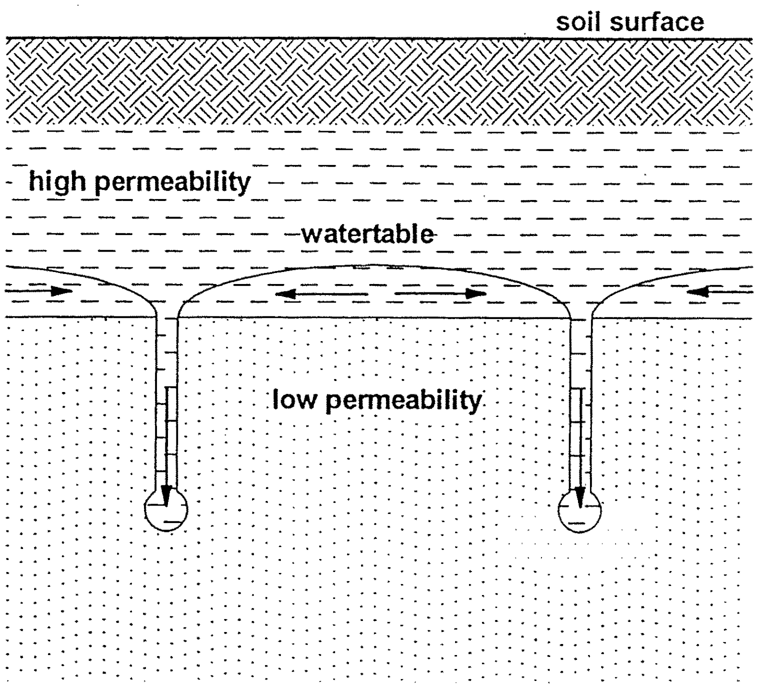

Figure A.9 Flow paths to drains in clay soils

Appendix 5 Converting laboratory salinity measurements to plot scale salt balances

A5.1 Background

Determining the efficiency of salt removal during reclamation requires conversion of the measured salinity of the laboratory determined soil extracts to **Leachable Salts** in the plot.

Calculations are made on a salt equivalent mass basis and can then be converted to % values if required.

The sequence is:-

- The salt concentration of a soil extract (Sc), either with a saturation paste or a 1:2 Soil/Water extract, is determined in units of milliequivalents per litre (meq l^{-1}).

- The concentration is converted to a salt content (Sm) per unit of soil mass according to:-

$$\underset{(\text{meq kg}^{-1})}{\mathbf{Sm}} = \underset{(\text{meq l}^{-1})}{\mathbf{Sc}} \times \underset{(\text{l kg}^{-1})}{\mathbf{Sp}}$$

  where:-

  Sp = Gravimetric moisture content

- For the whole plot volume (or a part such as a layer) the total mass of salt (TMS) is calculated from:-

$$\underset{(\text{meq})}{\mathbf{TMS}} = \underset{(\text{kg m}^{-3})}{\mathbf{BD}} \times \underset{(\text{meq kg}^{-1})}{\mathbf{Sm}} \times \underset{(\text{m}^{3})}{\mathbf{V}}$$

  where:-

  BD = Dry bulk density

  V = Soil volume in plot

A5.2 Soil bulk density

Estimation of the salt content in the soil requires a measurement of total soil mass and hence soil bulk density.

Determining the soils bulk density before and after subsoiling provides a useful indicator of the effectiveness of restructuring. A measure of bulk density at the end of the reclamation process provides a measure of the consolidation of the restructured clay during and after wetting.

A relatively large sample must be used and the simplest procedure is to dig a pit, 1m x 1m (at least one per plot), to the minimum depth of subsoiling. The volume of the pit should be measured, the extracted soil weighed and its moisture content determined:-

$$\underset{(\text{kg m}^{-3})}{\textbf{Dry Bulk Density}} = \frac{\textbf{Dry Soil Mass (kg)}}{\textbf{Volume of Pit (m}^{3}\textbf{)}}$$

Where samples below the depth of subsoiling are required, then, unless the soil has dried and cracked deep into the subsoil, they can usually be taken in cores from the bottom of the pit.

A5.3 Leachable salts

In calculating the efficiency of salt removal it is important to recognise that not all salts can be displaced. The minimum achievable salinity is determined as:-

(Volume of soil moisture at end of reclamation) x (Salinity of irrigation water)

Generally the final moisture content will by the soils `Field Capacity'. For the Horizontal Leaching Method, at the final moisture content the clay peds are saturated but with the macropores emptied by drainage.

Any parameter for expressing leaching efficiency must adopt this minimum achievable salinity value as its base line, and express salt removal in terms of **Leachable Salts**. The concept is illustrated in the example below.

A successful reclamation trial might produce the following data:-

Initial Soil Moisture Content = 0.25 kg kg^{-1} (25 % gravimetric) = 0.25 l kg^{-1}

Final Soil Moisture Content = 0.50 kg kg^{-1} = 0.5 l kg^{-1}

Initial Soil Salt Content = 50 meq kg^{-1}

Final Soil Salt Content = 20 meq kg^{-1}

Irrigation Water Salinity = 15 meq l^{-1}

A5.4 Initial leachable salt

When the soil is initially unsaturated it has the capacity to absorb irrigation water, and the salt it contains. The Initial Soil Salt Content just before leaching begins can be considered to be made up of three components:-

- The total amount of salt present initially when the soil is at a moisture content of 0.25 kg kg^{-1}, before any wetting = 50 meq kg^{-1}

- The amount of salt added in the irrigation water in bringing the soil from initial moisture content 0.25 kg kg^{-1} to final moisture content 0.5 kg kg^{-1}

  = (0.5 - 0.25) x 15 = 3.75 meq kg^{-1}

- The non-leachable fraction. The minimum achievable salt level when the peds are saturated with irrigation water and the final moisture content is 0.5 kg kg^{-1}

  = 0.5 x 15 = 7.5 meq kg^{-1}

Therefore:-

The Initial Leachable Salt = (50 + 3.75 - 7.5) = 46.25 meq kg^{-1}

A5.5 Final leachable salt

The leachable salt remaining at the end of the reclamation period is represented as:-

Final Leachable Salt = Total Salt Content at End of Reclamation - Non-Leachable Salt Content

= 20 - 7.5 = 12.5 meq kg^{-1}

Hence the Leaching Efficiency in terms of the fraction of Leachable Salts removed is represented by:-

$$\text{Leaching Efficiency} = \frac{(46.25 - 12.5)}{46.25} \times 100 = 73\ \%$$

NB: Had leaching efficiency been determined in terms of the Total Salt Content of the soil before and after leaching, rather than the Leachable Salts, the calculation would have been:-

$$\text{Leaching Efficiency} = \frac{(50 - 20)}{50} \times 100 = 60\ \%$$

A5.6 Leachable salt removed in drainwater

The salt concentration of the drainflow needs to be corrected for the proportion of salts attributable to the irrigation water (see Figure A.10):-

$$\mathbf{LSD = (Cd - Ci) \times Vd}$$

LSD	=	Leachable salt (equivalents) removed in drainwater volume, Vd
Cd	=	Drainwater salt concentration, (meq l^{-1}))
Ci	=	Irrigation water salt concentration, (meq l^{-1})
Vd	=	Drainage volume, (m^3)

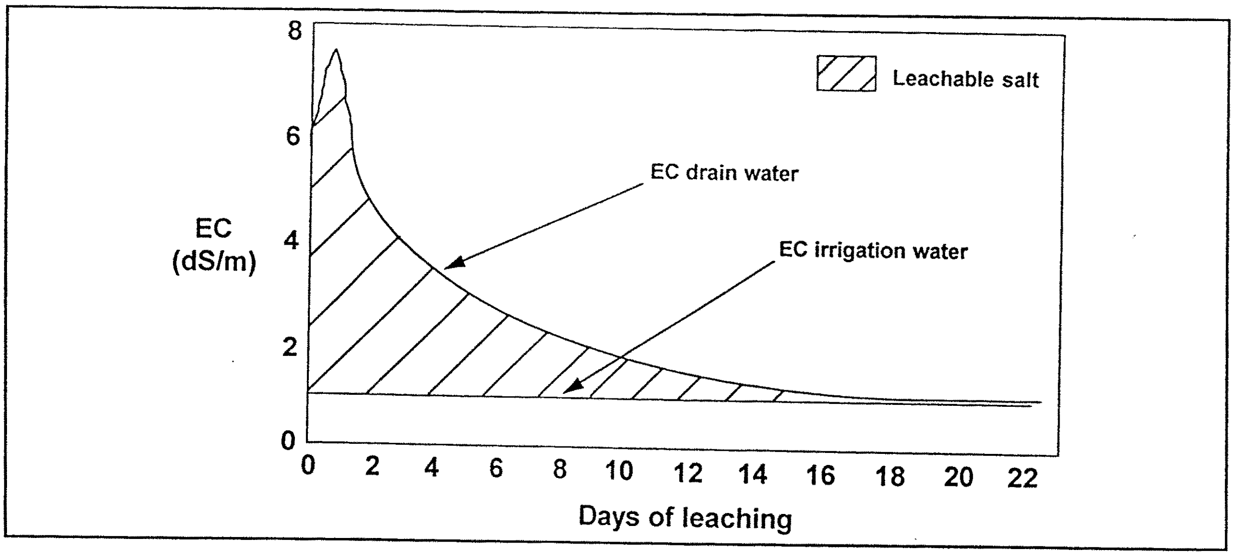

Figure A.10 **Variation of EC with time showing salt removed by drainwater during HLT in excess of the traces of salt introduced by the irrigation water**

Ideally the salt removal estimated from a soil balance should equal the amount removed in the drainwater (i.e. all of the salts removed from the restructured soil are leached through the installed drainage system).

Both figures can be relatively easily estimated from routine monitoring. Where there is a major discrepancy between the two figures it is useful to identify the sink for the `missing' salts.

A5.7 Deep percolating salts

Salts may have been displaced vertically into the non-subsoiled clay below the depth of subsoiling.

Estimation of the proportion of `deep percolation' requires soil samples to be taken to at least 1.5 metre depth before and after reclamation.

NB: There may be significant Bulk Density differences in the soil below subsoiling depth. Therefore bulk density determinations to the depth of salt sampling are needed to estimate the amount of salt movement on a mass basis.

Appendix 6 Estimating soil hydraulic conductivity and water levels

An estimate of the hydraulic conductivity of the restructured soil can be obtained by measuring the `water-table' drawdown between the head pond and the drain (see Figure A.11). The hydraulic conductivity value between any two points can be represented by the formula:-

$$K = \frac{2 \times Q \times X}{(h_2^2 - h_1^2) \times W}$$

where:-

K	=	Hydraulic conductivity (m d^{-1}) between points 1 and 2
Q	=	Drain discharge from restructured soil (m^3 d^{-1})
X	=	Distance (m) between points 1 and 2
h_1, h_2	=	Height (m) of `water-table' at points 1 and 2
W	=	Width (m) of trench or plot

The formula given is applicable to steady state conditions, so K should be estimated during a period when the water levels (h) and the discharge (Q) are relatively constant.

The K value obtained is depth-averaged between the points of measurement. Because upper profile tends to be more permeable, this is reflected in larger K estimates where the water levels are highest (i.e. furthest from the drain).

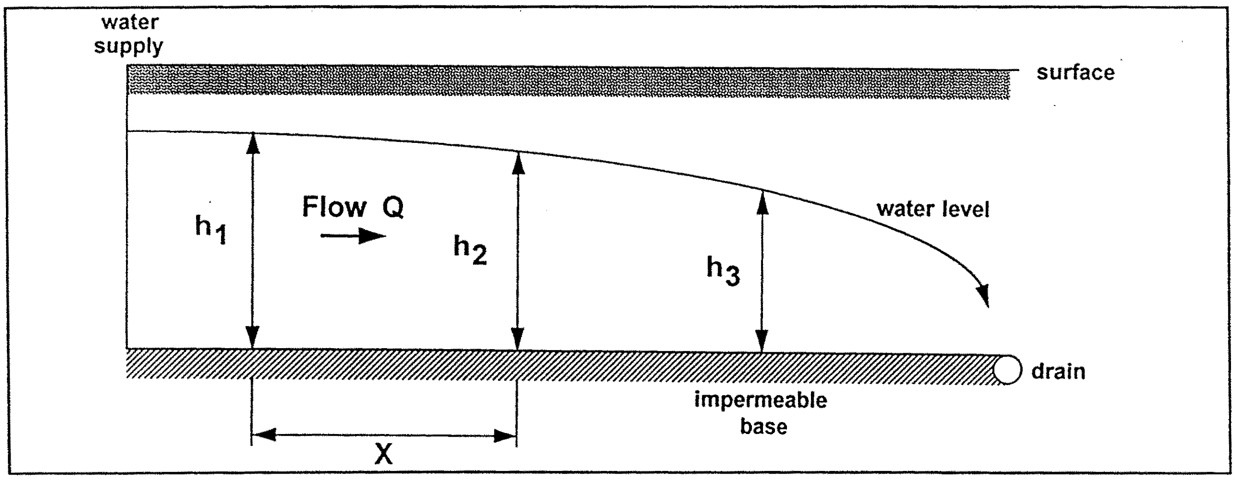

Figure A.11 Calculation of hydraulic conductivity from dipwell readings

The simplest method for measuring the `water-table' within the restructured soil is by recording the height of the saturated water level in a series of dipwells inserted into the restructured soil (see Figure A.12). These can be constructed from plastic (P.V.C.) tube of 25-40mm internal diameter and cut to 1.2m length. The bottom 0.3m of the tube should be perforated with holes of 2-3mm diameter and covered with a suitable filter to stop fines from entering e.g. nylon stocking. The dipwells are inserted into holes which are augered into the restructured soil to about 0.8m depth and with a slightly wider diameter than the plastic dipwells. The space between the dipwell and the surrounding soil is then backfilled with sand to the top of the perforations and with loose soil to the soil surface.

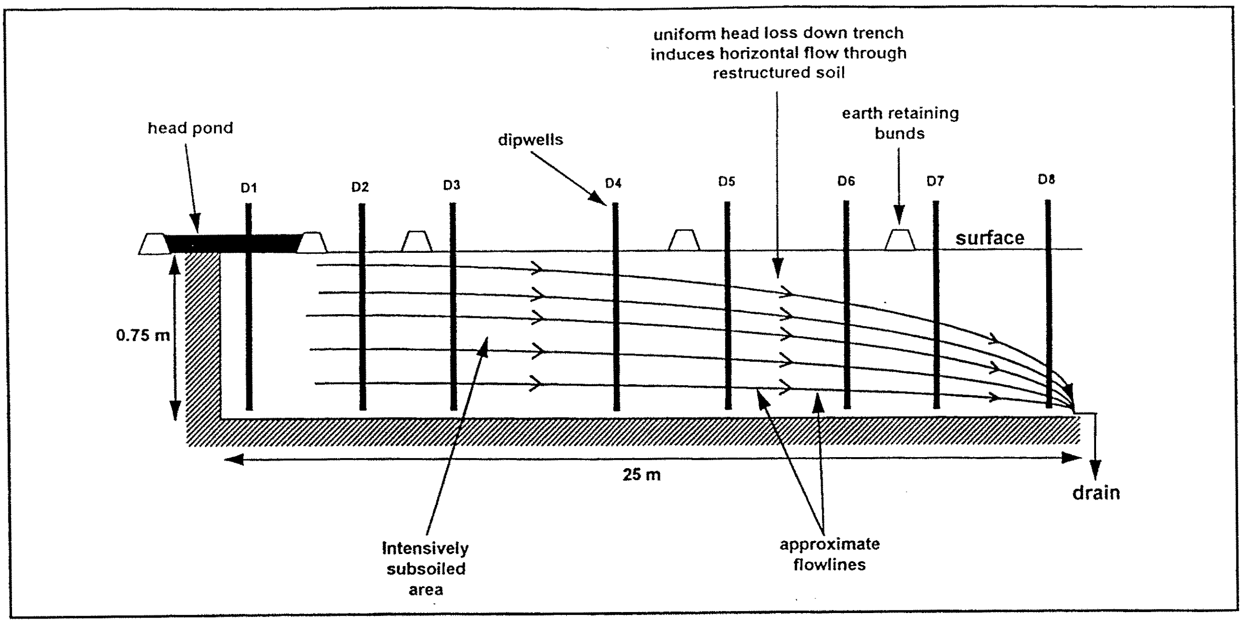

Figure A.12 Schematic representation showing position of dipwells longitudinally along direction of leaching flow

If the dipwell tubes are accessible the saturated water levels can be measured by any suitable water level recorder such as a `plopper' or a metre stick fitted with an electronic probe.
Where the dipwells cannot be easily reached, a graduated stick supported by a float can be used to measure the water level (see Figure A.13). A bamboo stick taped or glued onto a small plastic bottle can fulfil this function.

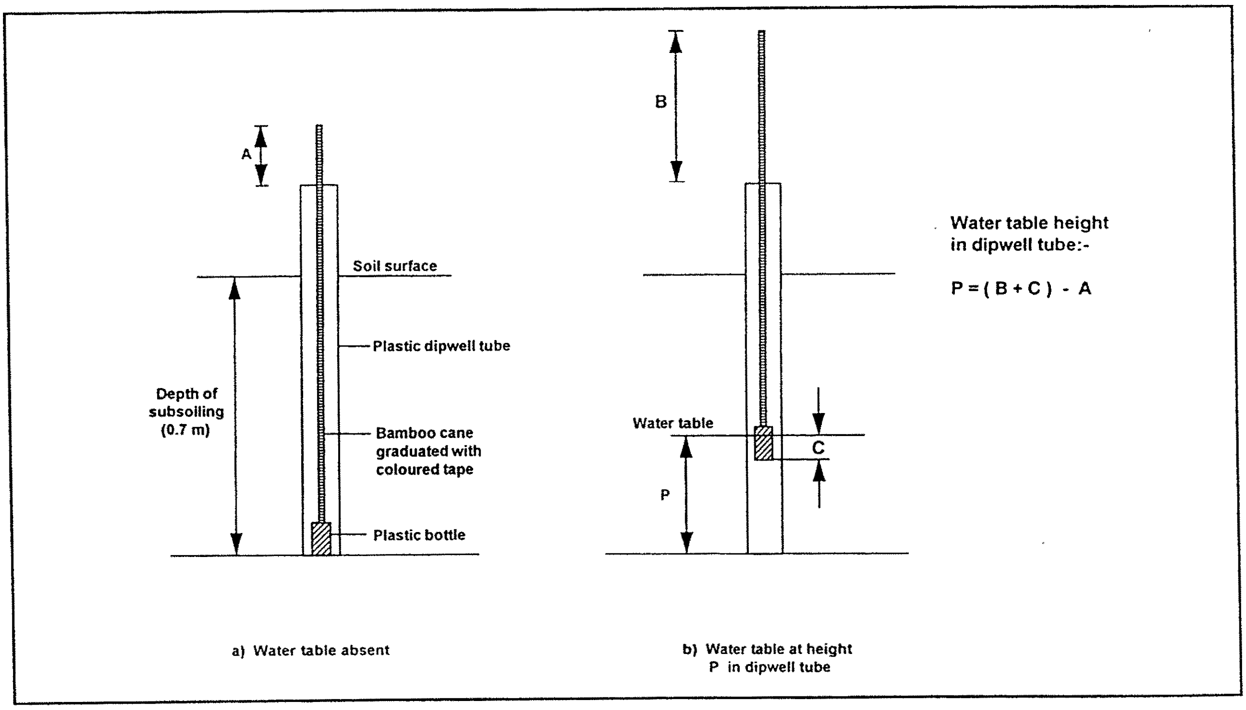

Figure A.13 Measurement of water levels in plastic dipwell tubes

Because it is difficult to insert the dipwell tubes to a constant level, all measurements (dipwell tube position, water levels and head, depth of subsoiling) should be calculated relative to a suitable datum.

Appendix 7 Assessment of subsoiling efficiency and machinery specification

A7.1 Assessment of subsoiling efficiency

A7.1.1 Introduction

Trials are recommended to investigate the efficiency of subsoiling at various soil moisture contents since the quality of the end result determines the performance of the horizontal leaching technique.

A7.1.2 Objectives and method

The first objective is to determine subsoiling efficiency in terms of soil heave, shatter profile, and aggregate size, at varying moisture content. Secondly, it is to identify the moisture content at which subsoiling efficiency is significantly reduced, and hence provide a guideline for subsequent machinery operations. The method outlined below is a simple and rapid way of achieving these objectives:-

- Mark out a trial plot measuring 25m long by 5m wide.
- To obtain the desired range of moisture contents i.e. from 20% up to the lower plastic limit (e.g. 33%), the plot at 20% moisture content can be irrigated with varying amounts of water to obtain the range of required moisture content. After a period for infiltration and absorption, soil samples should be taken from 3 depths at 5m intervals along the plot for gravimetric moisture content determination. If the range of moisture contents are attained the next stage can start.
  NB: Alternatively, if more land is available, several plots, each having a different moisture content can be used.
- Place markers at 5m intervals along the side of the trial plot, and stretch a tape measure between them. Take measurements of land level at 0.1m horizontal intervals, using the tape as a guide for positioning of the survey staff.
- The plot should then be subsoiled using the intended subsoiling regime with the exception that the cross ripping operation at depth, be replaced by a further longitudinal pass at depth, at half spacing.
- Repeat the land levelling measurements across the sections at 5m intervals, and compare to those taken before subsoiling.
- Open up inspection pits within the 5m sections to inspect the extent of cracking, and aggregate size distribution.

A7.1.3 Results and conclusions

The values of soil heave at different moisture contents combined with visual inspection will enable a range of moisture contents to be identified at which effective subsoiling can be achieved. The trial will also indicate machinery performance, and highlight any traction problems.

A7.2 Machinery specification

A7.2.1 Tractor

Caterpillar D6D SA Crawler or equivalent

Flywheel Power 123 kW (165 h.p.)
Drawbar Power 100 kW (134 h.p.)

Forward Gear	km/h	mph	Drawbar Pull kN	kg	lb
1	4.0	2.5	88.3	8999	19840
2	4.8	3.0	74.3	7570	16690
3	5.5	3.4	62.5	6377	14060
4	6.4	4.0	52.5	5357	11810
5	7.4	4.6	45.1	4599	10140
6	8.9	5.5	36.1	3683	8120

Estimated Draft or Drawbar Pull for two tine subsoiler:-

Depth	Maximum Draft
750-800mm (30-32")	5500kg (12000lb)

A7.2.2 Subsoiler

The subsoiler used in the experimental trials in Jamaica had the following specification:-

200mm x 100mm beam, fitted with two heavy duty 200mm x 50mm winged tines. The bottom foot of each tine was fitted with a replaceable hardened steel point.

A7.2.3 Work rates

Time trials in Jamaica for each stage of subsoiling indicated an average work rate for the three subsoiling passes, including turning, of 0.33 hectares per hour.

Construction of perimeter bunds using a backactor involved a work rate of 15 metres of bund per hour.

Appendix 8 Saline-sodic soils

A8.1 Background

In many areas, soil salinity occurs in conjunction with raised sodium levels and leads to the development of saline-sodic soils. Saline-sodic soils are technically more difficult and expensive to reclaim. It is therefore strongly recommended that where saline-sodic clays constitute a major problem, local research organisations should initiate suitable research programmes.

Saline-sodic clay soils ($EC_e > 4$, $ESP > 15$) are prone to structural breakdown when leached of salts, either by rainfall or by the application of high quality irrigation water (i.e. low salinity water).

Structural deterioration occurs because of:-

- Swelling of aggregates or peds.
- Dispersion of clay and subsequent breakdown of the peds.

Both processes reduce the volume and the continuity of the larger water conducting pores and drastically reduce the soils permeability to water and air.

Swelling may be partially reversible, but dispersion involves the complete breakdown of structure and this can only be re-established by long-term wetting/drying supported by biological activity.

It is important to recognise that dispersion can become a problem in swelling smectitic clays when Exchangeable Sodium Percentage (ESP) levels are as low as 5.

The soil structure will only become unstable when the soil is exposed to low salinity water. The point of breakdown is very soil and management specific, being dependent on clay mineralogy, clay content, organic matter content, water quality, cultivation history, etc. Guidelines for the classification of irrigation waters based on salinity/sodicity levels and intended to minimise infiltration problems are provided in standard texts (FAO Water Quality for Agriculture, 1985).

A8.2 Use of gypsum

In most cases reclamation of saline-sodic soils is achieved using gypsum ($CaSO_4.2H_2O$).

Structural stability is provided by two processes:-

- Dissolution of the sparingly soluble gypsum raises the concentration of salts in the leaching water to a level which inhibits swelling and dispersion.
- Calcium released from the dissolving gypsum replaces sodium on the soils exchange complex.

A8.2.1 Sources of gypsum

Phospho-gypsum, a by-product of phosphoric acid manufacture, is a particularly efficient form of gypsum because of its fineness and it is usually inexpensive.

Rock gypsum may be available locally. Its effectiveness can be improved considerably by grinding finely and by minimising impurities.

In many saline soils, naturally occurring lime or gypsum exists within the soil profile. Acid forming amendments such as sulphur, or sulphuric acid may be used to release calcium without the need for additional gypsum. Deep ploughing may be used to bring the gypsum and lime to the surface.

A8.2.2 Gypsum requirements

Gypsum requirements can be calculated by standard methods based on the depth of soil needing to be reclaimed, the initial and final exchangeable sodium percentages in the soil, and an efficiency factor to account for the solubility of gypsum and the effectiveness of exchange. These factors are incorporated in the equation below:-

$$GR = \frac{0.861 \times (ESP_a - ESP_f) \times CEC \times D \times BD}{1000 \times f}$$

where:-

GR	=	Gypsum requirement ($t\ ha^{-1}$) to reclaim depth, D
D	=	Depth of soil profile to be reclaimed (m)
BD	=	Bulk Density ($kg\ m^{-3}$)
ESP_a	=	Initial Exchangeable Sodium Percentage in soil
ESP_f	=	Final ESP level to be attained
CEC	=	Cation Exchange Capacity ($meq\ kg^{-1}$)
f	=	Efficiency of gypsum application (%)

A8.2.3 Timing of gypsum applications

If the horizontal leaching method is used in saline sodic soils, gypsum will have to be applied before leaching begins. Providing gypsum afterwards or after partial leaching is much too risky because:-

- Using the Horizontal Leaching Technique to leach the soil before providing gypsum exposes the soil to the risk of structural failure as the saline pore water is displaced by fresh. Even if the water moving through the restructured clay contains enough salt to maintain stability, the end result will be a sodic clay. Such soils are highly unstable, and such risks are considered to be much too high.

- The dissolution rate and effectiveness of gypsum in replacing exchangeable sodium can in theory be improved by partial leaching before gypsum is applied. However, a fundamental requirement of the Horizontal Leaching Technique is that once water is applied the soil is not allowed to desaturate because of the loss of buoyancy, the resulting consolidation and the loss of permeability. Hence, this strategy is not considered feasible.

A8.2.4 Placement of gypsum

There are 3 possible ways of applying the required gypsum:-

- To the upper 0.3-0.4m of the restructured soil only.

- To the entire depth (0.7-0.8m) of restructuring.

- In the water supply.

Addition of gypsum to the water supply is the least favoured option because it is expensive and inefficient in gypsum and water use. This is because the calcium contained in the leaching water will be exchanged very efficiently in the soil at the upper end of the plot. The sodium levels in this zone will be reduced below the desired level (e.g. ESP 5) needed for stability, leaving insufficient calcium in solution to reclaim the rest of the plot.

Reclamation of the full depth in a single operation is desirable but very costly, and requires specialised equipment to distribute the gypsum evenly throughout the soil profile during or as part of subsoiling operations.

The main advantage of the preferred option, gradual reclamation, is the reduced gypsum requirement. Conventional harrowing and subsoiling operations should allow the gypsum broadcast on the surface to be well mixed in throughout the upper 0.3-0.4m of restructured soil.

The consequences of allowing the subsoil to remain sodic during horizontal leaching are also unlikely to be too serious because:-

- Restructuring and desalinization tend to be less effective below about 0.5 m. The salinity levels in the soil are expected to remain high enough and the ped sizes large enough to minimise swelling and dispersion during reclamation.

- The potential for structural deterioration in a sodic topsoil is much greater than in the subsoil. The water/rainfall entering the topsoil will have a low salinity whilst the mechanical forces involved during cultivations accelerate the breakdown of aggregates.

- If the sodium levels are reduced in the topsoil during horizontal leaching, subsequent gypsum applications will tend to gradually increase the depth of reclamation under normal irrigation practices.

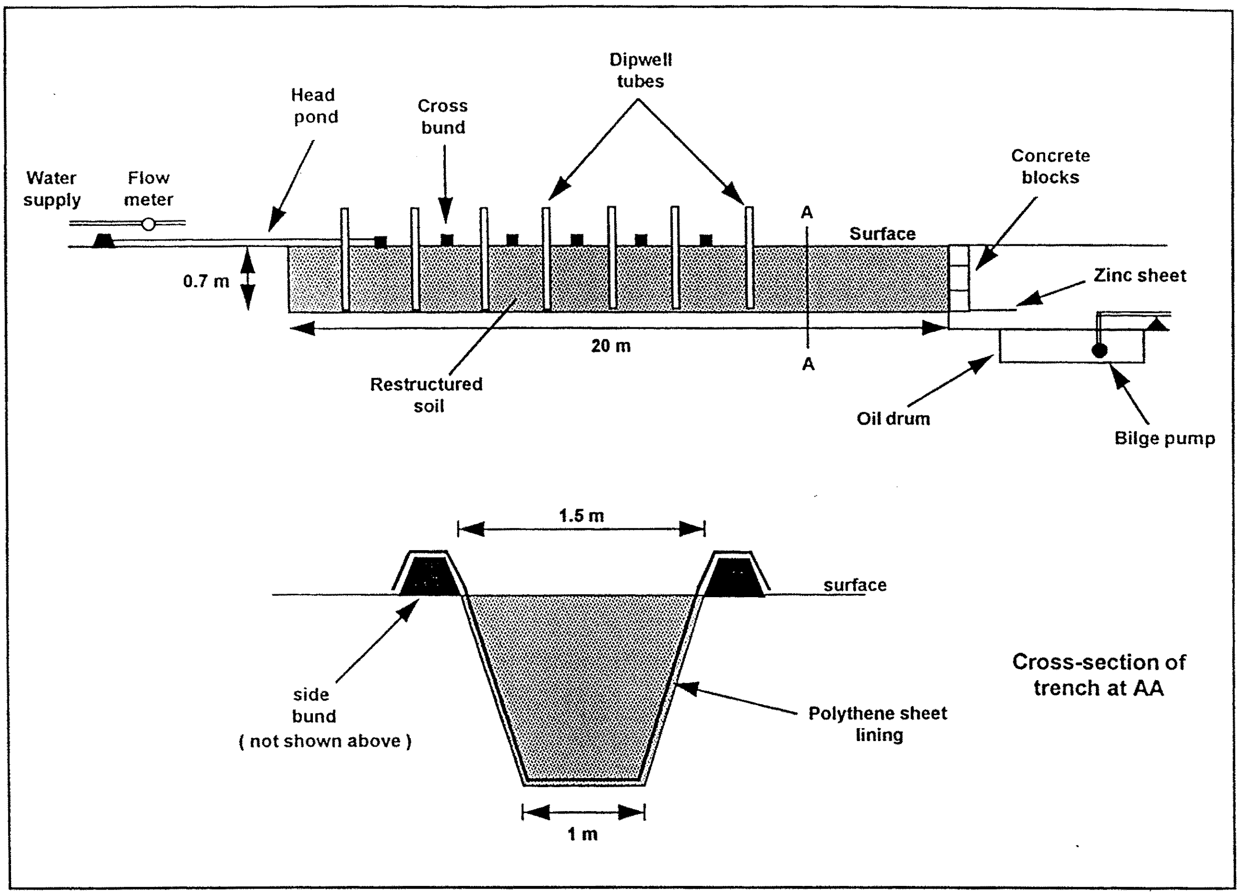

Figure A.14 Schematic longitudinal diagram of trench trial

Plot trial, Jamaica, showing use of gated pipe (grey) to deliver water to the head pond. Vertical pipes contain float scales to indicate the position of the saturation front beneath the soil.

Trench trial, Seyhan, Turkey, showing position of bunds that encourage subsurface flow. Vertical pipesenable soilwater EC and the position of the saturation front to be monitored.

The Horizontal Leaching Technique enables excess salt to be removed from clay soils in a relatively short period. It is particularly intended for salt-affected, heavy clay soils of more than 1m depth and of permeability less than 0.1m/day. Such soils are commonly found in irrigated plains in arid and semi-arid countries, and suffer from rapid swelling when water is applied to them. The new technique has been developed from field studies, carried out on saline lands in Jamaica and Turkey.

This manual enables the reader to assess whether the technique is suitable for his particular soil salinity problems, and provides sufficient technical information for him to implement it.

Double subsoiler used to shatter clay blocks into small aggregates.

Subsoiling operation, Jamaica

ISBN 1 898485 03 8

Published jointly by:
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(Tel 01703 593728: Fax 01703 677519)

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