Soil Salinity Processes Under Drainwater Reuse in the Nile Delta, Egypt

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HR Wallingford in collaboration with the Water Management Research Institute, Cairo

Report OD/133
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Contract

This report describes work carried out by the Overseas Development Unit (ODU) of HR Wallingford, in collaboration with the Water Management Research Institute (WMRI), of the National Water Research Centre in Egypt. The work was funded by the UK Overseas Development Administration. The ODA Technology Development and Research Theme and Project details are as follows:

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Summary

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In many parts of the world agricultural drainage water is reused for irrigation. Although the practice can bring significant benefits to watershort areas, it can also lead to accumulation of salts and toxins in soils, with detrimental consequences to agricultural production. Reuse areas contribute to the estimated 20 million hectares of agricultural land worldwide that are affected by salinity (Hamdy, 1988). In these areas, crops suffer large yield reductions and soil suitability for agriculture can be reduced to the point where farmers are forced to abandon land.

In many cases this scenario is avoidable with an understanding of the processes involved in salinity accumulation, and the implementation of appropriate management techniques to control salinity and toxin build up. In the Drainwater Reuse Effects Project, the processes of salt accumulation and movement under drainwater reuse have been studied and management guidelines developed to minimise adverse effects.

This report presents results from the second fieldwork component of the project (known as the microstudy). This has been carried out in the Nile Delta, Egypt, where increasing demands on a limited water supply have necessitated the reuse of drainage water for irrigation. Processes of salt accumulation and movement in working farmers' fields of this region have been studied *in situ*. Information on salt leaching and diffusion processes from this study has been used to develop and improve predictions of salinity buildup under drainwater reuse.

The microstudy monitored salt and water movement in a typical farmer's field on the Nubariya Scheme in the western Nile Delta, which had been reusing saline drainwater for irrigation for over ten years. Detailed investigation over a one year period has provided information on the processes occurring and on how very saline drainwater can be successfully used for agricultural production with the adoption of appropriate management methods.

It was estimated that about 62 tonnes of salt were added to the 2 hectare field during the study. In the summer season the vast majority of applied salt remained in the soil profile. Very little water and salts went to deep percolation. During the fallow period, mass flow of water and salts was negligible and the only process of salt movement was diffusion. In the winter season there were six significant leaching events which removed 93% of the applied salt in the soil profile to deep percolation.

The process of leaching during the winter crop season was critical in successful use of drainwater for crop production in the study area. Soil salinity levels were acceptable and crop yields were good. However, the investigation was not long enough to show whether or not soil salinity levels in the soil were gradually increasing as a trend from year to year. The long term sustainability of the salt balance cannot be guaranteed since shallow groundwater levels can be quickly raised at any time, bringing salt back into the root zone by capillary rise and diffusion.

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1. INTRODUCTION

1.1 Background

The use of marginal quality water for irrigation is becoming more and more widespread across the world. There is not always enough good quality water available to meet demands from agriculture, domestic use and industry. One strategy to increase available water resources is to reuse agricultural drainage water for irrigation. Reuse of drainage water is already extensively practised in countries such as Egypt, Pakistan and the USA.

The reuse of drainage water for irrigation involves the application of water that is inherently of lower quality than fresh water. Water that has passed through the agricultural system may contain increased levels of salts, toxic ions, heavy metals and organic residues. The entry of these pollutants into water courses, and accumulation in soils poses a threat to agricultural production and the environment.

1.2 Drainwater reuse in Egypt

The 1959 treaty with Sudan fixed Egypt's share of the Nile water at 55.5 billion m^3/yr (Amer and de Ridder, 1989). It is currently approaching full utilisation of this allocation and demands are high. Drainwater reuse is a major component of the country's water strategy. It is the largest source of irrigation water after the river Nile and contributes an estimated 4 billion m^3/yr to the agricultural sector. Current policies are based on increasing this figure to 7 billion m^3/yr. by the year 2000 (Abdel Dayem and Abu-Zeid, 1991). Drainage water reuse occurs along the Nile Valley because all drains lead back to the main river course. In the southern part of the Nile Delta drainwater is mixed with fresh water and used for irrigation. In the northern Nile Delta, the amount of drainwater increases but the irrigation area is less. Additionally the soils are heavier and more saline. The national strategy is therefore to use drainwater in the irrigation of reclaimed lands in the eastern and western fringes of the Nile Delta. Major initiatives include the Salam Canal project in the east and the Omoum Reuse Project in the west. The Salam Canal will irrigate 78,000 hectares west of the Suez Canal and about 168,000 hectares in the Sinai Peninsula with blended drainage water. The Omoum Reuse Project will put drainage water into the Nubaria Canal which is used to irrigate 420,000 hectares of reclaimed agricultural land in the western Nile Delta.

1.3 Project aims

The Overseas Development Unit of HR Wallingford is carrying out research in collaboration with the Water Management Research Institute, WMRI, (previously known as the Water Distribution and Irrigation Systems Research Institute, WDISRI) of the National Water Research Centre, Egypt into the effects of drainwater reuse and the development of practical guidelines for safe reuse. The work has been carried out with funding from the UK Overseas Development Administration. Project fieldwork was undertaken in agricultural areas of the Nile Delta, Egypt between 1992 and 1995. As part of their ongoing research programme, WMRI are continuing with aspects of the fieldwork.

The project has comprised the following stages:

a) ***An assessment of the effects to date of irrigating with drainwater on Nile Delta soils.*** Levels of salinity in the soil profile were determined at locations selected to cover a range of soil types found in the Nile Delta. This phase of the project has been called the macrostudy and is presented in HR report OD/TN71 (Abbott and El-Quosy, 1995).

b) ***A study to determine processes of salt accumulation in the soil profile following the reuse of drainwater for irrigation.*** A detailed study was carried out in the Western Nile Delta, in a farmer's field which was typical of the region. Salt and water distribution and movement was monitored to provide information on accumulation of salts in soils and acceptable salinity levels in applied drainage water. This phase of the project was known as the microstudy and is presented in this report.

c) ***The development of practical guidelines on the safe use of drainage water for irrigation.*** This has culminated in the development of an assessment procedure for safe reuse of drainwater to be presented in a future report.

d) ***The development of a suitable field technique for measuring environmental contamination levels in the water system, that will contribute to assessments of current levels of pollution.*** The project has assessed methods of measuring pesticide and pathogen levels in the field. This work is reported in Girard (1993) and Retournay (1995).

2. DRAINWATER REUSE AND SALT ACCUMULATION IN AGRICULTURE SOILS

2.1 Hazards of drainwater reuse

The reuse of agricultural drainage water for irrigation involves the application to soils and crops of water that is inherently of lower quality than freshwater. Water that has passed through the agricultural system may contain increased levels of salts, toxic ions, heavy metals and residues such as pesticides. In areas such as the Nile Delta, the most serious threat to sustainable agriculture posed by drainwater reuse comes from the recycling of salts. Soil salinisation is the prime reason for abandonment of agricultural land in irrigated areas of the world (Hinnawi and Hashmi, 1987). The accumulation of salts in soils can lead to severe soil damage and reduction in crop growth and yields.

Sustainable agriculture is dependent on fertile soils. The clay fraction present in soils is subject to physico-chemical interactions with salt ions, which can alter soil structure and hydraulic properties. Monovalent ions (particularly sodium) have a destabilising effect and their presence in irrigation water is of considerable concern.

Although certain ions, present in excess, are toxic to crops, the crop stress effects caused by accumulation of salts in the rootzone are mainly dependent on total salt concentration in soil water. Extensive research has been carried out and guidelines developed which link average rootzone soil salinity EC_e (electrical conductivity of saturated soil extract) to a likely reduction in crop yield. Tolerance of crops to salinity varies between crops and also with stage of growth. For instance, whilst barley is likely to be unaffected at rootzone EC_e levels of 8dS/m, beans and carrots will suffer yield reductions with salinity levels as low as 1dS/m (Maas, 1986). For a general summary of the effects of soil salinity on agricultural crops table 1 can be used:

Table 1 Summary table indicating the effect of soil salinity on crop yields

Average Rootzone Soil Salinity	Predicted crop effects
EC_e < 5dS/m	LITTLE EFFECT - most crops suffer no yield reductions. Only salt sensitive crops (e.g. maize and broad beans) affected (less than 50% yield reduction).
5 < EC_e <15dS/m	SIGNIFICANT EFFECT - sensitive crops suffer large yield reductions (greater than 50%). Salt tolerant crops (e.g. cotton, wheat and barley) are now affected (up to 40% yield reduction).
EC_e > 15dS/m	SEVERE EFFECT - sensitive crops will not grow. Tolerant crops now suffer large yield reductions (greater than 50% yield reduction).

A full discussion of the hazards of drainwater reuse is given in HR Report OD/TN 72 (Abbott, 1995).

2.2 Salinity accumulation in soils of the Nile Delta

In the previous study (the macrostudy) soil salinity levels were monitored in a large number of farmers' fields in the Nile Delta (Abbott and El-Quosy, 1995). The study provided evidence from agricultural areas of the delta that drainwater reuse (both directly and after blending with freshwater) has led to significantly higher soil salinity levels. Increases in soil salinity levels pose a threat to sustainable agriculture. Monitoring continues as part of a long-term programme by WMRI.

Large amounts of salt are accumulated in the soil profile throughout the root zone during periods of peak demand due to high evapotranspiration rates and shortage of supply. During low demand periods, more water is available and leaching can take place. However, if it is only possible to achieve partial leaching, long-term salinity build-up may take place.

To understand whether this is occurring there is a need for long-term regular monitoring to be carried out. If the trend is occurring, then simple methods that can be utilised by farmers throughout the effected parts of the Nile Delta need to be developed. An example of this could be to encourage farmers to leach at the end of crop seasons, particularly after summer harvest, when water is more plentiful.

2.3 Processes of salinity accumulation

Solute transport is governed by the processes of convection (viscous movement of the soil solution or mass flow) and diffusion (movement of ions within the soil solution along a concentration gradient). In a wet permeable soil, mass flow is likely to be the dominant mechanism for salt movement through the profile. The other process, diffusion, is the random movement of ions in the soil solution and redistributes salts from areas of high concentration to areas of low concentration. Although diffusion occurs in both wet and dry soils, it is only likely to be the main process of salt movement when the soil is dry and the mass flow of water and salts is relatively small.

2.4 Methods of predicting salinity accumulation

Salt contained in irrigation water applied to agricultural lands has three possible fates. It can:

i) leave the soil profile via a subsurface drainage system;

ii) be carried through the soil profile to enter deep groundwater, or

iii) accumulate in the soil profile.

Although both movement of salts into groundwater and entry of salts into drainage systems necessitate careful management, it is the third possibility, the accumulation of salts in the soil profile that poses an immediate threat to crop production and soil fertility.

The salinity level which develops in the soil profile under irrigation depends on many factors including soil type, level of salinity in the applied water, and the fraction of water and salts moving through the soil profile to drainage and deep percolation.

The fraction of applied water that passes through the entire rooting zone and percolates below is called the leaching fraction (Ayers and Westcot, 1985).

$$\text{Leaching Fraction (LF)} = \frac{\text{depth of water leached below the root zone}}{\text{total depth of water applied at the surface}}$$

After several years of irrigation (with drainwater or other saline water source), the salt accumulation in the soil approaches an equilibrium concentration depending predominantly on the salinity of the applied water and the leaching fraction.

This level of steady-state soil salinity can be estimated using several methods:

2.4.1 Rhoades and Merrill Relation

The Rhoades and Merrill relation was developed to estimate the leaching requirement (LR), with a given salinity of irrigation water (EC_w) and an acceptable soil salinity level (EC_e). As the terms leaching fraction

(LF) and leaching requirement (LR) are interchangeable, the relation can also be used to estimate soil salinity (EC_e) levels achieved with irrigation water of salinity EC_w and a given leaching fraction (LF). The relation is given as (Rhoades and Merrill, 1976):

$$LR = \frac{EC_w}{5(EC_e) - EC_w}$$

EC_w = salinity of applied irrigation water (dS/m)
EC_e = average soil salinity in rootzone (saturated soil extract basis, dS/m)
LR = leaching requirement/fraction

2.4.2 Ayers and Westcot Relation

This simple equation is used for predicting the soil salinity expected after several years of irrigation with water of salinity EC_w:

$$EC_e = EC_w \times X$$

EC_e is soil salinity (electrical conductivity of saturated extract, dS/m)
EC_w is applied water salinity (electrical conductivity, dS/m)
X is a concentration factor dependent on the leaching fraction, given in the table below:

Table 2 Concentration factors (X) for predicting soil salinity (EC_e) from the irrigation water salinity (EC_w) and the leaching fraction (LF).

Leaching Fraction (LF)	Concentration Factor (X)
0.05	3.2
0.1	2.1
0.15	1.6
0.2	1.3
0.25	1.2
0.3	1
0.4	0.9
0.5	0.8
0.6	0.7
0.7	0.6
0.8	0.6

Ayers and Westcot, 1989

The method assumes a crop water use pattern of 40%-30%-20%-10% through the rootzone.

2.4.3 Rhoades Relation

Steady-state soil water salinity (EC_e) is estimated by multiplying the electrical conductivity of the irrigation water (EC_w) by a relative concentration factor, F_c, appropriate to the leaching fraction and depth in the rootzone (Rhoades, 1982):-

Values of F_c are given in the table below:

$$EC_e = EC_w \times F_c$$

Table 3 Electrical conductivity of soil water (saturation paste extract) at steady-state compared to that of irrigation water (F_c).

Rootzone interval	Leaching Fraction					
	0.05	0.1	0.2	0.3	0.4	0.5
Upper quarter (linear average')	0.65	0.64	0.62	0.6	0.58	0.56
Whole rootzone (linear average')	2.79	1.88	1.29	1.03	0.87	0.77
Whole rootzone (water uptake weighted average [2])	1.79	1.35	1.03	0.87	0.77	0.77

Rhoades, 1982

[1] Use for conventional irrigation management.

[2] Use for high frequency irrigation management or where matric potential development between irrigations is insignificant.

2.4.4 Hoffman and Van Genuchten Equation

The linearly averaged, mean rootzone salinity was determined by solving the continuity equation for one-dimensional flow of water through soil, assuming an exponential soil water uptake function (Raats, 1974). Steady-state mass balance was assumed. The linearly averaged salt concentration of the rootzone EC_e as a ratio of the salt concentration of the irrigation water EC_w is given as (Hoffman and van Genuchten, 1983):

$$\frac{EC_e}{EC_w} = \frac{1}{L} + \frac{\delta}{ZL} + \ln[L + (1-L)e^{-Z/\delta}]$$

L = leaching fraction.
Z = depth of rootzone.
δ = an empirical constant set to 0.2Z.

The relation is shown graphically in figure 1.

2.4.5 Computer Models

A number of computer models have been developed which are useful in making predictions of soil salinity accumulation under drainwater reuse. These include:

SALTMOD

The SALTMOD program was developed to predict the long-term effects of varying water management options on desalinisation or salt accumulation in the soil of irrigated agricultural lands. The water management options include irrigation, drainage, and the reuse of surface drainage water or subsurface drainage water from pipe drains, ditches or wells for the irrigation. In addition, predictions are made on the depth to watertable, the salt concentration of the groundwater and of the drain or well water.

WATSUIT

WATSUIT predicts the salinity, sodicity and toxic-solute concentration of the soil-water within a simulated crop rootzone resulting from the use of a particular irrigation water of given composition and at a specified leaching fraction. The concentrations of the major cations and anions in the soil water within an irrigated rootzone are predicted at equilibrium as a function of irrigation water composition, leaching fraction, soil calcium carbonate presence or absence, and several alternative amendment treatments.

3. MICROSTUDY METHODOLOGY

3.1 Aims of the Microstudy

The main fieldwork from the project provided quantitative evidence that the reuse of agricultural drainage water (both directly and after blending with fresh Nile water) has led to increased salinity levels in farmer's fields of the Nile Delta (Abbott and El-Quosy, 1995). Without careful management, crop production will be reduced and agricultural land will be degraded.

To implement appropriate management techniques to control soil salinity and toxic ion buildup, it is necessary to have an understanding of processes of salt accumulation under drainwater reuse and be able to make predictions about likely accumulation over time. The aims of the microstudy were thus:

1) to investigate the processes occurring in an agricultural field representative of the Nile Delta where drainwater is reused for irrigation, and

2) to provide data and information to develop and test a predictive procedure for salt accumulation under drainwater reuse over time.

This report presents results from the study and discusses processes of salt accumulation and movement occurring under drainwater reuse. Testing of predictive procedures on the study findings is also presented.

3.2 Location

The Nubaria Canal is fed from the Rossetta Branch of the Nile and conveys water to reclaimed lands in the western Nile Delta. It has enabled large areas of desert land to be utilised for agricultural production. This includes 4,000 hectares of land in the Western Nubaria Agricultural Project (figure 2) which was reclaimed in the 1960s. Within the project some areas of land receive water via the Mechanised Farm Canal (figure 3) which branches off the Nubaria Canal downstream of a number of major drains. Water in the canal consequently contains a large proportion of drainage water and is quite saline (EC_w is from 3-5 dS/m).

Situated on the western fringes of the Nile Delta, the area has a desert climate with high daytime and low night-time temperatures. Precipitation is low and usually occurs only in the winter months (October to January). Soils are predominantly sand in composition with a high calcium carbonate content.

As in other parts of the Delta, there are two main growing seasons per year. The winter season runs from October to May and the summer season from April/May until October. The most common winter crops in the area are wheat, broad beans, barley and berseem. Watermelon, maize, cotton and sunflower are the most common summer crops.

A typical agricultural field was selected from the area, on which traditional farming methods were used, including surface irrigation in furrows and basins. Farming operations (including weeding and surface soil cultivation) were mostly carried out by hand. Agricultural crops were grown mainly for sale to the local markets and those in the nearby city of Alexandria.

The field was approximately 2 hectares in size with a deep watertable and an existing subsurface drainage system. The site was instrumented to monitor inputs of water and salt to the field and their movement within the soil profile. Monitoring was carried out over the year between April 1994 and April 1995.

3.3 Study field layout

The study field was situated north of the Mechanised Farm Canal just downstream of Pumping Station Number 1 (Figure 3). Water for irrigation was lifted by diesel pump into a small concrete lined channel (meska) leading into the field. Irrigation water was then distributed about the field via furrows or in basins, depending on the crop grown. A subsurface drainage system was present at about 1.5 metres depth, although natural drainage kept the watertable at 3-4m depth.

3.4 Monitoring programme

The field's total cropped area was 1.85ha (Figure 4). The instrumentation was installed in April 1994 to study water and salt application to the field and movement through the soil profile. The parameters measured were:

Irrigation Water Application

Water application rate was measured by a Cut-throat Flume situated as shown in figure 4. Time of application was also recorded.

Irrigation Water Salinity

A handheld electrical conductivity meter was used to measure salt content of irrigation water. Temperature adjustment was automatic.

Salinity is given by:

$TDS = 44.84 + (633 \times EC_w)$

TDS is total dissolved salts in parts per million (ppm) and EC_w is electrical conductivity in deci Siemens per metre (dS/m).

Soil Moisture

Gravimetric soil samples down to 1.6m were taken from six positions once per week (see appendix 1). A neutron probe was used to measure moisture contents from two access tubes (figure 4) down to 1.6m on a weekly basis. Neutron probe calibration is shown in appendix 2.

Soil Water Potential

Two profiles of six tensiometers were installed in the study field (figure 4). Installation depths were 0.15m, 0.3m, 0.4m, 0.8m, 1.2m and 1.6m. These were monitored daily in the crop seasons and every two days in the fallow period.

The tensiometers measured total and matric potential of water in the soil profile at different depths. The total potential values were used to indicate direction of water movement in the soil profile and the matric potential values were used to give a measure of soil wetness (see appendix 3).

Soil Salinity

Soil samples were taken down to 1.6m depth from six positions on a weekly basis. Saturated soil extract salinity (EC_e) was determined (see appendix 4) at eight depths. An electromagnetic survey instrument (EM38) was used to monitor bulk soil conductivity (EC_a) in the soil profile at five set positions twice a week (see appendix 5).

Drainflow

A flow gauge/water sampler was attached to the subsurface lateral drain where it entered the maindrain. Salinity of drainflow was determined with an electrical conductivity meter.

Depth to Watertable

Two piezometers were installed in the field (figure 4) down to 3m depth to monitor watertable depth and salinity.

Evaporation and Rainfall

A class 'A' evaporation pan and a raingauge were installed nearby, both of which were monitored each day.

4. RESULTS AND DISCUSSION

The study ran from April 1994 to April 1995. For ease of analysis, days were numbered from 20th April 1994, which was taken as day 1.

4.1 Seasonal land use

The year of study was divided into three seasons. These were two crop seasons with a fallow season in between. The first crop grown in the study field was watermelon which is a summer crop in Egypt. It was planted mid April and harvested between 19th July and 24th August (day 91 to day 127). The field was then left fallow until November 5th (day 200) when winter wheat was planted. This crop was harvested on May 3rd (day 379).

4.1.1 Summer crop

Watermelon is a common summer crop on the fringes of the Nile Delta as it is well suited to the desert climate. It prefers hot, dry conditions with mean daily temperatures of 22 to 30^{o}C and a sandy loam soil. It is moderately sensitive to salinity. The international guideline on yield decrease due to salinity is shown in figure 5.

The watermelon crop was planted on the tops of furrows spaced about a metre apart. Irrigation applications were via the furrows. The watermelon root system was deep and extensive down to a depth of 1.5 to 2m.

4.1.2 Fallow period

The study field was left fallow between August and November. There were no irrigation applications during this period.

4.1.3 Winter crop

Wheat is a common winter crop throughout the Delta. It can be grown on a wide range of soils but medium textures are preferred. The crop is relatively tolerant to salinity but the EC_e should not exceed 4dS/m in the upper soil layer during germination. The international guideline on salinity yield reductions is given in figure 5.

The winter wheat crop was planted in 100m^2 basins. Irrigation water was applied to the basins via earth channels through the field. Although the normal rooting depth for winter wheat is 1.2m, in deep soils (such as the study field), roots may reach 1.5 to 2m.

4.2 Soil properties

4.2.1 Textural analysis

Soil samples were taken down to 1.6m depth. Gravel (diameter > 2mm) was present at all depths (about 10% by weight). The remaining soil fraction was analysed for particle size distribution. Results are shown in figure 6. The soil was predominantly sand in composition (about 95%) with a small percentage of silt/clay (about 5%). Variation in texture with depth was small, although there was a slight increase in the proportion of smaller soil particles with depth.

Bulk density was also determined at all depths, shown in figure 7. It was lowest at the soil surface due to loosening of soil layers by cultivation. Bulk density did not vary greatly with depth and the average value was 1.51g/cm^3.

4.2.2 Infiltration rate

Soils with a high sand content are usually very permeable with high values for infiltration rate and hydraulic conductivity. Saturated hydraulic conductivity rate may be several metres per day.

Double ring infiltrometer tests were carried out at the soil surface at the study site. Figure 8 shows that steady-state infiltration was achieved in about three hours and was approximately 120mm/hr, confirming the high permeability of the soil.

4.2.3 Soil moisture release curves and field capacity moisture content

Soil moisture release curves were prepared *in situ* for the study site using coinciding soil moisture and potential measurements at five depths in the soil profile. These curves indicate how much water will be lost from the soil profile for a given decrease in potential caused by, for example, root water abstraction or gravity drainage. As the pressure potential in a soil decreases, the largest pores empty of water first, followed by successively smaller pores.

Figure 9 shows the derived curves from the study site. Several conclusions can be drawn:

1) Most water was removed from the soil at very low suctions, probably between saturation (0 cmH_2O) and -50 cmH_2O. As the soil dried beyond this it became increasingly difficult to extract water. Thus, the soil is characterised by large pores which hold most water. It is very permeable and dries out rapidly following water application. As expected for a sandy soil, it drains quickly and has a small water holding capacity.

2) The moisture content for a given potential value became higher with depth. This implies there are textural differences with depth. The soil's water holding capacity increased with depth, implying a higher percentage of small pores. This is borne out to some extent by the textural analysis which indicated increasing proportions of fine soil particles with depth.

3) The curves can be used to estimate a moisture content for field capacity of the soil profile. This approximates to the amount of water in the profile after it has been fully wetted and all gravitational water has drained away, usually in a day or two. It is an important parameter in irrigated agriculture for the following reasons:

    a) It has a critical bearing on irrigation scheduling. If the soil has a low field capacity moisture content, then irrigation applications should be small and frequent, otherwise large amounts of water will be lost to deep percolation or drainage. If the field capacity moisture content is high, irrigations can be larger and less frequent due to the increased storage potential of the soil, but overwetting the profile and waterlogging the crop should be avoided.

    b) It controls amounts of water going to deep percolation. In agricultural areas where deep percolation and leaching of solutes is desirable (such as drainwater reuse areas), the field capacity moisture content must be exceeded to facilitate deep percolation.

To determine a value of field capacity moisture content for the study site, a water release curve was prepared for the whole soil profile (figure 10). The large scatter of data was due to hysteresis (moisture content at a given potential varies depending on whether the soil is wetting or drying), and the use of data from different depths to get one relation. Definitions of field capacity matric potential vary between -50 and -200 cmH_2O. From figure 10 this equates to a moisture content of between 18 and 22% by volume. This is a low moisture content for field capacity and highlights the poor water holding capacity of this soil and the ease with which deep percolation and leaching can occur.

4.3 Water inputs and outputs

4.3.1 Irrigation

Irrigation applications are shown in appendix 6 and in figure 11. Total irrigation application was 333mm for the watermelon crop (4 months) and 639mm for the wheat crop (5 months).

4.3.2 Rainfall

Rainfall occurred between day 185 and day 223 (21st October and 28th November) and is detailed in appendix 7 and also shown on figure 11. The total was 84.4mm.

4.3.3 Groundwater and capillary rise

Groundwater levels in the region were 3-4m below the soil surface, although there were significant local variations. The piezometers installed in the study field at 3m depth remained dry during the study showing that the watertable remained below this depth. Capillary rise of water and salts from below 3m is not likely in a sandy soil and was thus assumed to be negligible.

4.3.4 Subsurface drainage

No subsurface drainflow was recorded during the study. The system remained dry so no water or salts left the field via this route.

4.3.5 Crop water abstractions and bare soil evaporation

An attempt was made to estimate crop evapotranspiration rates from evaporation pan measurements made adjacent to the study site. Unfortunately the data were spurious and this approach was abandoned.

Bare soil evaporation was not monitored.

4.4 Water movement in the soil profile

4.4.1 Horizontal

The field was surrounded by similar agricultural land and the soil profile remained unsaturated throughout. Horizontal movement of water in the soil profile was thus assumed to be negligible during the study.

4.4.2 Vertical

Soil wetness and water movement during the study are shown in figures 12 and 13. Figure 12 shows matric potential measurements during the study. This figure gives a good indication of soil wetness in the profile during the study period. Figure 13 shows total potential values which give information on water movement during the study. The soil response to water inputs (irrigation and drainage) is clearly shown.

The year long study was divided into three distinct periods:

1) The summer season from day 1 (20th April) to day 127 (24th August), when the watermelon crop was grown.

2) The fallow period from day 127-196 (24th August to 1st November) with no cops and no irrigation.

3) The winter season from day 196 (1st November) to the end of the year, when irrigation resumed and a winter wheat crop was grown.

The soil profile was clearly wetter during the two crop seasons (with irrigation and rainfall) and drier during the fallow period when there were no water applications.

Summer Crop Season

Irrigation inputs during the summer season showed up clearly as an increase in matric potential of the soil down to 80cm (figure 12). The soil below 80cm depth was little affected by water applications at the soil surface. The only irrigation application which affected the soil below 80cm was the first and largest (60mm). Figure 14 shows that this irrigation application promoted water movement to deep percolation. It was the only leaching event during the summer season. The lower soil profile dried out evenly during the second half of the season due to root water abstractions by the maturing watermelon crop. Hydraulic gradients (figure 13 and figure 14) in the surface layers were generally downward. The frequency of irrigation applications (18 applications over three months) prevented the formation of significant upward gradients in the shallow soil layers, except at the end of the season. Strong gradients did not develop in the deeper profile and there was little evidence of deep percolation during the period. Typical profiles are shown in figure 14.

Fallow Season

Following the final summer irrigation on day 83 (11th July) and harvesting of the watermelon crop the rest of the soil profile dried out. After a period of water redistribution within the profile, matric potential values (figure 12) became stable for the fallow period. The profile during this time was very dry due to high evaporation rates over the dry summer and no water applications. The apparent moisture at 160cm depth was most likely due to instrument error (quite likely when potentials are so low) and soil at this depth can be presumed to be as dry as the rest of the profile. Hydraulic gradients were small over this period. (Figure 15 shows a typical profile). Hydraulic conductivities were also very low at these low moisture contents, so water movement was negligible during this season.

Winter Crop Season

The first major application of water during the winter wheat season was on day 196 (1st November)). The profile wetted up rapidly down to 80cm depth (figure 11) but it took a further 3-4 weeks for the deeper profile to wet up fully. During this period water movement was slow. Deep percolation was not possible until about day 220 (25th November) when a downward gradient through the soil profile was established. Figure 16 shows typical profiles.

Once the whole profile had been rewetted a pattern was established. Irrigation applications during the winter wheat season were fewer (only 13 applications over five months) and larger than for the summer crop season. Soil moisture response and movement were thus different. In general the whole soil profile wetted up quickly following irrigation to near saturation (figure 12). For the winter crop, strong downward hydraulic gradients (figure 13) and high hydraulic conductivities allowed water to move rapidly to the deeper soil layers and deep percolation. Between irrigations the soil dried out from surface evaporation and increasingly, as the wheat developed, from root water abstraction.

There was clearly water going to deep percolation during the winter wheat season. The potential data indicated five significant leaching events during the season and several smaller events. Each of these events would have removed salts from the soil.

4.5 Leaching fraction determination

Soil moisture potential measurements from the study indicated movement of water to deep percolation during the study, particularly during the winter wheat season. As there was no drainflow during the study, this was the major route by which salts left the study field. This leaching of salts out of the soil profile would thus have had a significant impact on soil salinity levels.

To determine the frequency and magnitude of leaching events it is necessary to examine each water application (irrigation or rainfall) in turn and determine whether deep percolation occurred and estimate the amount of water concerned.

Significant deep percolation and leaching can only occur if the soil moisture content is above field capacity.

Figure 17 shows total profile volumetric moisture contents (down to 1.6m) for the study (details in appendix 8). The figure shows that when irrigation was applied or rain occurred the profile wetted up very quickly. Initial drying out was also rapid for about two days (particularly in the winter wheat season) before progressing more slowly.

It was estimated from figure 17 that "field capacity" for the study field corresponded to a volumetric moisture content of about 22% (moisture content of 352mm in a soil profile down to 1.6m depth), which agrees well with the estimate from the soil profile moisture release curve. Any water added to the soil above 22% (352mm) would be utilised by the crop over a 1-2 day period or have gone through the soil profile to deep percolation.

Figure 17 also shows the calculated moisture contents of the soil profile immediately following irrigation or rainfall. It is clear to see when irrigation (or rainfall) took the moisture content above field capacity and deep percolation was possible. There were two occasions during the summer crop, none during the fallow season when the soil moisture content was always below field capacity, and six occasions during the winter crop. Table 4 shows the likely amounts of water going to deep percolation on each of these occasions (appendix 8).

Table 4 Leaching events during the study and amounts of water going to deep percolation

Day number when field capacity moisture content was exceeded	Water added above field capacity moisture content (mm)	Month	Estimated 2 day crop water use (mm)	Deep Percolation (mm)
6	30	April	2.2	27.8
29	4	June	7.6	0
Summer total				27.8
218	9	Nov	0.48	8.5
257	87	Jan	2.8	84.2
285	76.5	Jan	2.8	73.7
307	70	Feb	3.6	66.4
335	60	Mar	6.4	53.6
355	50	April	7	43
Winter total				329.4

Table 4 indicates that there was one leaching event during the summer crop season, very near the start, when 27.8mm of water was estimated to have gone to deep percolation. This was caused by the irrigation on day 6 of 60mm (largest of the summer season, see section 4.4.2). There were six leaching events during the winter crop season, giving a total of 329.4mm water going to deep percolation. The first one (smallest) was caused by the rainfall event on day 218. The other five (larger events) were due to irrigation applications. This agrees well with the tensiometer indications of deep percolation discussed in section 4.4.2. The seasonal leaching fractions are shown in table 5.

Table 5 Seasonal water applications, deep percolation amounts and leaching fractions

Season	Irrigation and effective rain (mm)	Deep Percolation mm	Leaching Fraction
Summer	332.6	27.8	0.08
Winter	673.3	329.4	0.49
Total	1005.9	357.2	0.36

There was little deep percolation during the summer season and the vast majority (92%) of leaching thus occurred in the winter season. As this was the main mechanism by which salts left the soil profile, we would expect added salts to accumulate during the summer season and then be leached downward during the winter season.

4.6 Salt inputs and outputs

4.6.1 Irrigation

Irrigation water provided the only salt input to the study field. Salinity (EC_w) of irrigation applications is detailed in appendix 6. The average salinity of the applied water was 5.38 dS/m (approximately 3450 ppm). Water of this salinity is considered (Ayers and Westcot, 1985) unsuitable for agriculture as it poses a 'severe' threat to production.

The total amount of salt added to the study field (see appendix 9) was 62.1 tonnes. This comprised 21.2 tonnes during the summer season, none in the fallow season and 40.9 tonnes during the winter crop season.

The effect of irrigation applications on soil salinity is illustrated by figure 18, which shows bulk soil electrical conductivity (EC_a) measurements from 0.7m and 1.5m depth across the field (see appendix 5). Soil salinity was always greater at the base (1.5m) of the soil profile. During the summer crop season, all irrigation applications, except the first, caused an increase in soil salinity. In the fallow period, fluctuations in soil salinity were reduced as there were no irrigation applications. The figure indicates a gradual decrease in soil salinity over the fallow period, which is probably due to diffusion processes taking salts deeper into the soil. The early irrigation applications of the winter crop season increased soil salinity as there was no leaching, but subsequent applications promoted leaching and soil salinity levels reduced again.

4.6.2 Soil salinity levels

Soil salinity levels were determined on a weekly basis from eight depths down to 1.6m. Figure 19 shows EC_e (electrical conductivity of saturated soil extract) values for the upper soil profile (0-1.0m depth) and for the lower soil profile (1.2-1.6m depth) throughout the study.

Figure 19 shows that salinity levels in the upper soil profile were fairly stable throughout the year with EC_e values around 5-10 dS/m. Salinity in the lower soil profile was generally slightly higher except during the summer season when EC_e values averaged about 20 dS/m. Thus salts appeared to accumulate in the lower soil profile during the summer season, but not during the fallow period or winter wheat season.

The likely effects on crops of these salinity levels are shown in Figure 20 in terms of the salinity classes discussed earlier. These were:

EC_e < 5 dS/m - Little crop effect

EC_e = 5-15 dS/m - Significant crop effect

EC_e > 15 dS/m - Severe crop effect

Figure 20 clearly shows that during the summer crop season large portions of the soil profile (up to 60%) exhibited salinity levels that would be generally expected to pose a severe threat to crop growth and yield. These high salinity areas persisted for the whole crop season, only disappearing at the end. During harvest of the summer crop, soil salinity decreased although no leaching was observed. There was some movement of water (section 4.4.2) during the watermelon harvesting period, which may have enabled salts to move out of the soil profile, but it is more likely that the salts moved downward predominantly by diffusion processes during this period.

Soil salinity was relatively stable during the fallow season with the whole profile exhibiting moderately significant levels of salinity. There was no mass flow of water and salts during the fallow period, and diffusion would be the only mechanism by which high soil salinity areas would be removed.

In the winter season the soil profile was dominated by soil of low salinity (little crop effect expected), suggesting a significant movement of salts out of the soil profile. Significant leaching events occurred during the winter crop season, which carried salts below the soil profile to deep percolation. Although portions of high salinity soil occurred during the season they were shortlived.

The average soil salinity (EC_e) for the soil profile was 12.6 dS/m for summer, 8.4 dS/m for the fallow period and 6.4 dS/m for winter.

4.6.3 Salt balance

It was estimated that a total of 62.1 tonnes salt (see appendix 9) was added in the irrigation water to the study field during the two crop seasons. As there was no drainage during the study, this salt would either have accumulated in the soil profile, or left the field via deep percolation or diffusion to deeper layers. A salt balance was calculated for the crop seasons (there were no water or salt additions during the fallow period and no deep percolation) in the study field. The results are summarised below (details in Appendix 9):

Table 6 Seasonal salt balance for the study field

	Salt added (tonnes)	**Change in soil salt content (tonnes)**	**Salt to Deep Percolation (tonnes)**	**Water to Deep Percolation (mm)**	**Salinity of Deep Percolation water (dS/m)**
Summer Crop Season	21.2	+20.8 (98%)	0.4 (2%)	28	11.5
Winter Crop Season	40.9	+2.8 (7%)	38.1 (93%)	329	9.8
Total	62.1	+23.6	38.4	357	9.1

For the summer crop season, 98% of salt added with the irrigation water remained in the soil profile. Only 0.4 tonnes left the soil by deep percolation (and diffusion at the end of the season). This was expected as there was only one leaching event during the season which was small (28mm).

The winter crop season was quite different. 40.9 tonnes salt was added to the land but the salt accumulation was only 2.8 tonnes. This was due to the large number of salt leaching events which occurred during this season. There were six significant events with a total of 329mm of water going to deep percolation. This water removed an estimated 38.4 tonnes salt from the soil profile.

Salinity content of deep percolation water was high. During the summer season it was estimated to be about 11.5 dS/m and for the winter season the average salinity was 9.8 dS/m.

4.7 Application of predictive methods to study results

Drainwater reuse has been practised in the study area for over ten years. It is thus possible that steady-state soil salinity levels have been attained, especially as the soil is very permeable and free draining. There was not a great variation in soil salinity levels during the study (figure 19). The average rootzone (taken as 0-1.6m) soil salinity (EC_e) over the year was 8.6 dS/m. For the summer season it was 12.6 dS/m (when leaching was very small) and for the winter season (when leaching was much higher) it was 6.4 dS/m. The applied water salinity (EC_w) was very stable, averaging 5.38 dS/m for the whole year, and the two crop seasons.

The predictive methods described in section 4.2 (except WATSUIT) were applied to the study findings. The results are summarised in table 7.

Table 7 Application of predictive methods for steady-state soil salinity levels to study findings

	Period	Summer	Winter	Whole Year
Study results	EC average (dS/m)	5.38	5.38	5.38
	Leaching Fraction (LF)	0.08	0.49	0.36
	EC average	12.6	6.4	8.6
Predictive Methods and EC predicted	Rhoades and Merrill	14.5	3.3	4.1
	Ayers and Westcot	13.7	4.3	5.1
	Rhoades	12.1	4.2	5.1
	Hoffman and van Genuchten	17.2	4.8	6.1
	SALTMOD	11.3 (LF=0.09)	10.0 (LF=0.42)	10.7(LF=0.26)

These results are shown graphically in figure 21. All five predictive methods gave reasonable estimates of soil salinity levels at the study site, for the year as a whole and for the separate crop seasons. This is probably because drainwater reuse had been practised for some time and an equilibrium situation had been established. Also the soil had a low clay content (ie. physico-chemical reactions with clay particles would be minimal) and was highly permeable and freely draining (leaching efficiencies should thus be very high).

At the lowest leaching fraction (0.08), the Rhoades relation and the SALTMOD model gave the closest predictions. For a leaching fraction of 0.36, the Hoffman and van Genuchten equation and SALTMOD gave the best predictions, and for the highest leaching fraction (0.49) the Hoffman and van Genuchten equation gave the closest prediction.

5. CONCLUSIONS

The microstudy was a detailed investigation into the processes of salt accumulation and movement under drainwater reuse. It was carried out in a farmer's field in the western Nile Delta, about 2 hectares in size and typical of those in the region.

The region is a reclaimed desert area which has a harsh arid climate and sandy soils. Soil permeability at the study site was high and the field capacity moisture content was low. Storage of water in the soil profile was thus poor. In areas where water scarcity is an issue (and leaching is not required to remove salts or other pollutants), such soils can be very wasteful of irrigation water. They are generally not well suited to traditional surface methods of irrigation, where large amounts of water are applied. They are better adapted to modern irrigation methods (e.g. drip) where small amounts of water can be applied accurately and frequently.

There were three seasons in the study field during the year of investigation. During the summer crop season, of approximately 4 months, watermelon was grown with 18 applications of irrigation (10 "gifts" see appendix 6). This was followed by a fallow season of about 3 months when no crop was grown and no irrigation was applied. The winter crop was wheat grown over the last 5 months. There was some rainfall at the beginning of this season and 13 irrigation applications (6 "gifts").

The drainage water used for irrigation in the study field was very saline. The average salinity was over 5 dS/m which is about 3200ppm. Water of this salinity is generally not considered suitable for agricultural production.

Average rootzone soil salinity (EC_e) levels during the two crop seasons were 12.6 dS/m for the summer season and 6.4 dS/m for the winter season. Both crops reached maturity and produced good yields, although the international guidelines on crop yield reduction due to salinity predict 100% yield reduction for the watermelon crop for EC_e levels greater than 10 dS/m. It has been suggested by a number of researchers that these guidelines are conservative and this would certainly seem to be the case in this instance.

It was estimated that 62 tonnes of salt were added to the field during the study. In the summer season the vast majority of applied salt remained in the soil profile. Very little water and salts went to deep percolation. During the fallow period, mass flow of water and salts was negligible and the only process of salt movement was diffusion. Most of the salt applied in the winter season was taken through the soil profile to deep percolation. There were six significant leaching events during the winter which took 49% of applied water and 93% of applied salt out of the soil profile.

Five predictive methods for steady-state soil salinity determination were applied to the study findings. All methods gave reasonable agreement between predicted levels and actual levels recorded during the study. This is probably because drainwater reuse had been practised for some time and an equilibrium situation had been established. Also the soil at the study site had low clay content (ie physico-chemical reactions with clay particles would be minimal) and was highly permeable and freely draining (leaching efficiencies should thus be very high). The best predictions were given by the methods of Rhoades, Hoffman and Van Genuchten, and the SALTMOD computer model.

The process of leaching during the winter crop season is critical in successful use of drainwater for crop production in the area. Leaching of salts is only sustainable with availability of extra irrigation water and the presence of deep groundwater.

Over the year of study it was estimated that over 350mm of water and 38 tonnes of salt went through the soil profile to the subsoil. This could lead to two problems:

1) *Salinisation of groundwater*. This is known to be only 3-4m deep. Groundwater is extracted by farmers in the area to use for irrigation and domestic purposes. Salinisation of groundwater will occur if drainwater reuse continues to add salts to the soil profile and carry them downward by deep percolation.

2) *Elevation of groundwater*. Continued percolation of water to the groundwater may raise levels towards the rootzone. This will hamper both leaching and diffusion processes and bring extra salts into the rootzone via secondary salinisation.

The salinity of drainwater being reused for irrigation in this area was high. However, the study has shown that this water can be successfully used for agriculture with the adoption of appropriate management techniques. Leaching is the key to salinity control in the area, with diffusion playing a minor role in maintaining acceptable soil salinity levels. Nevertheless, there is a danger that leaching may not be able to prevent long-term salinity build-up in areas such as this; an alternative method of control is to ensure that the salinity of mixed water used for irrigation is not excessive.

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Appendices

Appendix 1

Gravimetric soil moisture determination

Appendix 1 Gravimetric soil moisture determination

Soil samples were augured from six positions in the study on a random basis once a week during the study period. Sampling depths were 0.2m, 0.4m, 0.6m, 0.8m, 1m, 1.2m, 1.4m and 1.6m. Gravimetric soil moisture was determined by weighing and oven drying.

$$\theta_g = \frac{m_w}{m_s + m_w}$$

θ_g = gravimetric moisture content
m_w = mass water
m_s = mass of oven dry soil

Appendix 2

Calibration of neutron probe

Appendix 2 Calibration of neutron probe

The CPN 503DR neutron probe was calibrated with volumetric soil moisture samples taken on 29th April 1995.

Neutron probe measures volumetric soil moisture content, calculated as below:

MVF = [a x R_c/R_s] + b

MVF is moisture volume fraction %
R_c is the count rate in the soil
R_s is the standard count rate
a is a site specific constant
b is a site specific constant

Figure 22 shows the obtained calibration line for which:

a = 68.841
b = 8.65
$r^2 = 0.9$

Appendix 3

Mercury manometer tensiometers

Appendix 3 Mercury manometer tensiometers

Two profiles of mercury manometer tensiometers were installed in the study field to measure total potential. Installation depths were 0.15m, 0.3m, 0.4m, 0.8m, 1.2m and 1.6m.

Total potential is defined as:

$$\Psi_{total} = \Psi_{grav} + \Psi_{mat} + \Psi_{os}$$

where

Ψ_{total} = total potential (cmH_20)

Ψ_{grav} = gravitational potential (cmH_20)

Ψ_{mat} = matric potential (cmH_20)

Ψ_{os} = osmotic potential (cmH_20)

Gravimetric potential is due to elevation above a datum.
Matric potential is due to surface water tension forces in pore structure.
Osmotic potential is caused by salts in soil water.

Matric potential values give a measure of the wetness of the soil at a given depth. A matric potential value of 0 cm H_2O indicates saturation at the soil surface. Readings become more negative as the soil dries out.

Total potential measurements are used to indicate direction of water movement within the soil profile. Water moves along potential gradients from high potential to low potential.

Appendix 4

Soil salinity determination

Appendix 4 Soil salinity determination

Samples taken for gravimetric soil moisture were also used to determine soil salinity at eight depths through the soil profile. Six random positions were used once a week at depths 0.2m, 0.4m, 0.6m, 0.8m, 1m, 1.2m, 1.4m and 1.6m.

Soil water extracts were prepared from the samples using 40g of oven dry soil and 200g distilled water (known as a 1:5 extract). The extracts were left to stand, filtered and then analysed. Samples were analysed for total salt content by determining the electrical conductivity (EC_5) of the extract.

To obtain electrical conductivity of saturated extracts (EC_e), an inverse linear relation was assumed between the EC value and the soil moisture content(θ), as suggested by Smedema and Rycroft (1983).

ie. $EC_5 = \theta_5/\theta_{sp} \times EC_e$

where θ_{sp} is the moisture content of the soil extract at saturation point, and $\theta_5$is the moisture content of the 1:5 extract.

For the study site:-

$\theta_5 = 500\%$

$\theta_{sp} = 41\%$

$EC_e = 12 \times EC_5$

Appendix 5

EM38 measurements

Appendix 5 EM38 measurements

A Geonics electromagnetic instrument (EM38) was used to measure bulk soil electrical conductivity (EC_a) in five positions in the study field twice per week. The EM38 measures predominantly the average soil salinity up to 0.7 and 1.5m of the ground layers when placed in horizontal and vertical positions on the ground surface respectively. (Around 70% of the signal response arises from these depths.)

Calibration of EC_a measurements with EC_e levels was not attempted at the fieldsite. The calibration relation of Rhoades 1990 was used to obtain EC_e levels:

EC_a mS/m	EC_e dS/m
20	1.18
31	1.83
41	2.42
54	3.19
90	5.34
269	15.96

Transformation from soil electrical conductivity (EC_a) measured with horizontal EM38 to electrical conductivity of saturation extract (EC_e).

Appendix 6

Irrigation applications

Appendix 6 Irrigation applications

Summer Crop Season					Winter Crop Season				
Date	Day No	Irrigation Time (hrs)	Depth (mm)	EC (dS/m)	Date	Day No	Irrigation Time (hrs)	Depth (mm)	EC (dS/m)
25/4	6	10	60.32	6.7	1/11	196	12	53.71	5.9
18/5	29	5	22.38	5.5	2/11	197	10.8	47.07	5.9
19/5	30	3.5	15.66	5.6	30/12	255	7.0	39.5	5.7
27/5	38	2	10.12	5.1	31/12	256	9.8	55.02	5.8
29/5	40	2.5	10.7	5.0	1/1	257	4.5	25.39	5.7
30/5	41	3.5	16.35	5.1	28/1	284	6.5	36.68	5.6
6/6	48	5.5	18.19	6.2	29/1	285	12.0	67.72	5.0
7/6	49	3	13.43	5.9	19/2	306	13.5	76.18	5.5
12/6	54	1.5	6.71	5.6	20/2	307	5.0	28.22	5.6
13/6	55	3	15.18	6	19/3	334	14.5	81.83	4.8
14/6	56	3	13.43	5.2	20/3	335	5.5	31.04	5.1
22/6	64	7	35.42	0.8	8/4	354	14.5	81.83	5.0
27/6	69	7.5	33.57	6.0	9/4	355	2.5	15.08	5.3
29/6	71	2	8.56	5.9					
6/7	78	3	13.43	5.5					
7/7	79	4	17.9	6.0					
11/7	83	4	18.68	5.9					
20/7	92	0.35	2.6	6.0					

Note: Each irrigation application was assumed to cover the whole cropped area. It is usual practice that irrigation applications on consecutive days (e.g. day 29 and 30) would cover half the field at a time. An irrigation "gift" thus covered the whole cropped area in 2-3 days. There were 10 "gifts" during the summer season and 6 "gifts" during the winter season. As can be seen from the table each gift is grouped.

Appendix 7

Rainfall

Appendix 7 Rainfall

Date	Day Number	Rainfall (mm)	Effective Rainfall (mm)
21/10	185	4.4	-
23/10	187	2	-
24/10	188	4.6	-
25/10	189	4.4	-
27/10	191	2.8	-
28/10	192	1.2	-
29/10	193	1.8	-
5/11	200	1.2	-
15/11	210	2.6	-
16/11	211	14.4	9.4
17/11	212	2.8	-
20/11	215	1.8	-
22/11	217	6	1
23/11	218	23.8	18.8
24/11	219	0.8	-
28.11	223	9.8	4.8
Total		84.4	34

Note: Effective rainfall for each event = Rainfall in event - 5mm

Appendix 8

Deep percolation calculation

Appendix 8 Deep percolation calculation

Moisture contents

Tensiometer measurements of matric potential were converted to moisture content (mvf) for the whole soil profile using the derived soil moisture release curve (figure 10).

The relation between soil matric potential and moisture content is of a power relation form:-

$Y = ax^b$

Y = matric potential

x = moisture content

For the study site soil, it was found:

$a = 28.15$
$b = -0.07$

Figure 17 shows total profile soil moisture contents for the study year. Peaks are due to irrigation applications or rainfall. Water potentially available for deep percolation is depth of water (mm) in the soil above field capacity moisture content. Field capacity (section 4.2.3) = 22% for a soil profile of 1.6m, i.e. field capacity equals 352mm.

Estimated 2-day crop water usage

Crop water use figures for Egypt given as:-

	J	F	M	A	M	J	J	A	S	O	N	D	Units	Total
Wheat	176	231	403	441	143	-	-	-	-	-	30	185	m^3/F/month	1609
Water Melon	-	-	-	-	139	483	538	428	412	-	-	-	m^3/F/month	2000
Wheat	42	55	96	105	34	-	-	-	-	-	7	44	mm/month	380
Water Melon	-	-	-	-	33	115	128	102	98	-	-	-	mm/month	476
Wheat	2.8	3.6	6.4	7.0	2.2	-	-	-	-	-	0.4	2.9	mm/2 days	
Water Melon	-	-	-	-	2.2	7.6	8.6	6.8	6.6	-	-	-	mm/2 days	

F = feddan = 0.42ha

Values used in Table 4

Deep percolation then calculated (for each leaching event) as below:-

Deep percolation (mm) = [Water added to soil above field capacity] - [2 day crop water requirement].

Appendix 9

Salt balance calculations (see section 4.6.3)

Appendix 9 Salt balance calculations (see section 4.6.3)

For the study field the salt balance was simplified to:-

Salt applied in irrigation water	=	buildup of salt in soil profile	+	salt leached downward by deep percolation

assumptions:

- no salt left field via subsurface drains (there was no drain flow)
- there was no horizontal flow of salts
- diffusion is small and can be included in deep percolation term

<u>Salt applied in irrigation water</u>

Irrigation water applied in summer and winter = 332.6mm + 639.3mm
= 0.972m

Irrigation water applied to field area of $18500m^2$ = $0.972 \times 18500m^3$
= $17982m^3$

Salt concentration = 5.38 ds/m
= $(633 \times 5.38) + 44.8\ g/m^3$
= $3450g/m^3$

Total salt added = 17982 x 3450gm
= $62.1 \times 10^6 gm$
= 62.1 tonnes

For summer season:

water added = $0.333m \times 18500m^2 = 6160m^3$
salt added = $6160m^3 \times 3450gm/m^3$ = <u>21.2 tonnes</u>

For winter season:

water added = $0.639m \times 18500m^2 = 11821m^3$
salt added = $11821m^3 \times 3450gm/m^3$ = <u>40.9 tonnes</u>

<u>Buildup of salt in soil profile</u>

Salt content of soil (profile to 1.6m) at start of year (day 8):-

EC_5 average = 0.5 ds/m
(where EC_5 is the extract of 40g (0.04kg) soil + 200 ml water)

$$= \frac{(0.5 \times 633) + 44.8}{1000} kg/m^3$$
$$= 0.362\ kg/m^3$$

So for 200 ml water:

Salt content = $200 \times 10^{-6} \times 0.362$kg

= 7.24×10^{-5}kg salt per 0.04kg soil in field

Total mass of field = $18500 \times 1.6 \times 1.51 \times 10^{3}$ kg/m^3 = 4.47×10^{7} kg

So salt in whole field at start of year $= \frac{4.47}{0.04} \times 7.24 \times 10^{-5}$ tonnes

= 80907 kg (80.9 tonnes)

In a similar manner:-

Day number	average EC_5 (ds/m)	salt content (kg)
8	0.5	80,907
127	0.648	101,786
375	0.668	104,615

By difference between salt content of the field, it can be seen:-

During summer season, the soil gained 20,879 kg salt
During winter season, the soil gained 2,829 kg salt

Total gain in salt for year = 23,708 kg

Therefore the salt removed from the soil profile by deep percolation was:-

- in summer season = 21256 - 20879 = 378 kg
- in winter season = 40888 - 2829 = 38059 kg

Therefore the salinity of the deep percolation water was:-

- in summer season = 378kg salt in 28mm water

$$= \frac{378}{0.0028 \times 18500} \text{ kg/m}^3$$

= 7297 ppm

$$= \frac{7297 - 44.8}{633} \text{ dS/m}$$

= 11.5 dS/m

- in winter season = 38059 kg salt in 329mm water

$$= \frac{38059}{0.329 \times 18500} \text{ kg/m}^3$$

= 6250ppm

$$= \frac{6250 - 44.8}{633} \text{ dS/m}$$

= 9.8 dS/m

Therefore salt removed to deep percolation in watermelon crop = 378kg
and salt removed to deep percolation in wheat crop = 38,061kg
So the amounts of salt being removed to deep percolation can be calculated. Therefore the salinity of the deep percolation water can be calculated.

The deep percolation (DPL) was 28mm for melon and 329mm for wheat.
Therefore DPL for melon had a salt content of 11.5 dS/m, and DPL for wheat had a salt content of 9.8 dS/m.

Figures

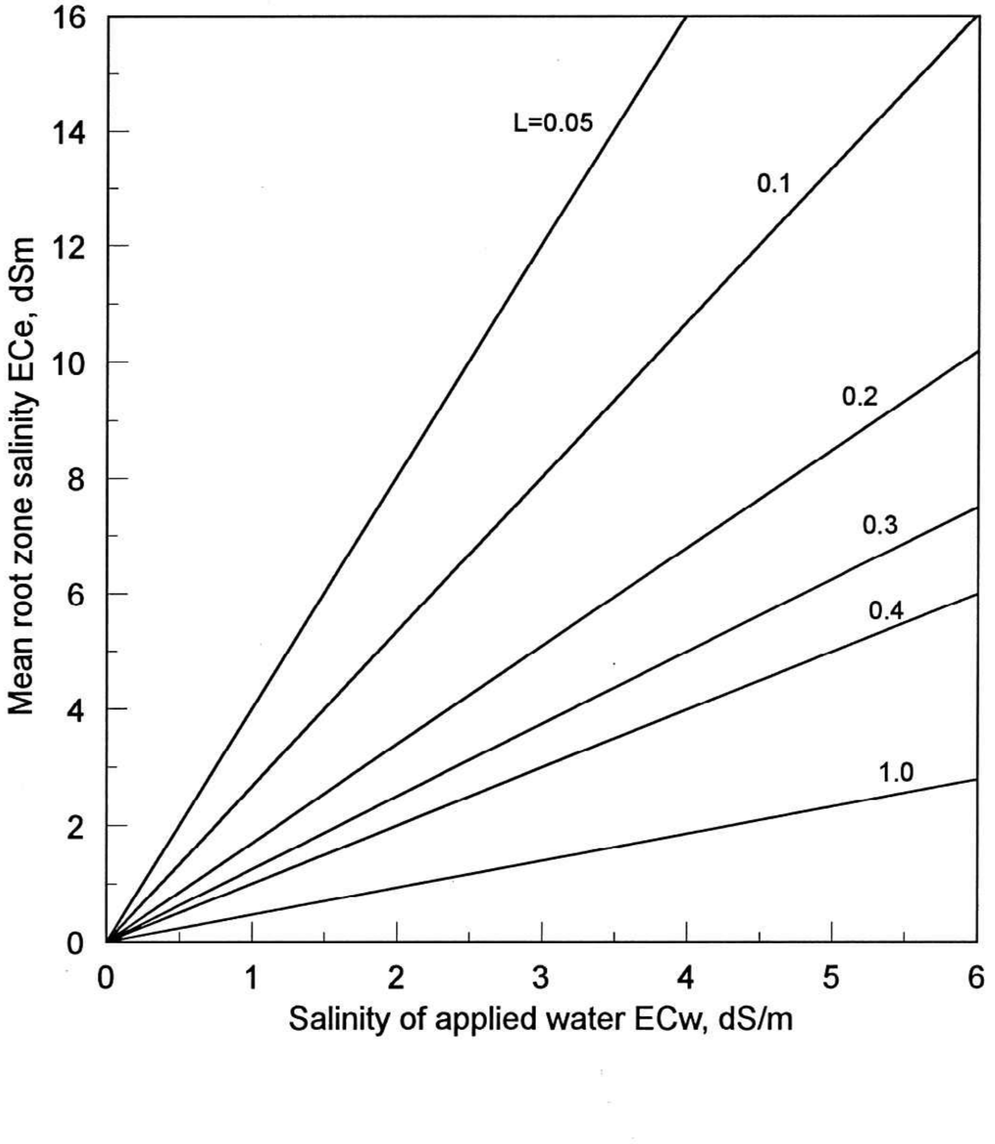

Figure 1 Mean root zone soil salinity as a function of applied water and leaching fraction

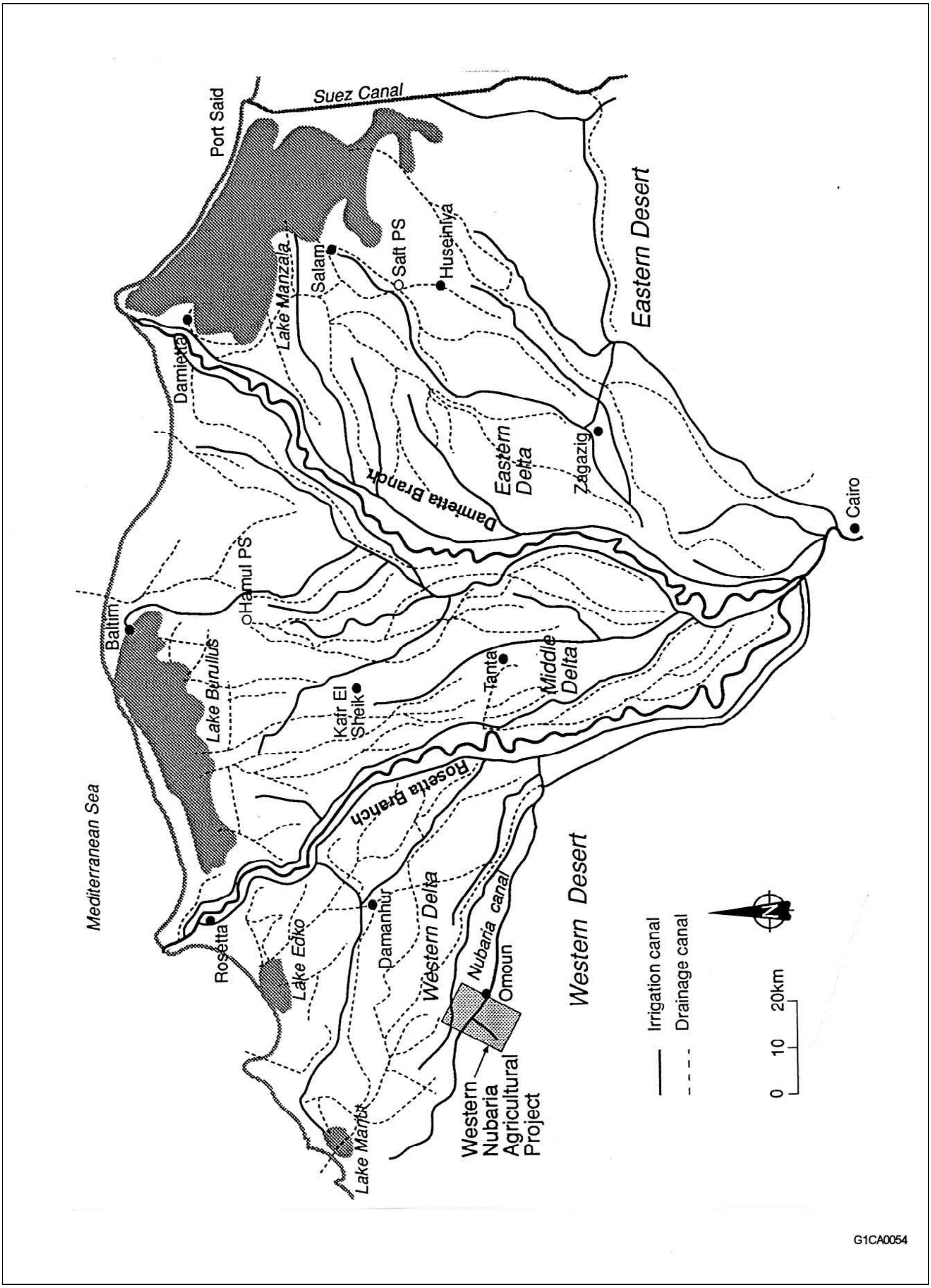

Figure 2 Map of the Nile Delta, Egypt, showing location of the Western Nubaria Agricultural Project, and main irrigation and drainage canals

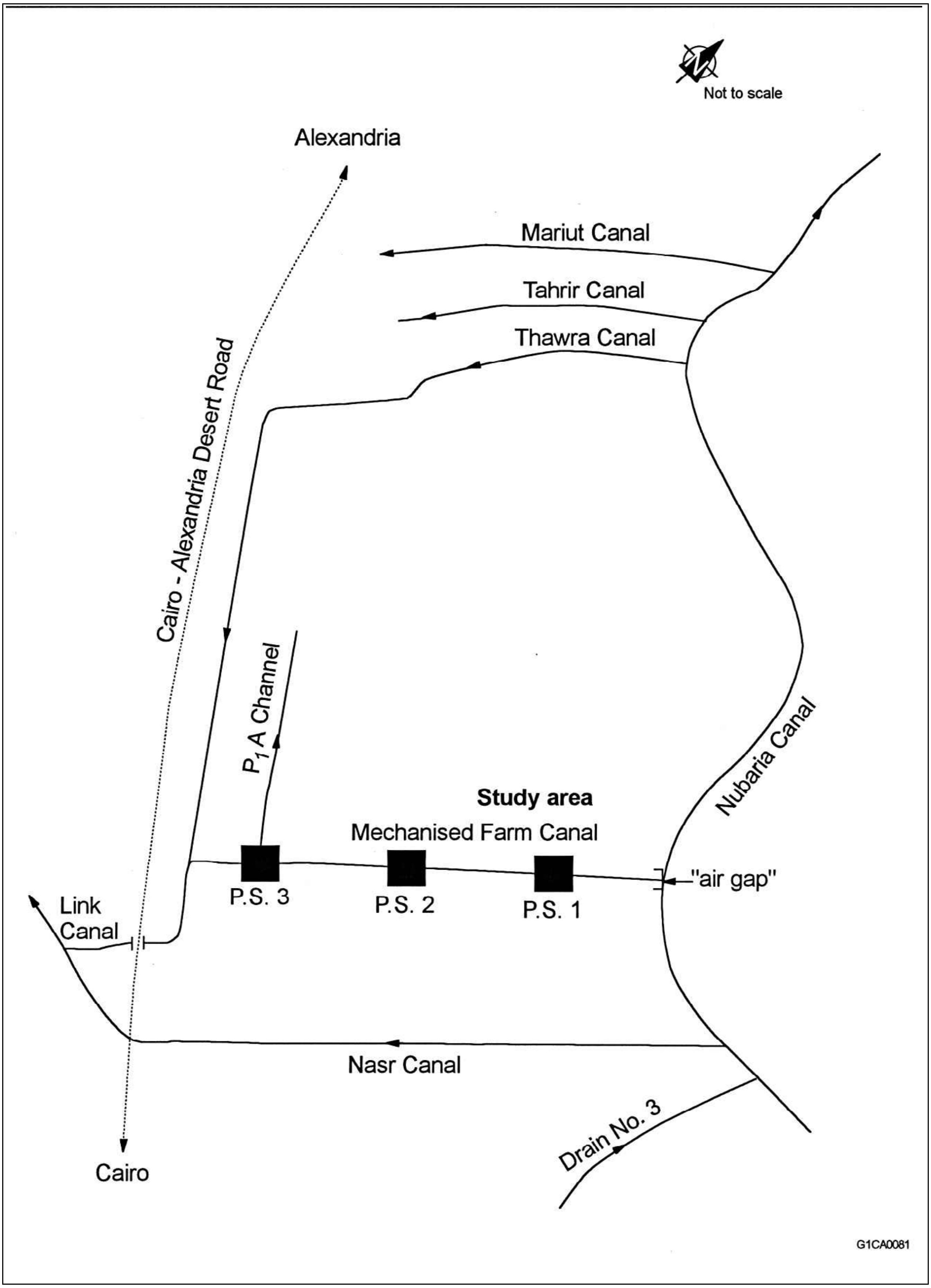

Figure 3 **Layout of irrigation canals and drainage channels on the Western Nubaria Agricultural project, showing location of the study area**

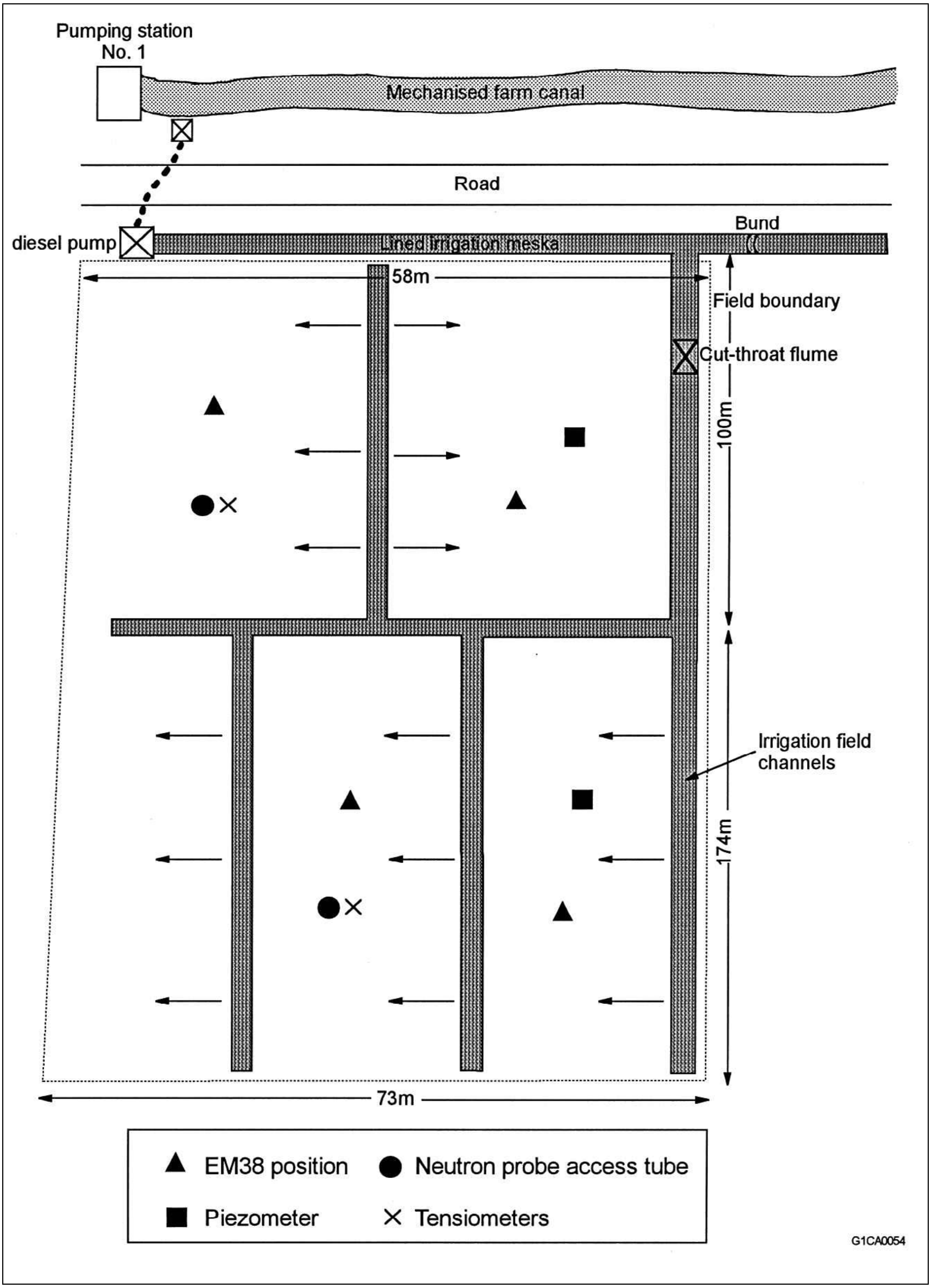

Figure 4 Study field layout

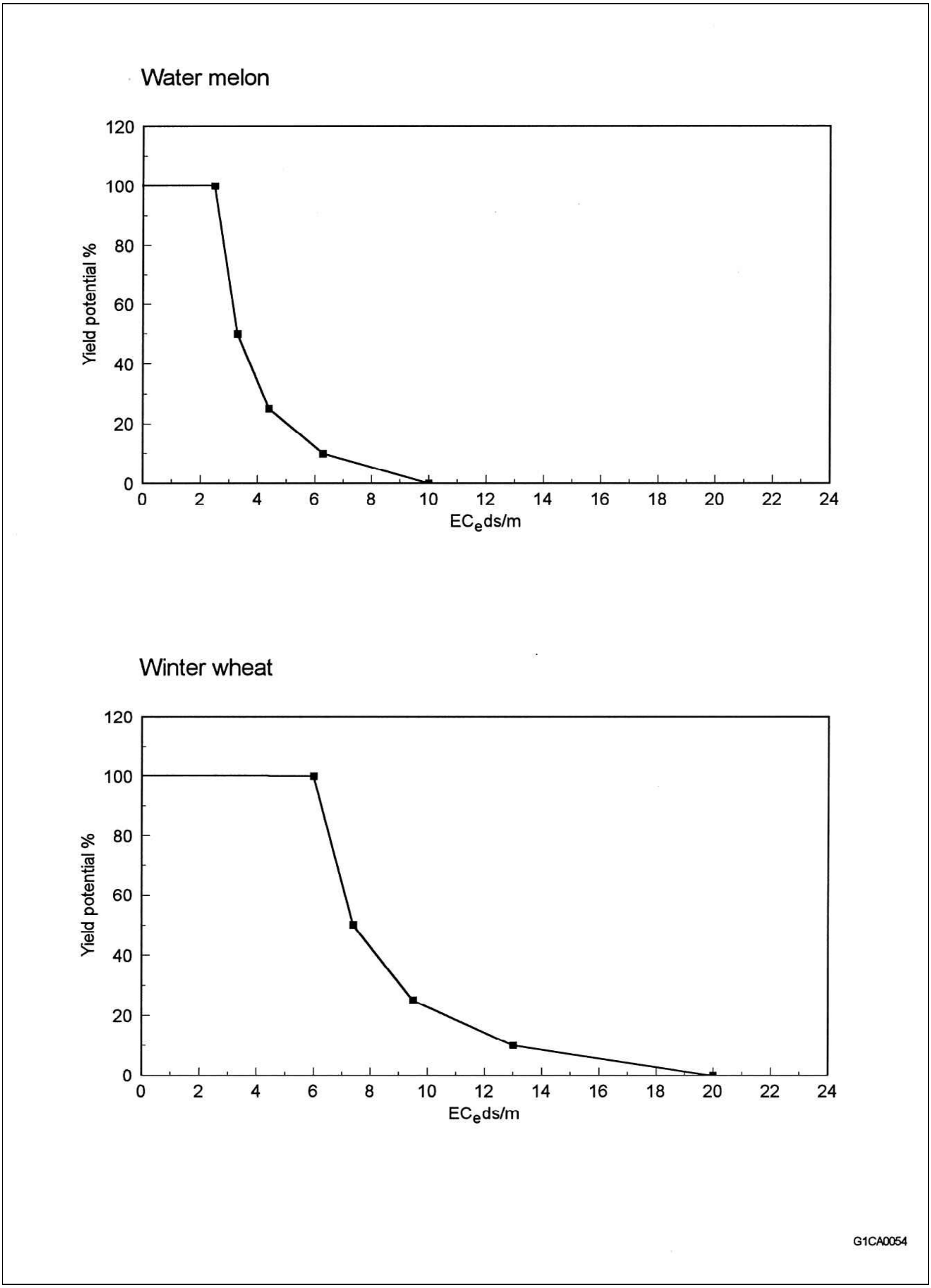

Figure 5 Relative salt tolerance of crops

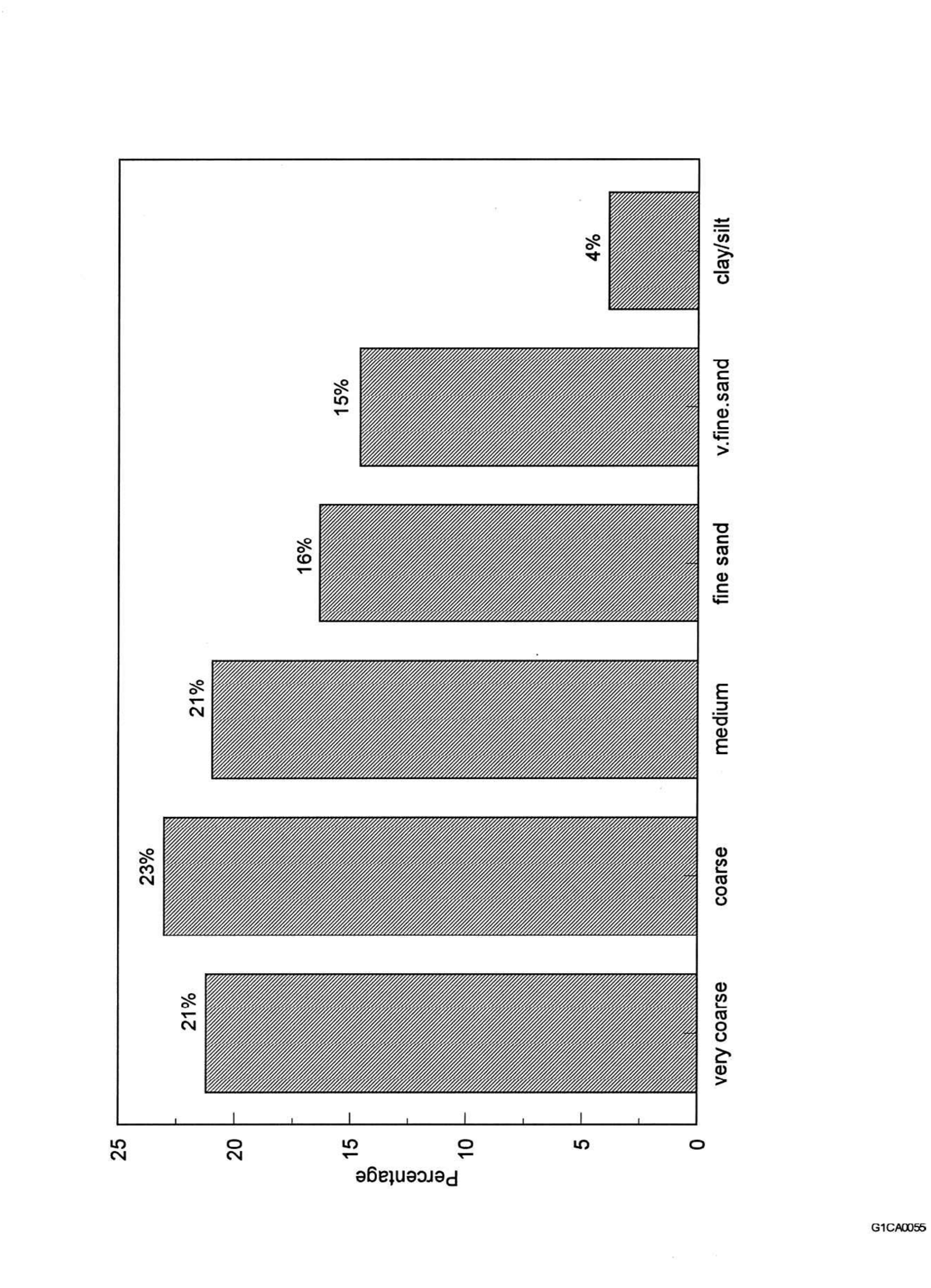

Figure 6 Soil texture

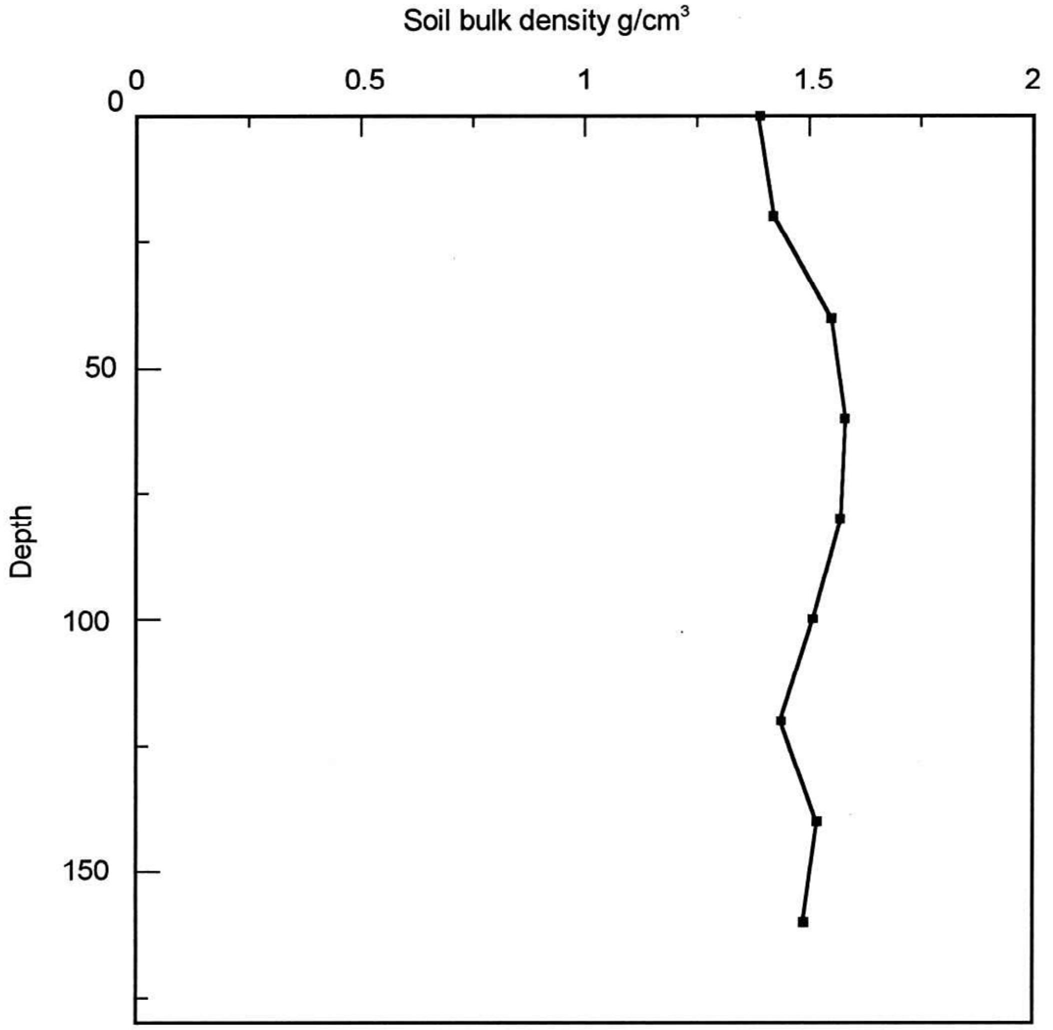

Figure 7 Soil bulk density

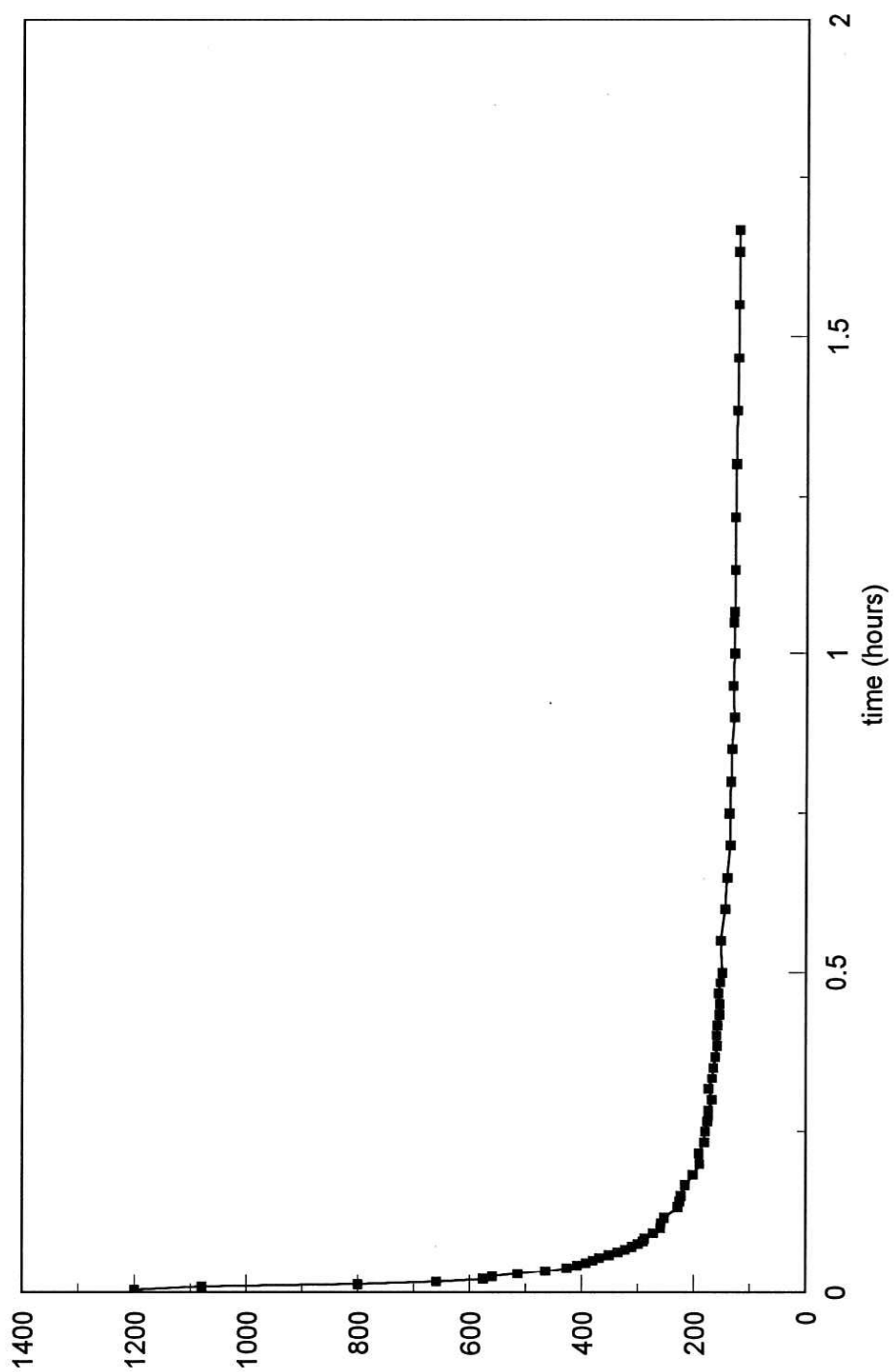

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Figure 8 Infiltration rate at study site

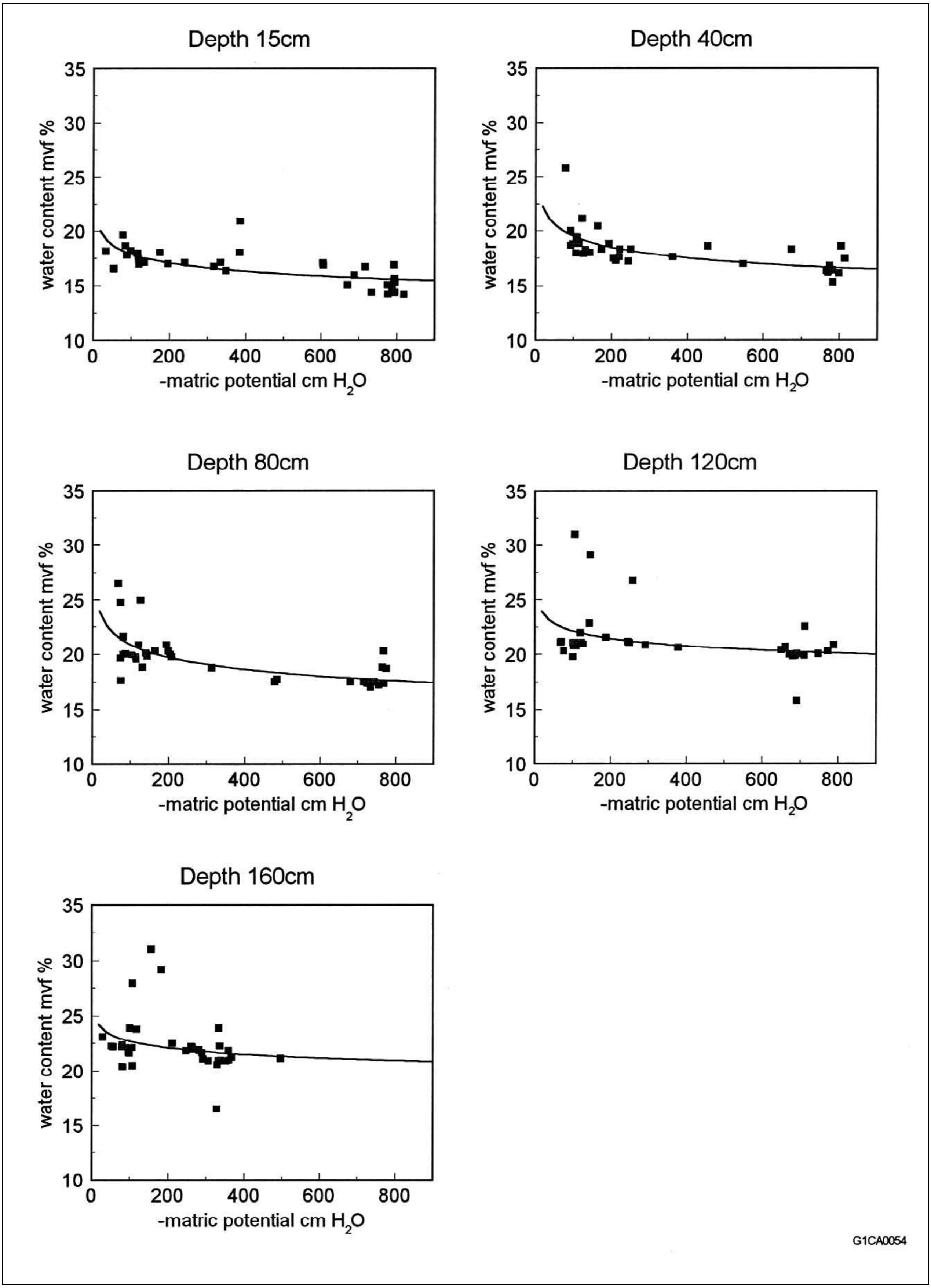

Figure 9 Soil moisture release curves at different depths

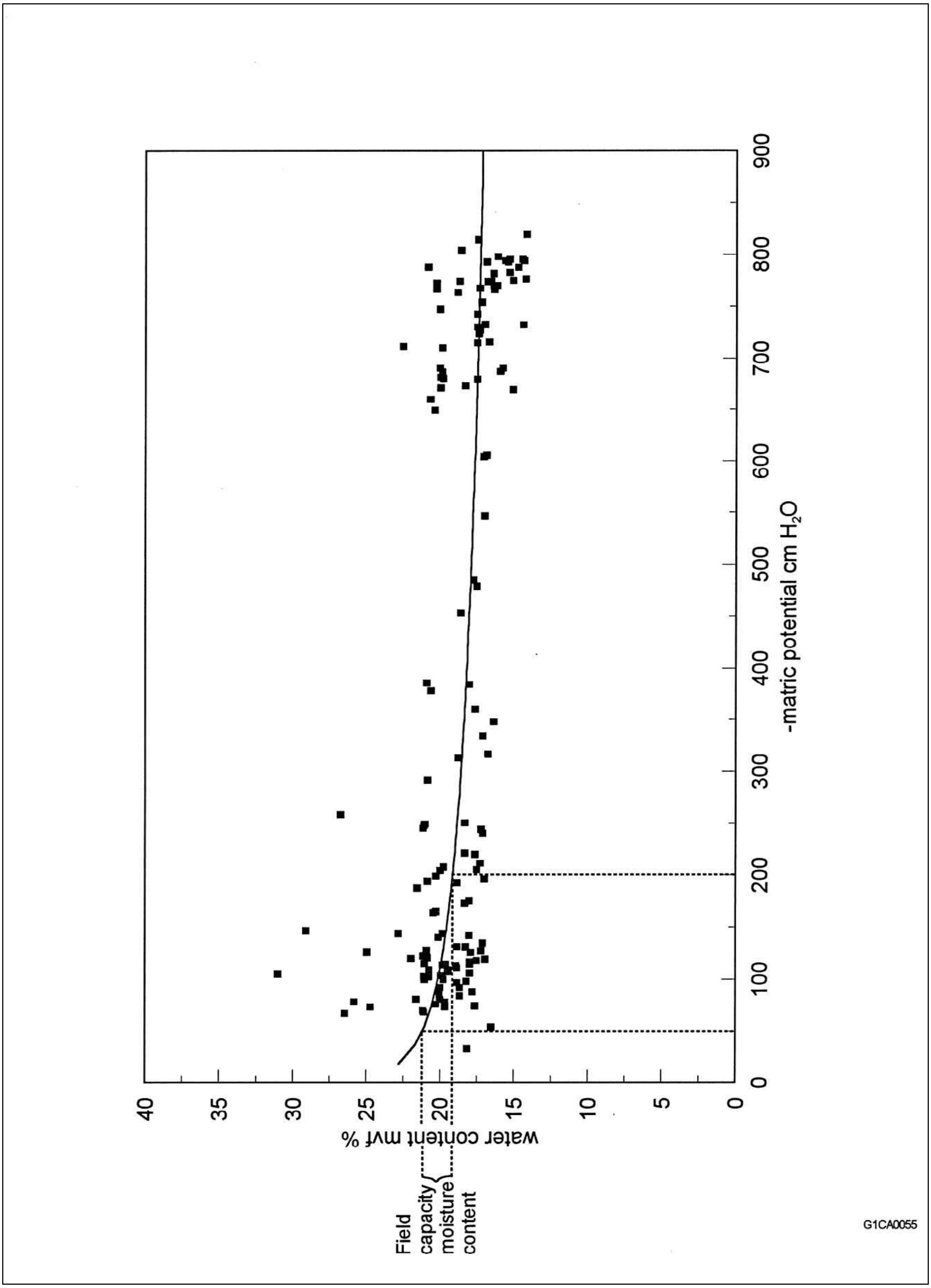

Figure 10 Whole profile soil moisture release curve

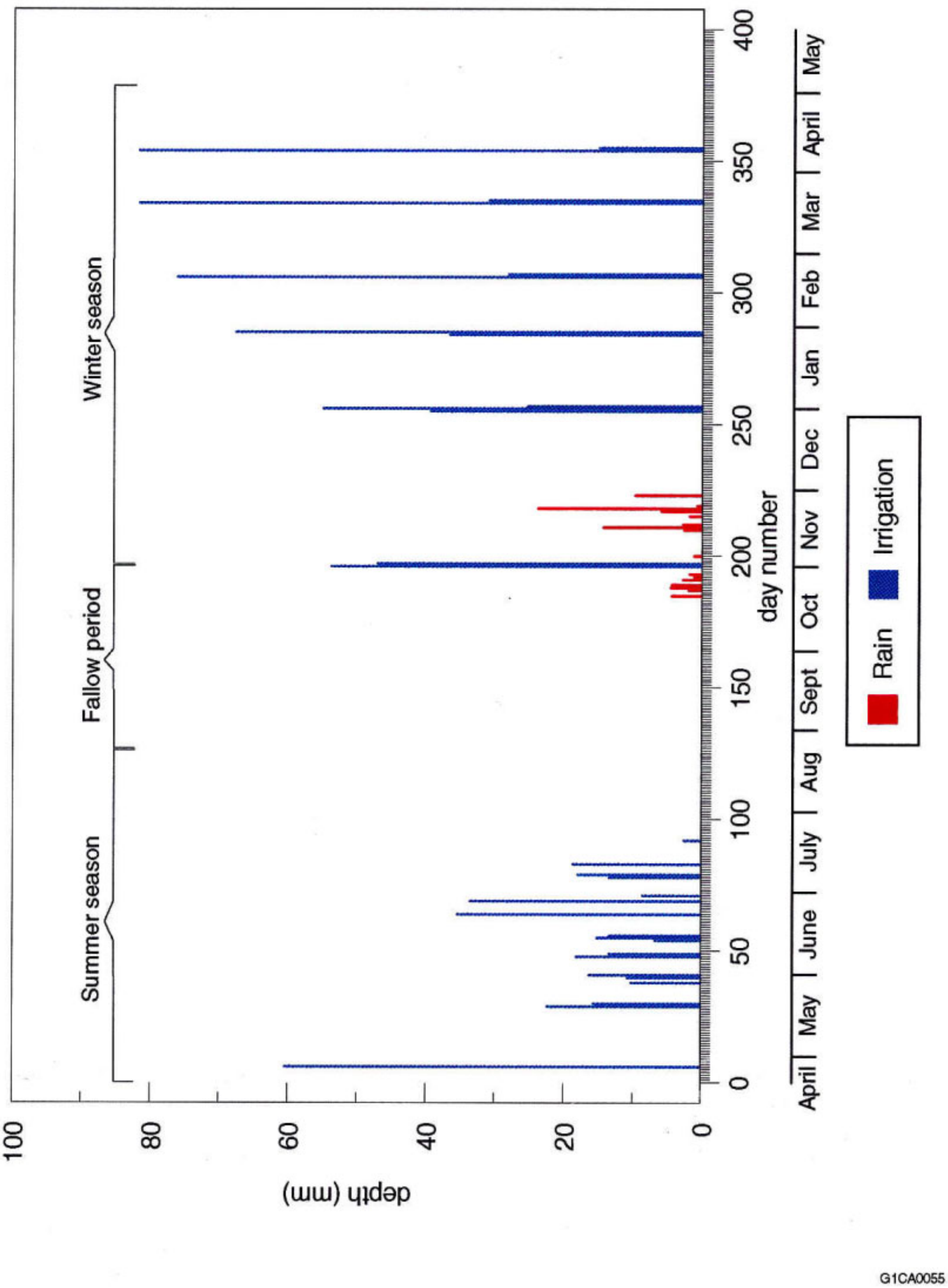

Figure 11 Irrigation applications and rainfall

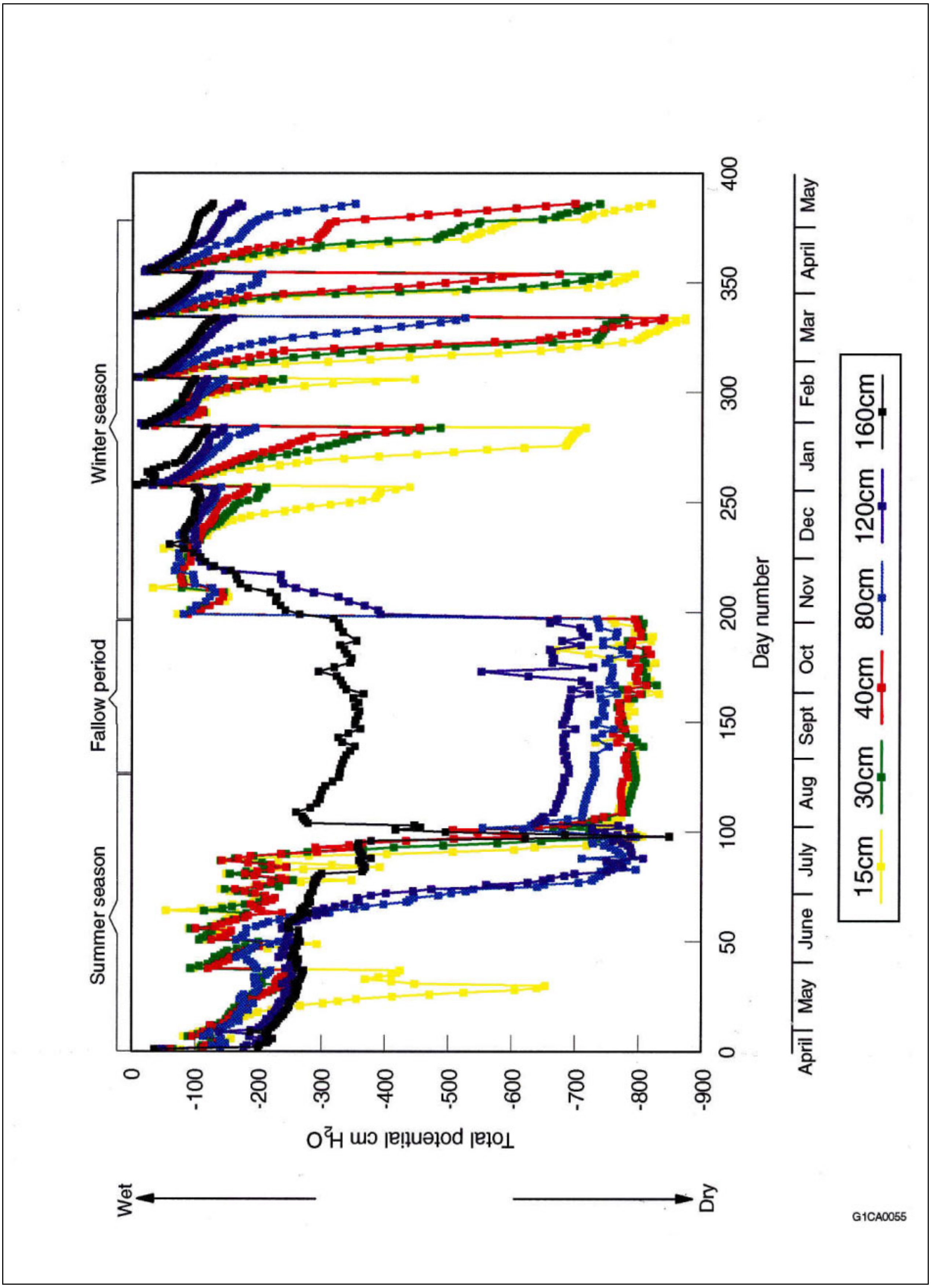

Figure 12 Matric potential (soil "wetness") at different depths in the soil profile

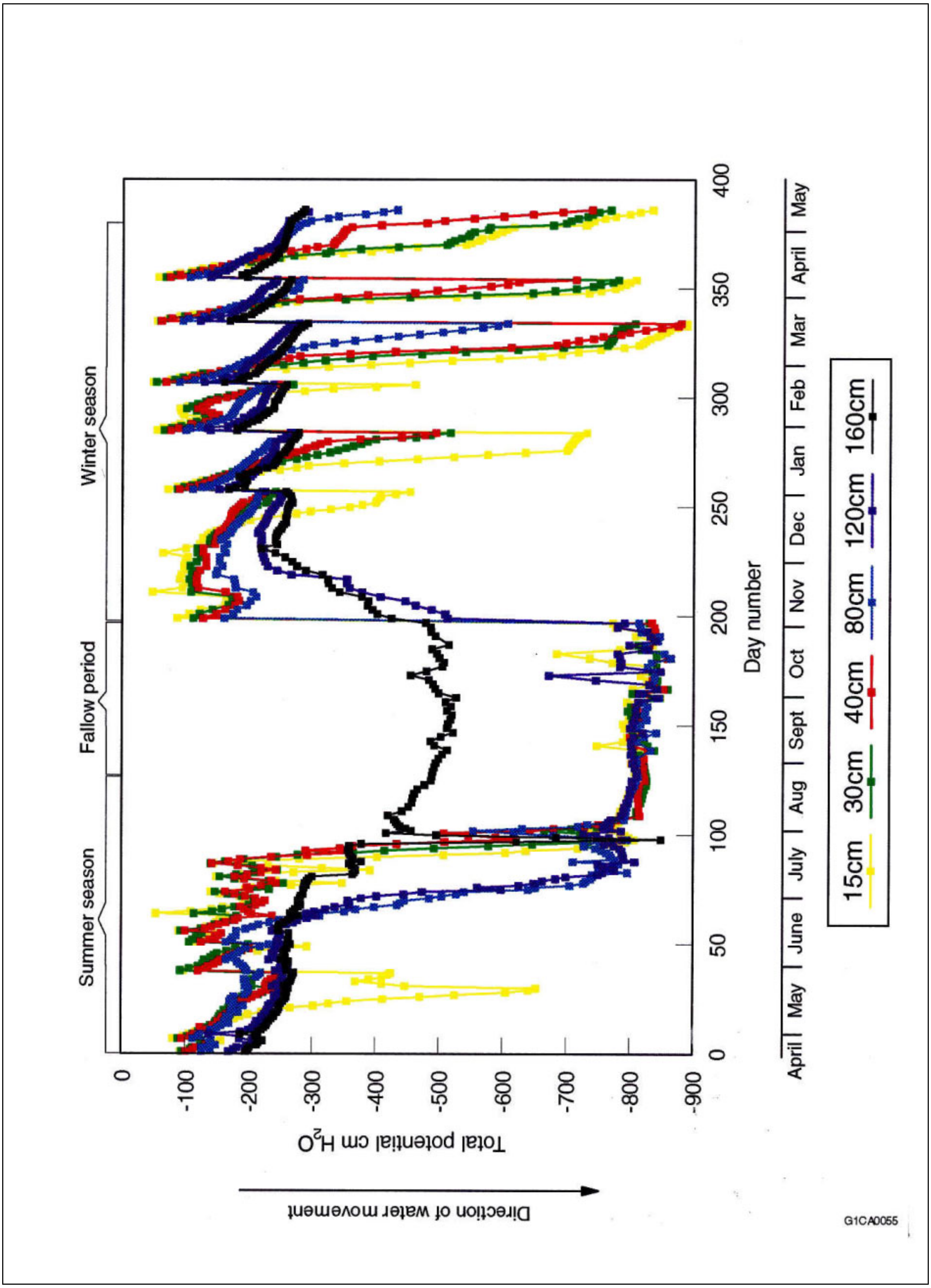

Figure 13 Total potential (water movement) at different depths in the soil profile

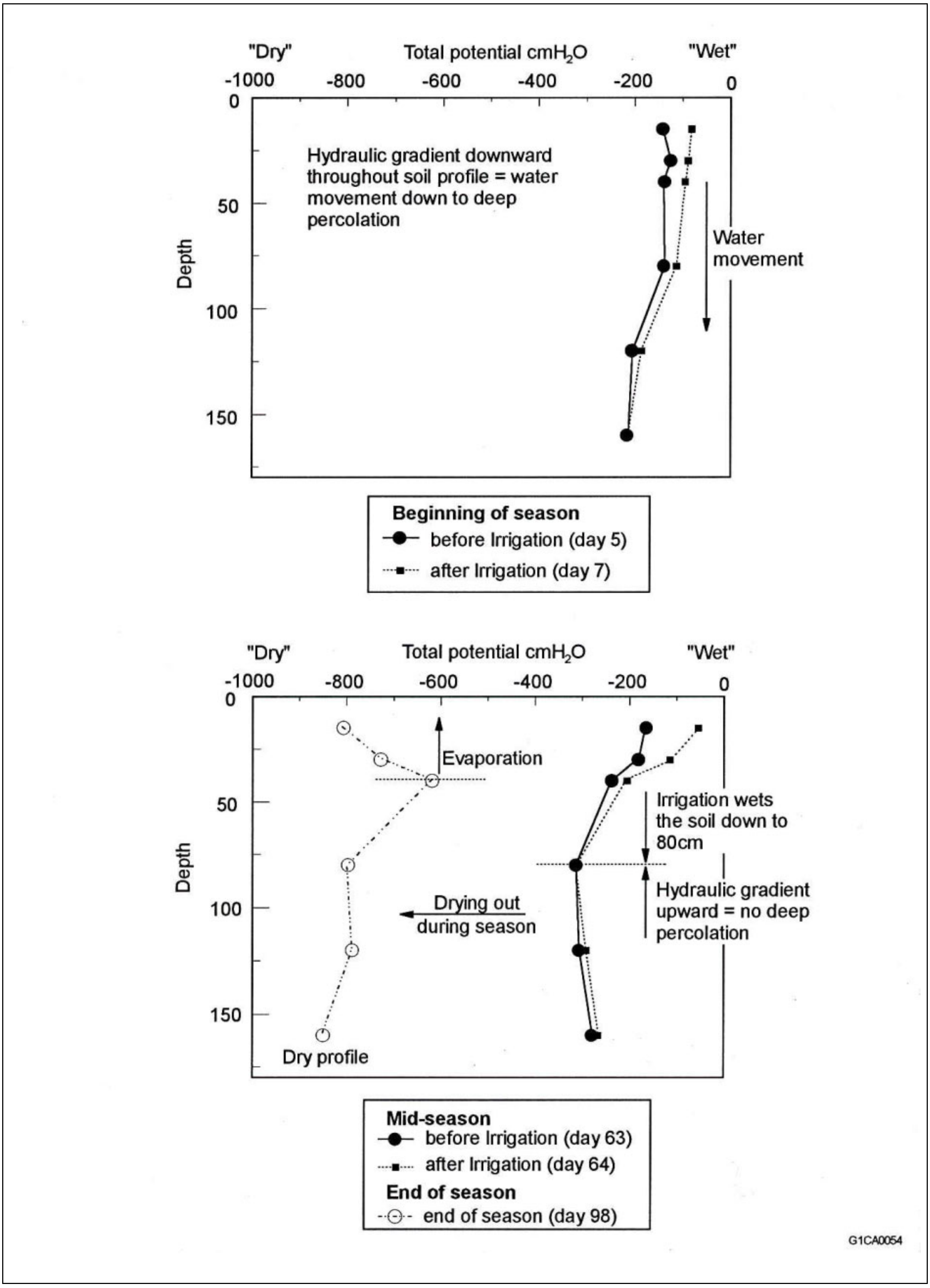

Figure 14 Typical hydraulic gradients in the soil profile during the summer crop season

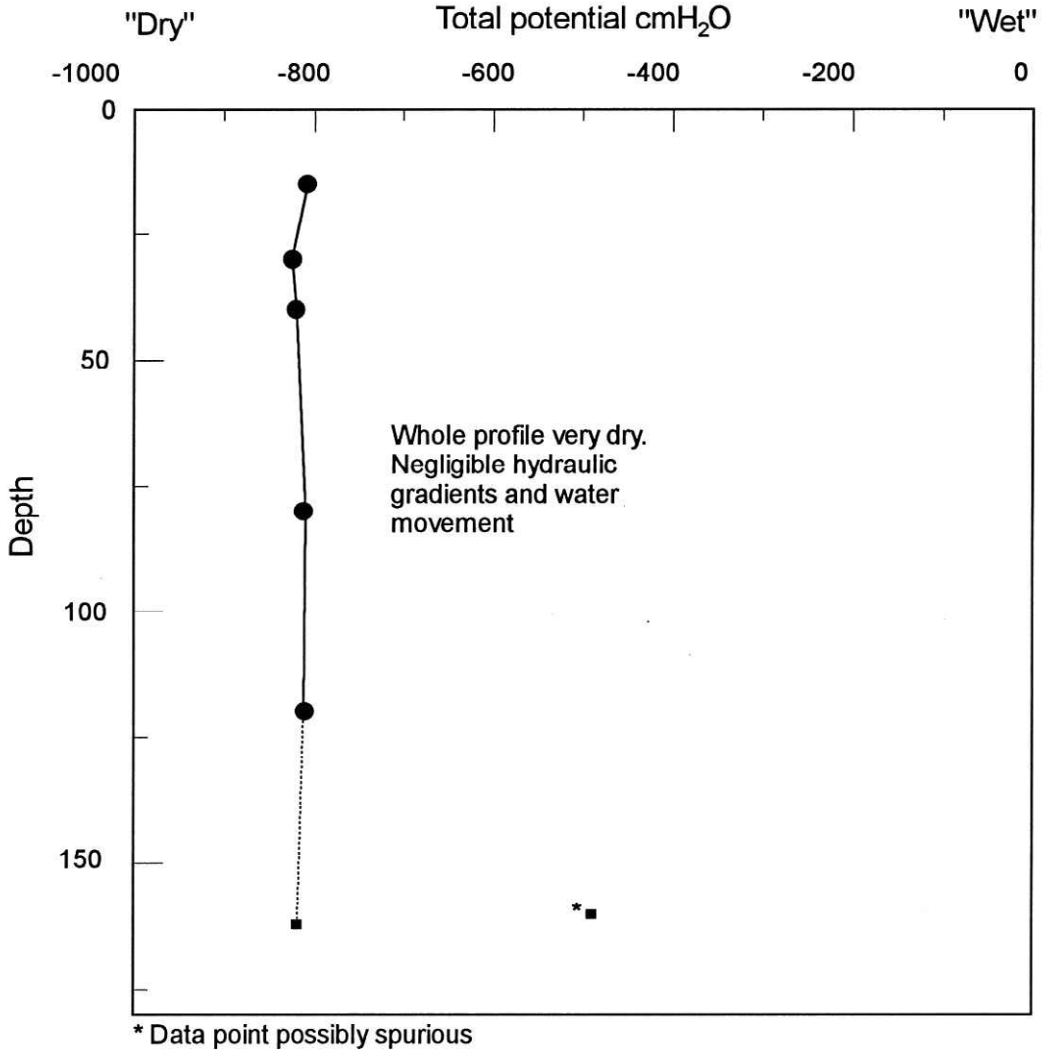

Figure 15 Typical hydraulic gradient in the soil profile during the fallow period

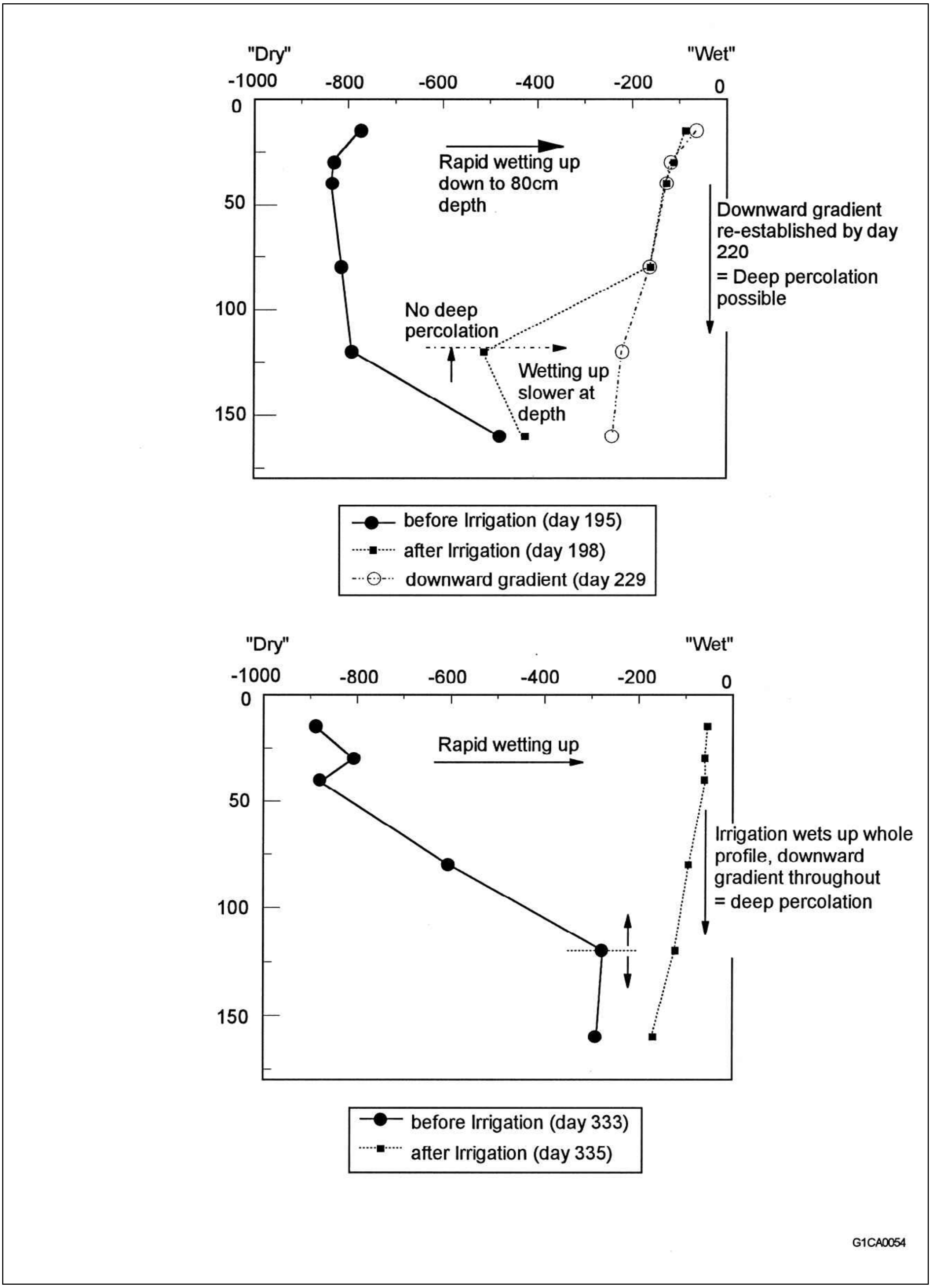

Figure 16 Typical hydraulic gradients in the soil profile during the winter crop season

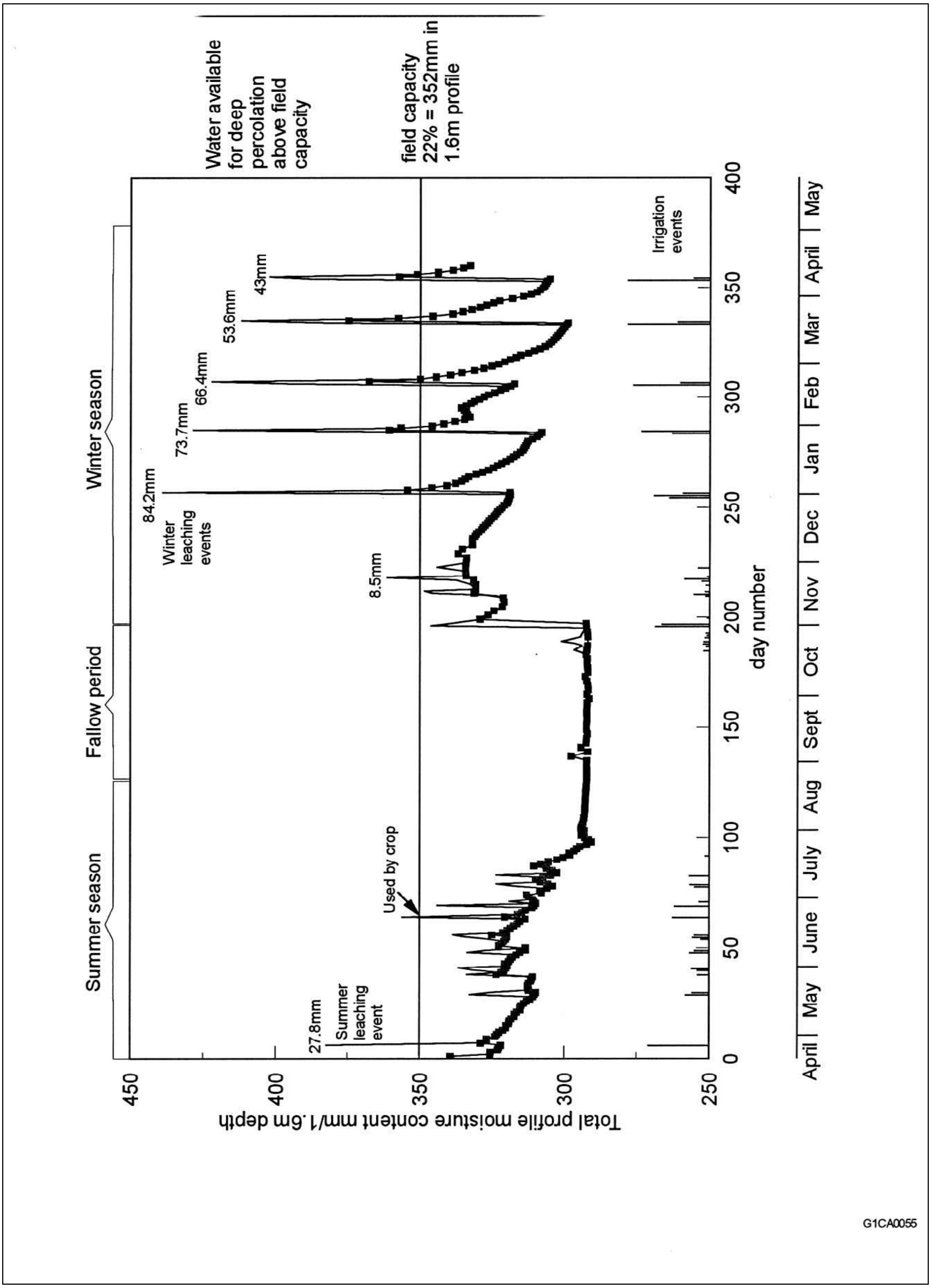

Figure 17 Total profile soil moisture contents showing leaching events

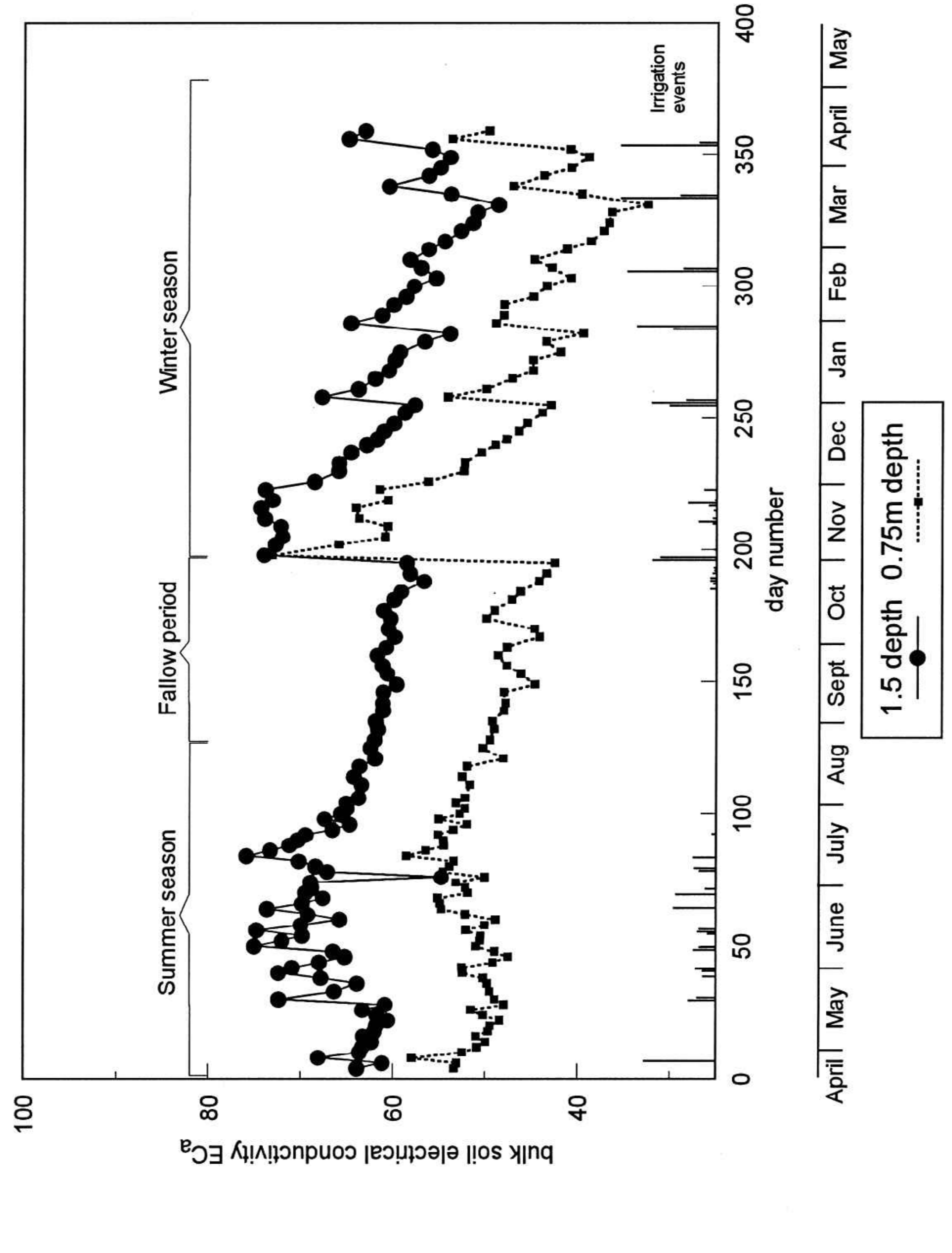

Figure 18 Bulk soil salinity measurements (EM38)

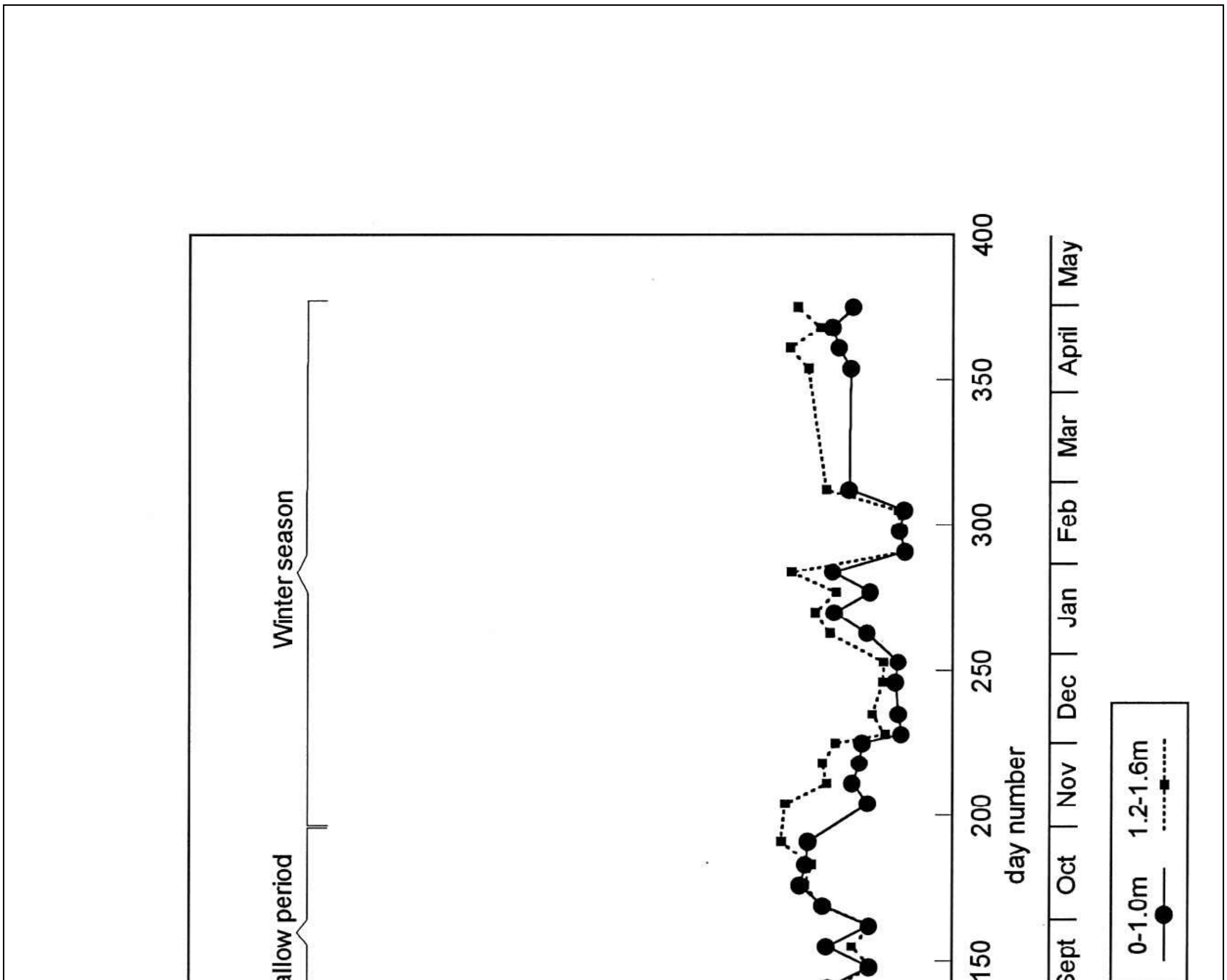

Figure 19 Soil salinity levels (saturated extract) for the upper and lower soil profiles

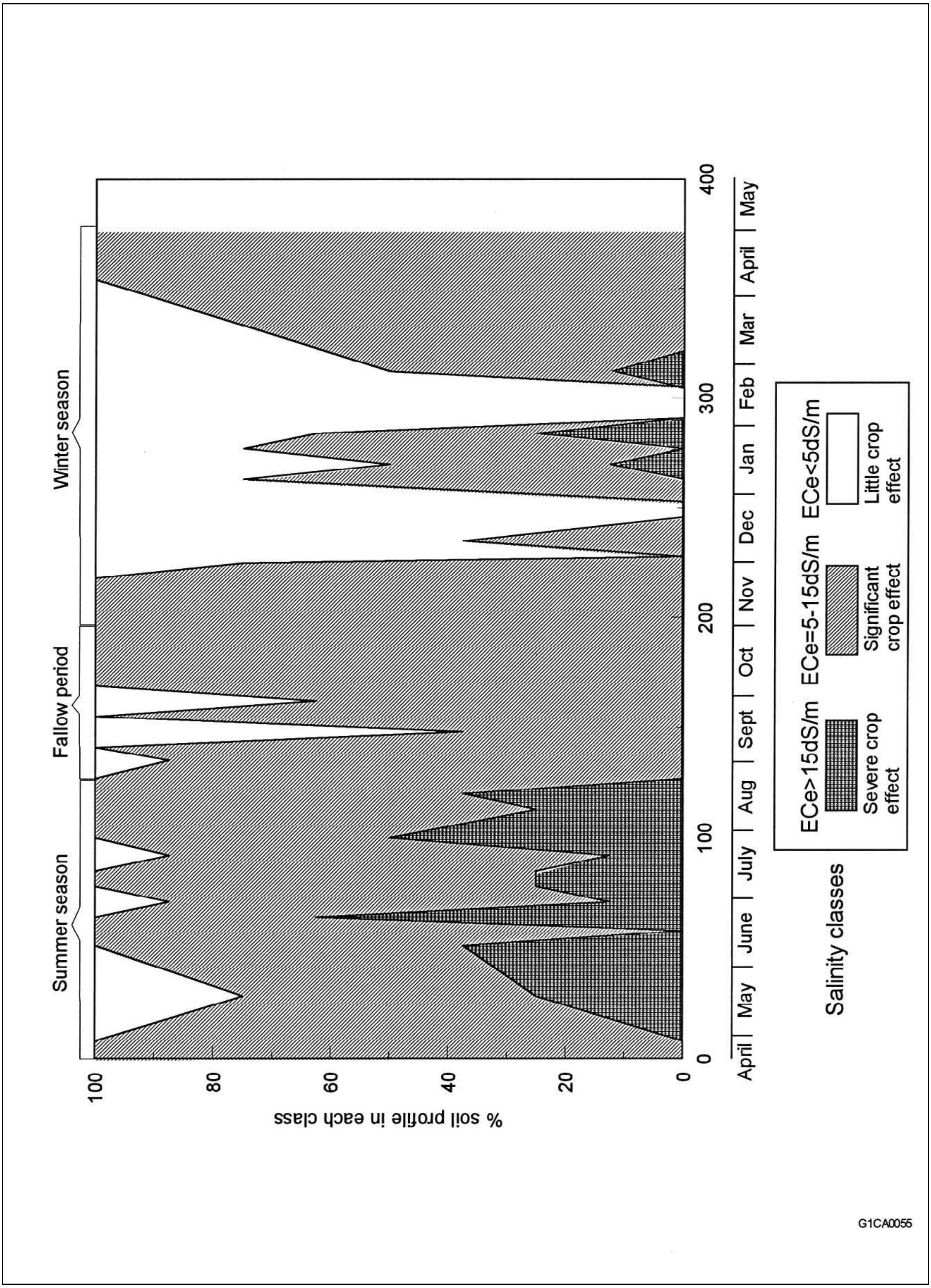

Figure 20 Soil salinity levels in terms of likely crop effects

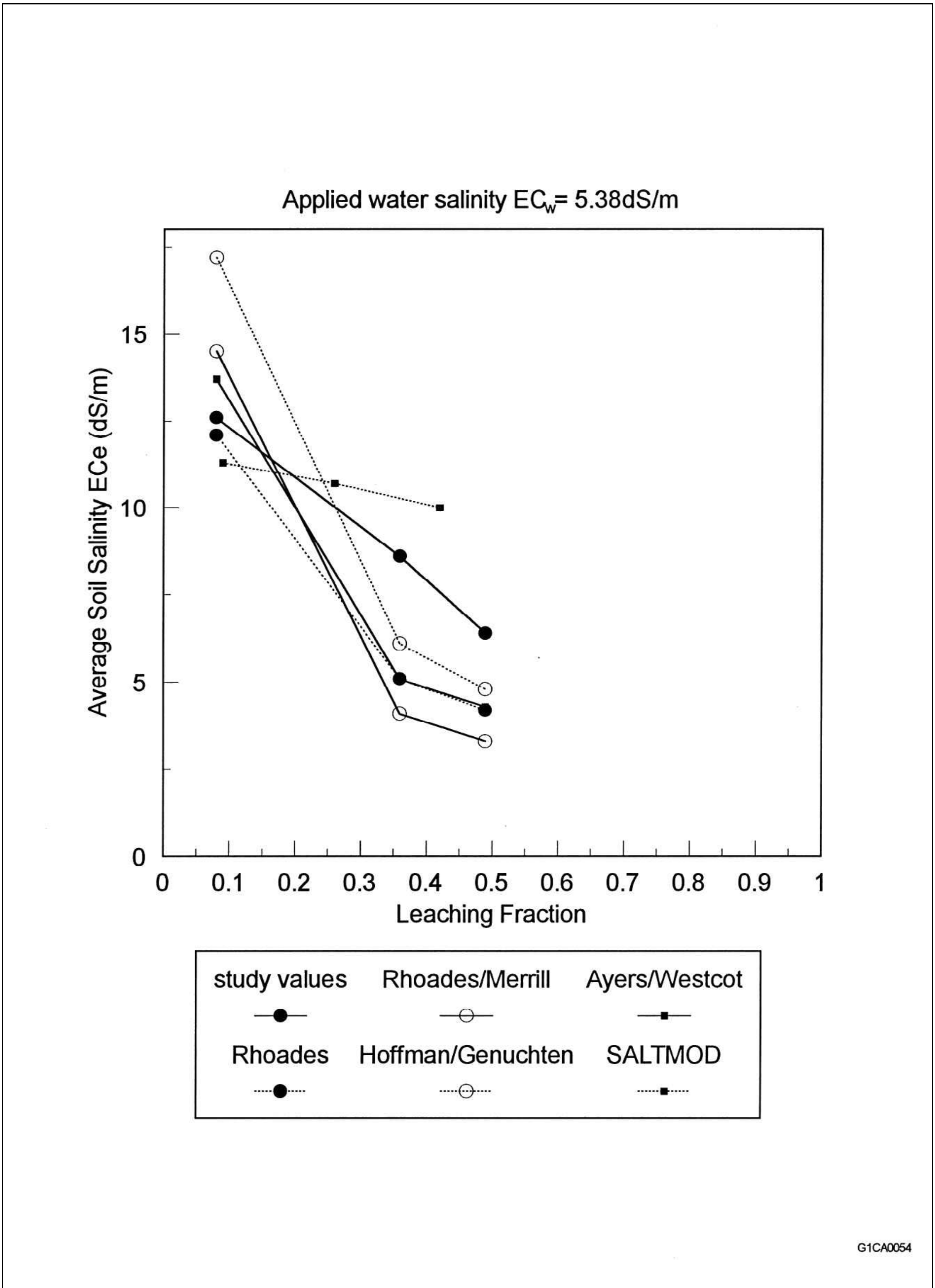

Figure 21 Application of predictive methods for steady-state soil salinity levels to study findings.

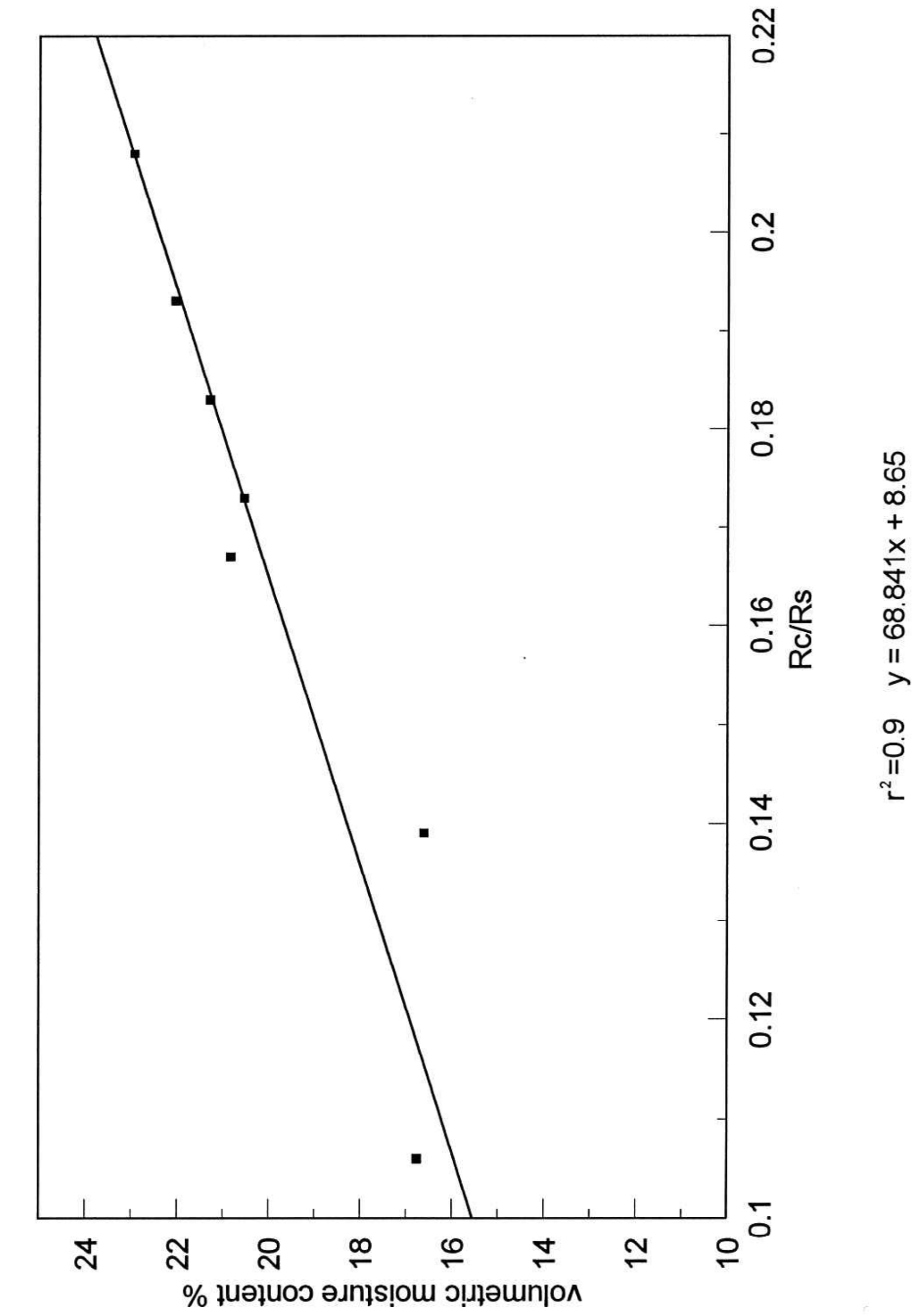

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Figure 22   Neutron probe calibration