DRAINAGE FOR SALINITY CONTROL
IN KIMORIGO / KAMLEZA IRRIGATION SCHEMES

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A thesis submitted to the University of Nairobi in partial fulfilment of the requirement for the degree of Master of Science in Agricultural Engineering.

September, 1990.
DECLARATION

I, hereby, declare that this thesis is my original work and it has not been presented for a degree in any other university.

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Date  
27.9.90

DR. F. N. GICHUKI  

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<tr>
<td>CEC</td>
<td>Cation exchange capacity</td>
</tr>
<tr>
<td>Dc</td>
<td>Critical watertable depth</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>ECE</td>
<td>Electrical conductivity of saturated soil extract</td>
</tr>
<tr>
<td>Eo</td>
<td>Evaporation</td>
</tr>
<tr>
<td>ET</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td>ETP</td>
<td>Potential evapotranspiration</td>
</tr>
<tr>
<td>ESP</td>
<td>Exchangeable sodium percentage</td>
</tr>
<tr>
<td>f</td>
<td>Leaching efficiency factor</td>
</tr>
<tr>
<td>G</td>
<td>Amount of groundwater rise by capillarity</td>
</tr>
<tr>
<td>I_i</td>
<td>Infiltrating irrigation water</td>
</tr>
<tr>
<td>I_{ss}</td>
<td>Total net groundwater flow</td>
</tr>
<tr>
<td>I_{ss}</td>
<td>Net lateral groundwater flow</td>
</tr>
<tr>
<td>h_n</td>
<td>Matric suction head</td>
</tr>
<tr>
<td>K_h</td>
<td>Capillary conductivity</td>
</tr>
<tr>
<td>K</td>
<td>Hydraulic conductivity</td>
</tr>
<tr>
<td>P</td>
<td>Percolation below crop rootzone</td>
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<tr>
<td>Q_{do}</td>
<td>Discharge from groundwater table downwards through a semi-permeable membrane</td>
</tr>
<tr>
<td>Q_{up}</td>
<td>Recharge to groundwater table from an aquifer through a semi-permeable membrane</td>
</tr>
<tr>
<td>Q_{dr}</td>
<td>Discharge from groundwater table to open water surfaces</td>
</tr>
<tr>
<td>Q_{inf}</td>
<td>Recharge into groundwater table from open water surfaces</td>
</tr>
<tr>
<td>Q_{lsi}</td>
<td>Lateral groundwater inflow</td>
</tr>
<tr>
<td>Q_{lso}</td>
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R Precipitation
Cap Rate of capillary rise
V Rate of capillary rise
\mu Drainable pore space
Z Height of capillary rise above groundwater table
Z_c Critical height of capillary rise above groundwater table
\Delta h Change in groundwater table height
\Delta S Change in salt content of the soil
\Delta S_{am} Change in soil moisture content
\Delta S_{grw} Change in groundwater storage

I am also greatly indebted to the Netherlands Development Assistance, through the Ministry of Agriculture, for sponsoring my project. I also wish to personally thank Dr. [Name], for the encouragement he gave me during the course of the study.

My sincere appreciation to the staff of the Soil Science Laboratory, University of Nairobi, for their support and guidance. I also wish to acknowledge the following: Messrs. [Names], for carrying out the topographical survey; Mr. [Name] of Taveta for his advice in charge of field staff during data collection; Mr. [Name] and Betty for the typing of this report and Mr. [Name] for the technical drawings.

Finally, I would like to acknowledge my wife Mary for her continued support and encouragement, and my children Evonne, Sam and George for their patience in putting up with my preoccupation and absences from home for long periods.
ACKNOWLEDGEMENT

First and foremost, I am most grateful to Mr. K. J. Lenselink and Dr. F. N. Gichuki of the Dept. of Agricultural Engineering, University of Nairobi, for their supervision and advice during the field study and writing of this report.

I am also greatly indebted to the Netherlands Government, through the Small Scale Irrigation Development Project (SSIDP), Ministry of Agriculture, for sponsoring my MSc. course and project. I also wish to personally thank Dr. Scheltema, Co-ordinator of SSIDP, for the encouragement he gave me during the course of the study.

My sincere appreciation to the staff of the Soil Physics and Chemistry Laboratory, University of Nairobi, Kabete Campus and of the Mines and Geology Department, Ministry of Environment and Natural Resources (Nairobi), for assisting in the soil and groundwater analysis.

I also wish to acknowledge the following: Mesars. Olale, Kones, and Mwarenga of Provincial Irrigation Unit, Coast, for carrying out the topo-survey; Mr. Opiyo of Taveta who was in charge of field staff during data collection; Margaret and Betty for the typing of this report and Mr. Odongo for the technical drawings.

Finally I would like to acknowledge my wife Mary and children Evonne, Sammy and George for their patience in tolerating my preoccupation and absence from home for long periods.
ABSTRACT

This thesis provides detailed information on the drainage and soil salinity status of the Kimorogo/Kamlezu irrigation schemes and adjacent areas. In order to provide information on the areas' drainage, a groundwater survey was carried out over an area of approximately 2400 ha. Investigations on the groundwater conditions consisted of watertable depth measurements and groundwater quality analysis over a period of 10 months from October, 1988 to July, 1989. Soil samples were collected from the field and analysed for salinity and sodicity levels and also soil texture. The underlying calcareous layer was investigated with respect to depth of occurrence below the surface, its slope and form so as to determine its influence on surface and subsurface drainage of the area. Hydraulic conductivity measurements, using the augerhole method, were carried out in several locations to help in obtaining field drain spacings in areas or parts which may require subsurface drainage.

A topographical survey of the area was carried out so as to determine the surface and subsurface drainage conditions with respect to ground slopes and outlet conditions. In addition, the topo-investigations were to provide a base map covering the two irrigation schemes and adjacent areas and finally to obtain ground elevations from which groundwater and the calcareous layer levels could be determined.

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A groundwater balance assessment was carried out for four areas within the two schemes using the indirect method to determine in quantitative terms the possible causes of the subsurface drainage problem in the schemes.

From the results obtained, surface drainage problems in the area can be attributed to flood flow and excess precipitation during the rainy season. Overflow from canals and excess irrigation also at times result in surface drainage problems. Subsurface drainage problems are mainly caused by deep percolation from flood flow, excess precipitation and irrigation and seepage inflow from higher to lower areas. The groundwater balance assessment shows that the net subsurface inflow from irrigated to lower irrigated or non-irrigated areas may be as high as the evapotranspiration rate or higher.

Capillary rise from the shallow and salty groundwater results in substantial salt transport to the surface, and hence high soil salinity conditions. Salinisation is most pronounced in non-irrigated or fallow land with high groundwater tables maintained by seepage inflow.

Remedial measures to improve the drainage and salinity status of the schemes include flood control, provision of surface and subsurface drainage facilities and improved water management.
1. INTRODUCTION

1.1 The problem

The problem affecting Kimorogo and Kamleza Schemes (see Fig.1.1), is one of land deterioration under irrigation due to rising salinity and sodicity of the soils. Under the salty soil condition, low crop production has resulted. Severely salt affected parts have been abandoned by farmers.

Past reports on the area by Asol (1984), Berger and Kalders (1983), De Ridder (1974), Farrant (1966), Kanake (1982), Underhill (1955) and Van Alphen et al. (1979), indicate that the development of salty soil conditions is due to poor or inadequate drainage, especially after the introduction of irrigated agriculture, and this has promoted capillary salinisation, more so as groundwaters in the area are salty (Kanake, 1982; Van Alphen et al., 1979).

1.2. Project justification

The project is justified as no studies have been done on the groundwater conditions to enable quantification of the possible causes of the drainage problem mentioned above. It is only when the causes are known and quantitatively characterized that the appropriate remedial measures can be recommended, as supported by De Ridder (1974) and Van Alphen et al. (1979).

The improvement of the drainage conditions in the schemes and adjacent area is important for the sustainability of the irrigation schemes. It is through drainage that excess salts are evacuated out of the soil and
Fig. 1.1: Locational map of the project area.
so long as leaching is sufficient, re-salinisation of the soils through upward salt movement by capillary action is controlled. According to Farrant (1966), the schemes have an importance in the district and need to be sustained in view of:

(a) value of existing installations;
(b) hardship to plot holders, if no irrigation;
(c) loss of local food production leading to district supply difficulties;
(d) loss of a source of local irrigation craft;
(c) loss of a centre about which development could take place; and
(f) loss of an alternative to sisal, which is predominantly grown in the area, should the price fall and hence become uneconomical (which has happened in the past).

A study of the drainage condition is therefore justified to enable determination of appropriate remedial measures.

1.3 The project objectives

The objectives of the study were set as follows:

(1) To document the current drainage problems in the schemes;
(2) To document the current salinity problems in the schemes;
(3) To quantitatively determine the cause(s) of the drainage and salinity problems within the schemes through groundwater and salt balance assessments; and
(4) To recommend appropriate remedial measures for solving the drainage and salinity problems.
2. LITERATURE REVIEW

2.1 Background information

(a) Location

The Kimorigo - Kamleza area is located in Taveta Division of Taita-Taveta District, Coast Province (see Fig. 1.1).

The Njoro Kubwa canal and the Taveta Sisal Estate form the northern and western boundary of the area. To the east, the Lumi river forms the border, and to the south, the area borders the Jipo and Ruvu swamps as shown in Fig.1.1.

(b) Climate and vegetation

The area belongs to the sub-tropical, semi-arid climate with an average annual rainfall of 600 mm and this is distributed mainly between two seasons. The long rains occur from March to May and the short rains from November to December. The highest monthly mean precipitation occurs in April and the lowest in July and August. Table 1.1 below shows the average monthly rainfall figures for Taveta D.O. Station No. 93.37/00 for a period of 43 years (1905 - 1914 and 1920 - 1971) as obtained from Berger & Kalders (1983).

The temperature ranges from a mean monthly minimum of 13°C to a mean monthly maximum of 33°C, with an annual mean temperature of 22°C.

The potential evaporation averages 1930 mm annually. In Table 2.1 the average evaporation figures are for Taveta Water Development, Station No.93.37/110 for a period of 17 years (1964-1981) as obtained from Berger & Kalders (1983a).
Table 2.1. Monthly average rainfall data (Taveta D.O Station) and potential evapotranspiration (Taveta Water Development).

<table>
<thead>
<tr>
<th>Month</th>
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<th>F</th>
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<th>J</th>
<th>A</th>
<th>S</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Rainfall (mm)</td>
<td>39</td>
<td>46</td>
<td>106</td>
<td>139</td>
<td>65</td>
<td>9</td>
<td>7</td>
<td>6</td>
<td>7</td>
<td>27</td>
<td>91</td>
<td>54</td>
<td>595</td>
</tr>
<tr>
<td>Eo (mm)</td>
<td>175</td>
<td>175</td>
<td>175</td>
<td>150</td>
<td>140</td>
<td>135</td>
<td>135</td>
<td>145</td>
<td>165</td>
<td>185</td>
<td>175</td>
<td>175</td>
<td>1930</td>
</tr>
</tbody>
</table>


From the above table it can be seen that the evaporation exceeds the mean monthly rainfall for all months except in April when there is a small surplus.

The vegetation in the area is not wholly indicative of what is expected for Agro-ecological zone V, that is, bushland. This is because the soil conditions have been altered by the existing high groundwater tables and irrigation schemes. Along the Lumi River, there exists a Riverine forest. Between the river and Kimorogo Scheme (Block C area) the vegetation is mainly woody acacias and salt-tolerant bushes, interspersed by short grasses which are also salt-tolerant. On the swampy edges water loving plants occur in abundance. In areas with high saline water-table, Doum palm and wild date palm are found. The drier areas around the hills are predominantly vegetated by drought-resistant acacias.

(c) Geology and physiography

The soils of the area are primarily developed on calcareous tuffaceous grits which are of Pleistocene to Recent Age (Bear, 1955; Kanake, 1982). Part of the area
however, falls in the floodplain of the Lumi river, which consists of Recent Alluvial silts and clays.

Physiographically, the area may be considered as part of the piedmont plain which forms the gap between the Pare Mountains, composed of Basement Systems Rocks, and the Mt. Kilimanjaro Volcanic pile. Two hills, Eldoro and Kitogoto, rise above the general level of the plain. The area is devoid of any marked natural drainage pattern, but it slopes gently (0-2% slope) to the marshes surrounding Lake Jipe.

(d) Hydrology and water resources

(i) Surface water

The main surface water source in the area is Lumi river from which Kimorogo scheme derives its water for irrigation.

The discharge of the Lumi river before the Kimorogo/Kamleza area averages 0.6 m³/s and it runs in a deeply eroded bed of approximate depth of 3.5 m. Just before it enters the Kimorogo - Kamleza area, more water is added from the Njoro Kubwa group of springs (total discharge = 6 m³/s) and this increases the discharge to an annual average of 6.6 m³/s (about 7 m³/s). The river in this section now flows full and its water level is often higher than the surrounding land. Consequently, the adjacent lands exhibit high groundwater tables and are often flooded during high flows. Flood discharge has been estimated to be as high as 250 m³/s (Underhill, 1955).

The quality of the river water is fairly good and would cause very low or no potential soil hazards. A chemical analysis report of the water is shown in Table 2.2.
Table 2.2: Report on chemical analysis of water sample
(Lumi River, 1982)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (μS/cm)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical conductivity (EC. at 25°C)</td>
<td>660</td>
<td></td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>239 mg/l</td>
<td></td>
</tr>
<tr>
<td>Carbonate</td>
<td>36 &quot;</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>70 &quot;</td>
<td></td>
</tr>
<tr>
<td>Sulphate</td>
<td>11 &quot;</td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>64 &quot;</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td>6 &quot;</td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td>47 &quot;</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>24 &quot;</td>
<td></td>
</tr>
</tbody>
</table>

Source: (Kanake, 1982)

(ii) Groundwater

The groundwater level in the area varies between 10 cm below the soil surface in the southern swamps to about 1.5 - 2.0 m below the surface in the northern sectors (dry season) - (Kanake, 1982).

The quality of the groundwater in the area is not good. Chemical samples taken in the past from various locations show that the water has a high degree of salinity and sodicity. It also has a high content of bicarbonates and other toxic elements (Kanake, 1982). Table 2.3 indicates that the EC varies between 950 μS/cm and 16,000 μS/cm (640 mg/l - 10,240 mg/l).
Table 2.3. Chemical analysis results of groundwater sample

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Groundwater (1)</th>
<th>Sample no. (2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>8.2</td>
<td>9.0</td>
<td>9.0</td>
<td>8.8</td>
</tr>
<tr>
<td>EC (µS/cm)</td>
<td>1400</td>
<td>16000</td>
<td>5500</td>
<td>950</td>
</tr>
<tr>
<td>Sodium (me/l)</td>
<td>6.3</td>
<td>156.0</td>
<td>50.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Potassium (me/l)</td>
<td>0.1</td>
<td>0.14</td>
<td>0.15</td>
<td>0.35</td>
</tr>
<tr>
<td>Calcium (me/l)</td>
<td>2.8</td>
<td>2.7</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Magnesium me/l</td>
<td>5.2</td>
<td>0.9</td>
<td>0.06</td>
<td>1.8</td>
</tr>
<tr>
<td>Carbonates (me/l)</td>
<td>0.4</td>
<td>27.0</td>
<td>10.0</td>
<td>0.4</td>
</tr>
<tr>
<td>bicarbonates (me/l)</td>
<td>9.2</td>
<td>52.0</td>
<td>40.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Chlorides (me/l)</td>
<td>4.1</td>
<td>77.0</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Sulphate (me/l)</td>
<td>0.35</td>
<td>4.7</td>
<td>0.05</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Source: (Kanake, 1982)

2.2: Soil salinity in project area

2.2.1: Origin of salty soils in the project area

Salty soils in the area were first noted to occur in areas with high groundwater tables near the Lumi River, according to reports by Farrant (1966). Where high groundwater tables occur, soil salinisation is common as upward capillary flow is able to reach the rootzone, bringing with it salts which are deposited on the surface as water is lost through evapotranspiration. It is therefore possible that capillary salinisation, promoted by the high evaporative conditions in the project area, caused the salty soil conditions in the high groundwater table areas close to the river.
After the introduction of irrigation in the Block C area in the early 1940’s (see Fig.1.1), many areas developed high groundwater tables, a condition which enhanced capillary salinisation. By the early 1950’s, severe saline and sodic soil conditions had developed leading to the abandonment of the Block C irrigation scheme.

Irrigation continued in the adjacent areas of Block C, but as noted by Underhill (1955), excess irrigation, in the absence of adequate drainage, caused groundwater tables to rise. At the time of the investigations (in 1954), groundwater was at a depth of about 1.0 m from the surface. Salinity and sodicity problems soon developed in these areas, which are no longer cultivated.

Investigations by Asol (1984) and Kanake (1982), revealed the occurrence of maximum salt concentration at the surface, in parts of the schemes, this being an indication of capillary salinisation (Ayers & Westcot, 1985; FitzPatrick, 1987; Smedema and Rycroft, 1983).

As no improvements have been made on the drainage conditions in the schemes to date, re-salinisation from the shallow and salty groundwaters continues to be a threat to areas presently under cultivation. Kimorigo Scheme, whose upper areas have already been abandoned, appears to be threatened most as a report by Asol (1984) indicates that both leaching and drainage are inadequate.

2.2.2 Past reclamation and control measures

A few attempts to improve the drainage conditions in the schemes, have been undertaken in the past. The first attempt was the plan to install a 2.0 m deep main drain for
Kimorigo scheme. This was, however, not possible as the occurrence of hard calcareous layer beneath the topsoil limited the drainage depth to only 1.0 m (Farrant, 1966). Field drains necessary for the control of salinity have never been installed.

The second attempt was a proposed pilot project by Berger and Kalders (1983), aimed at comparing the suitability of various field drainage methods, but as of now the project has never taken off. In the design of the field drainage system, the authors did not consider the influence of possible subsurface inflow which, according to De Ridder (1974), may be substantial and therefore needs to be investigated.

2.2.3 Soil salinity condition

Soil salinity/sodicity conditions in the area have been classified by Kanuke (1982), according to the US Salinity Laboratory Classification System. The classification of salty soils according to this system is as shown in Tab. 2.4.

Table 2.4: The US Salinity Laboratory System for Classification of Salty Soils (USDA, 1974).

<table>
<thead>
<tr>
<th>ECe &lt; 4 mS/cm at 25°C</th>
<th>ECe &gt; 4 mS/cm at 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESP &lt; 15% non-saline soil</td>
<td>saline soils</td>
</tr>
<tr>
<td>non-sodic</td>
<td>saline soils</td>
</tr>
<tr>
<td>ESP &gt; 15% sodic soil</td>
<td>sodic soil</td>
</tr>
</tbody>
</table>

For EC measurements carried out in the field at a soil to water ratio of 1:2.5, the classification as given in Table 2.5 below holds. These values are a third of the ECe-values.

Table 2.5: Classification of field measurements of electrical conductivity (EC$_{2.5}$).

<table>
<thead>
<tr>
<th>EC$_{2.5}$ (mS/cm)</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1.3</td>
<td>non-saline</td>
</tr>
<tr>
<td>1.3 - 2.7</td>
<td>slightly saline</td>
</tr>
<tr>
<td>2.7 - 5.3</td>
<td>moderately saline</td>
</tr>
<tr>
<td>&gt; 5.3</td>
<td>strongly saline</td>
</tr>
</tbody>
</table>


From the results of the soil survey investigations, Kanake (1982) prepared a soil salinity map according to the above classification. A simplified soils map consisting of the major soil salinity boundaries is shown in Fig.2.1.

Out of the total surveyed area of 2165 ha, 530 ha consisted of non-saline, non-sodic soils; 1394 ha consisted of saline-sodic soils and 138 ha of sodic soils. From the map in Fig.2.1, non-salty soils occur in many parts of Kamleza scheme and the central to lower parts of Kimorigo scheme. The whole of Block C area, the Northern parts of Kimorigo scheme and the Ngutini area consist mainly of saline and/or sodic soils. For the saline and/or sodic soils, the ESP-value in some places is as high as 90%, while the EC-values vary between 1.5 and 10 mS/cm.
Fig. 2.1: Soils map of the Kimorigo/Kamleza area (Kanake, 1982).
2.2.4 Indications of salinity conditions in the field

Kanake (1982), mentioned the existence of salty vegetation in the salt affected parts of the project area. An earlier report by Farrant (1986) mentions the occurrence of salt pans in the areas to the north of the schemes. Field identification of salty soils in the area will form part of the investigations and therefore the various field identification methods are reviewed below.

(a) Identification of saline soils in the field

Saline soils may be identified through some or all of the following ways;

- dark grey to greyish brown colours often with mottling, the greatest being in the middle of the soil (FitzPatrick, 1987 and Young, 1976).

- white salt crusts on exposed surfaces (Smedema & Rycroft, 1983 and Young, 1976).

- damp, oily looking soil surface (due to hygroscopy of salts such as CaCl₂ (Elgabaly, 1971) and Smedema & Rycroft, 1983).

- loose fluffy soil surface caused by the growth of long needle-like crystals of sodium sulphate (Young, 1976).

- (pseudo)-mycelia in the soil profile (Smedema & Rycroft, 1983).
(b) Identification of sodic soils in the field

For sodic soils, identification may be through:

- small dark (irregular) patches, referred to as slick spots (Young, 1976 and Smedema & Rycroft, 1983).
- columnar soil structure with rounded tops in the subsoil (Young, 1976).

- the existence of a thin sandy A-horizon from which all clay has been eluviated (Young, 1976).

Saline-sodic soils normally show properties of both saline and sodic soils.

2.2.5. Salinisation due to irrigation

Salts are added to the soil with each and every irrigation application. The amount of salts added by each irrigation is the product of flow rate x salt concentration x duration. Under conditions of inadequate leaching and drainage, salinisation from irrigation will result.

The existence of salty soils in the Taveta schemes indicates that the prevailing conditions favour the accumulation of salts in the soils. According to Smedema & Rycroft (1983), secondary salinisation by irrigation is likely to occur under conditions where the salt influx to the rootzone is high and/or the salt efflux from the rootzone is low.

High salt influx conditions prevail when:

(i) the climate is hot and dry necessitating high irrigation water supplies (and thus large quantities of salts are added).

(ii) saline water is used.
Low salt efflux conditions prevail when:

(i) insufficient water is used for irrigation leaving no excess for leaching requirements (under-irrigation);
(ii) the climate is hot and dry (low rainfall/high evaporation), so little excess rain goes into deep percolation for leaching;
(iii) drainage conditions are poor, allowing insufficient percolation and drainage discharge.

The quality of irrigation water used in the schemes is satisfactory and according to results obtained by Asol (1984), the electrical conductivity (EC) is approximately 0.25 mS/cm. However, even with good quality water, salinisation is bound to occur if the salts are not leached and evacuated out of the soil by drainage.

Reports by Farrant (1966) and Underhill (1955), mention that excessive irrigation is prevalent in the area. However, there is no supportive data. During the investigations, an indication will be given on the irrigation efficiency.

Excessive irrigation, under the poor drainage conditions, is likely to cause groundwater table rise and thus enhance capillary salinisation.

2.2.6 Salinisation from groundwater

Salinisation from groundwater (capillary salinisation) occurs when salts brought to the upper soil layers by upward capillary flow of groundwater are left behind as water is lost by evapotranspiration.

The extent of capillary salinisation and the depth at which salts accumulate are governed by the rate of
capillary rise and the groundwater salinity counteracted by the leaching intensity (by rain or irrigation water). For capillary salinisation to take place, a net upward movement of water (and salts) is a must. This often results in a maximum salt concentration at the surface followed by a sharp drop down the profile as shown in Fig. 2.2.

![Typical salinity profile for a soil under capillary salinisation (Ayers and Westcot, 1985).](image)
2.2.6.1 Rate of capillary rise and critical watertable depth

The amount of salts transported to the surface is the product of rate of capillary rise x salt concentration x duration of capillary rise. High rates of capillary rise lead to considerable salinisation. It has been shown that while the upward capillary flow can reach to great heights, the rate of flow generally decreases with increasing height above the watertable. Consequently, the rate of upward salt movements, being proportional to the rate of upward flow, also decreases as the distance between the evaporation zone (= upper soil layers = rootzone) and the watertable increases (Smedema & Rycroft, 1983 and Van Schilfgaarde, 1976).

The rate of capillary rise is therefore influenced by the depth of groundwater and in addition the potential gradient between groundwater and soil surface, and the capillary conductivity of the soil in relation to the soil moisture content (Verhoeven, 1979).

An expression relating the upward flux, \( V \), with the groundwater depth, potential gradient and the capillary conductivity has been presented by Groenovelt and Kijnc (1979) and Van Schilfgaarde (1976).

Starting with the steady state flow equation (unsaturated flow), the upward flux, \( V \), can be written in terms of matric and gravity potential gradient, both expressed on a weight basis, in the form:

\[
V = k_h \left( \frac{dh_m}{dz} - 1 \right) \quad \text{.................. (1)}
\]
Where \( k_h \) = capillary conductivity; \( h_m \) = suction head and \( z \) = height of capillary above the water table.

The above equation can be solved through integration and solving the resultant integral for known values of the capillary conductivity, \( k_h \). A graphical solution for a course textured soil is shown in Fig.2.3 which indicates the rate of capillary rise, \( V \), at different groundwater table depths and soil matric suctions.

![Graph showing potential profiles](image)

**Fig.2.3:** Potential profiles calculated for a coarse textured soil under influence of capillary rise. (adopted from Groenevelt & Kijne, 1979).
In Fig. 2.4, the variation in the rate of capillary rise with watertable depth for different soil textures has also been presented.

The rate of capillary rise corresponding to the soil capillary height, Zc, can be given varied values different researchers. According to field studies by Talsma (1963), an upward flux not exceeding 1 mm/day was found to be acceptable. According to Watts (1979), with a soil moisture buffer, the critical depth, below which the rate of capillary rise is more than 0.5 mm/day, a similar figure is given by Konya's report (Soils manual, 1984).

Values for critical capillary height, Zc, can be calculated after establishing the rate upward flux, V, and the soil capillary conductivity and the existing soil gradients. Smedema and Rycroft (1983) have given indicative values of Zc, although they do not state the upward flux, V, used. The values are indicative and do not apply to stratified soils where the high will generally be lower, and the low values may well have relatively high unsaturated capillary rise.

Fig. 2.4: Rates of capillary rise to the soil surface from stationary watertables at different depths when the soil moisture pressure at the soil surface is -16 bar (adopted from Smedema and Rycroft, 1983).

The two figures illustrate that as the groundwater table falls, so does the rate of capillary rise. The height above the watertable at which the rate of capillary rise becomes too small for any significant upward salt movement...
is called the critical capillary height, Zc, and the groundwater depth when this occurs is called the critical watertable depth, Dc.

The rate of capillary rise corresponding to the critical capillary height, Zc, has been given varied values by different researchers.

According to field studies by Talsma (1963), as reported by Van Schilfgaarde (1976), an upward flux not exceeding 1 mm/day was found acceptable. According to Kessler (1979), with saline groundwater, the critical depth, should be the depth at which the rate of capillary rise is less than 0.5 mm/day. A similar figure is given by Kenya's Ministry of Agriculture report (Soils manual, 1984).

Values for critical capillary height, Zc, can be calculated after assuming an appropriate upward flux, V, and knowing the soil's capillary conductivity and the existing potential gradient. Smedema and Rycroft (1983) have presented general indicative values of Zc, although they do not mention the upward flux, V, used. The values are in Table 2.6. These values are only true for uniform soil profiles and do not apply to stratified soils where the high values will generally be lower, and the low values may well be increased (Smedema and Rycroft, 1983).

As can be seen from Table 2.6, coarse textured soils have lower values of critical capillary height, Zc, than medium textured soils such as silt loam. Medium textured soils have relatively high unsaturated capillary conductivity, and thus relatively high rates of capillary rise compared with coarse or heavy clay textured soils (Kessler, 1979; & Smedema and Rycroft, 1983). Consequently, higher values of critical capillary height, Zc, are
inevitable to reduce the relatively high rates of capillary rise to acceptable levels, such as 0.5 mm/day for areas with saline groundwater and medium textured soils as in the Kimorigo/Kamleza area (see Table 2.6).

Table 2.6: Critical heights of capillary rise, $Z_c$, according to Smedema & Rycroft (1983).

<table>
<thead>
<tr>
<th>Texture</th>
<th>Critical Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (coarse - fine)</td>
<td>$Z_c = 50 - 75$ cm</td>
</tr>
<tr>
<td>Loam sand, sandy loam</td>
<td>$Z_c = 100 - 150$ cm</td>
</tr>
<tr>
<td>Fine sandy loam, silt loam</td>
<td>$Z_c = 150 - 200$ cm</td>
</tr>
<tr>
<td>Loam, clay loam, clay</td>
<td>$Z_c = 100 - 150$ cm</td>
</tr>
</tbody>
</table>

2.2.6.2 Other factors influencing critical watertable depth

Apart from the influence of soil texture on the critical capillary height, $Z_c$, other influencing factors which also affect the value of the critical watertable depth, $D_c$, include:

(a) salinity of groundwater;
(b) evaporation rate of the surface (climate);
(c) vegetation;
(d) groundwater recharge; and
(e) leaching intensity.

(a) Salinity of groundwater

As already mentioned, the rate of salinisation at the surface is the product of flow rate and salt concentration. Therefore, values of critical capillary height, $Z_c$, should increase with increasing groundwater salinity.
According to Elgabaly (1971), if there exists fresh circulating groundwater, a depth of 50 cm can be tolerated by many field crops. With saline groundwater, in arid and semi-arid regions, the critical watertable depth is recommended to lie between 2.5 - 3.0 m below the surface (Elgabaly, 1971). According to this same author, the critical salt concentration should be between 1500 - 3000 ppm (EC = 2.3 - 4.7 mS/cm) and for sodic groundwater it should not exceed 750 ppm (1.2 mS/cm). Smedema and Rycroft (1983), also mention that very little salinisation will occur provided the salt concentration in the upper groundwater layer remains < 1000 mg/l (1.5 mS/cm).

(b) Evaporation rate

Evaporation of moisture from the upper soil layers creates an upward moisture gradient leading to upward capillary flow. In arid and semi-arid areas, the existing high evaporation rates lead to marked upward capillary flow and consequently extensive salinisation (FAO, 1971). The watertable depth in these areas should therefore be maintained below the critical depth, \( D_c \), especially if the groundwater is saline as mentioned under (a); above the mentioned critical salt levels.

In areas with low evaporation rates e.g. humid areas the watertable depths may be higher, more so as the groundwaters are often fresh.
(c) **Vegetation**

In bare soil water is lost only through evaporation and the evaporation zone is shallow (15 - 20 cm). In vegetated areas, water loss occurs through both evaporation and transpiration and over a much deeper zone, about equal in depth to the main rootzone from which water is taken up for transpiration (Smedema & Rycroft; 1983 and Van Schilfgaarde, 1976). The result is that in areas with vegetation (grass or shrubs) and no leaching (i.e. under fallow), more water is lost and consequently more extensive salinisation occurs. This was shown to be true by studies carried out by Balba (1976). However, with adequate irrigation and/or rainfall to cause leaching, salinisation in cropped areas is reduced.

The critical watertable depth with vegetation and no leaching of salts is thus higher than for bare soil (Smedema & Rycroft, 1983; Van Schilfgaarde, 1970). The actual value depends on the rooting depth and the other factors mentioned in this section.

According to Van Schilfgaarde (1976), a favourable situation can be achieved by maintaining a downward flux sufficient in magnitude to prevent the accumulation of salts.

(d) **Groundwater recharge**

With no groundwater recharge (or subsoil water supply), the groundwater table falls as more and more water is lost by upward capillary flow. The watertable depth may fall to or even beyond the critical watertable depth, Dc, at which point capillary salinisation becomes insignificant.

With groundwater recharge, water lost by upward capillary flow is replaced and the groundwater tables remain high. This leads to continued transport of salts to the
surface and to substantial salinisation if the watertables remain high for prolonged periods.

The groundwater depth in areas with groundwater recharge (and saline groundwater) should therefore be maintained below the critical watertable depth, Dc, by providing adequate drainage, or by eliminating the source of the subsoil water supply (Smedema & Rycroft, 1983).

(c) Leaching intensity

Leaching of salts normally occurs during irrigation or rainy season. During this period the upward movement of salts is much reduced, occurring only for limited periods, i.e. in between two irrigations.

The reduction of the salt content in the soil brought about by irrigation water or rain depends on the quantity and quality of water percolating through the soil, water conducting properties of the soil (e.g. hydraulic conductivity) and the moisture content of the soil (Verhoeven, 1979).

According to Van Schilfgaarde (1976), a favourable rootzone free of excess salts can be achieved by maintaining a net downward flux sufficient in magnitude to prevent excessive accumulation of salts in the soil solution. Even with a high watertable, upward flow will only occur when there is an upward gradient; an appropriate irrigation regime, in principle, can prevent such a gradient.
2.2.7. Effects of salinity and sodicity on crops and soils

Soil salinity and sodicity in various parts of the project area have resulted in low crop production, forcing farmers to abandon the salt-affected parts according to a report by Asol (1984).

The effects of salinity and sodicity on crops and soils can be categorised into three:
(a) Osmotic effects;
(b) Toxicity effects;
(c) Dispersion effects.

2.2.7.1. Osmotic effects

High total salt concentration of the soil solution results in high osmotic pressures, making it more difficult for plant roots to extract water from the soil. The amount of water absorbed from the soil depends on the soil moisture stress which is the sum of the soil moisture tension and osmotic pressure due to dissolved salts (Michael, 1983; Brady, 1984).

The magnitude of osmotic pressure is linearly related to the electrical conductivity of the soil solution (and hence salt concentration). Shainberg & Oster (1978) and Smedema & Hycroft (1983) give the following relationship:

\[ \text{Osmotic pressure (bars)} = 0.36 \times \text{EC, (mS/cm)} \]

At low salt concentration the osmotic pressure is insignificant and water absorption depends more on the soil moisture tension. Enough water for plant growth is absorbed when the soil moisture tension is below 1 bar (Michael,
In saline soils (ECe > 4 mS/cm), the osmotic pressure is over 1.4 bars, from the above relationship. If the soil moisture tension is 1 bar, then the total stress becomes 2.4 bars, causing a reduction in plant water uptake. In the project area high ECe-values of 25 mS/cm in the topsoil (0 - 30 cm) were obtained by Asol (1984). This would result in an osmotic pressure of at least 9 bars and a total stress of 10 bars and above. Far much less water than optimal would be extracted from the soil and plant growth would be very much more retarded; especially knowing that the permanent wilting point for many crops is at about 15 bars.

2.2.7.2. Crop tolerance to salinity

The term "salt tolerance" indicates the degree of salinity a plant can withstand without being appreciably affected in its growth and development. For each crop a certain threshold value exists beyond which crop yields decrease linearly with increasing salinity (Ayers & Westcot, 1985; FAO, 1985; Jensen, 1983; Oosterbaan, 1987; Shainberg & Oster, 1978). Crop tolerance tables exist indicating the ECe-values at yield potentials of 100%, 90%, 75%, 50% and 0%. A table of crop tolerance for selected crops grown in the schemes is given in Table 2.7.

Crops with similar tolerance can be grouped together into 5 groups as shown in Table 2.8.
Table 2.7: Yield potential expected at the ECe-value indicated in the table, mS/cm.

<table>
<thead>
<tr>
<th>Crops</th>
<th>100%</th>
<th>90%</th>
<th>75%</th>
<th>50%</th>
<th>0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>7.7</td>
<td>9.6</td>
<td>13</td>
<td>17</td>
<td>27</td>
</tr>
<tr>
<td>Maize</td>
<td>1.7</td>
<td>2.5</td>
<td>3.8</td>
<td>5.9</td>
<td>10</td>
</tr>
<tr>
<td>Beans</td>
<td>1.0</td>
<td>1.5</td>
<td>2.3</td>
<td>3.6</td>
<td>6.3</td>
</tr>
<tr>
<td>Cowpea</td>
<td>4.9</td>
<td>5.7</td>
<td>7.0</td>
<td>9.1</td>
<td>13</td>
</tr>
<tr>
<td>Onions</td>
<td>1.2</td>
<td>1.8</td>
<td>2.8</td>
<td>4.3</td>
<td>7.4</td>
</tr>
<tr>
<td>Tomato</td>
<td>2.5</td>
<td>3.5</td>
<td>5.0</td>
<td>7.6</td>
<td>13</td>
</tr>
<tr>
<td>Cabbage</td>
<td>1.8</td>
<td>2.8</td>
<td>4.4</td>
<td>7.0</td>
<td>12</td>
</tr>
<tr>
<td>Orango</td>
<td>1.7</td>
<td>2.3</td>
<td>3.3</td>
<td>4.8</td>
<td>8.0</td>
</tr>
<tr>
<td>Lemon</td>
<td>1.7</td>
<td>2.3</td>
<td>3.5</td>
<td>4.8</td>
<td>-</td>
</tr>
<tr>
<td>Avocado</td>
<td>1.3</td>
<td>1.8</td>
<td>2.5</td>
<td>3.2</td>
<td>-</td>
</tr>
</tbody>
</table>


Table 2.8: Crop salt tolerance groups.

<table>
<thead>
<tr>
<th>Relative crop salinity tolerance rating</th>
<th>Soil salinity at which yield loss begins (ECe (mS/cm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive</td>
<td>&lt; 1.3</td>
</tr>
<tr>
<td>Moderately sensitive</td>
<td>1.3 – 3.0</td>
</tr>
<tr>
<td>Moderately tolerant</td>
<td>3.0 – 6.0</td>
</tr>
<tr>
<td>Tolerant</td>
<td>6.0 – 10.0</td>
</tr>
<tr>
<td>Unsuitable for most crops (unless reduced yield acceptable)</td>
<td>&gt; 10.0</td>
</tr>
</tbody>
</table>
satisfactory yields. The other more sensitive crops, according to Kanake (1982), are grown in areas with low soil salinity levels and adequate leaching. These areas are found close to the Lumi river and in some parts of Kamleza scheme where ECe-values of less than 1 mS/cm occur.

2.2.7.3. Toxicity effects

Problems due to toxicity are caused by a high concentration in the soil solution of some particular ion or by the imbalance between two or more ions, harming plant growth.

Most toxicity problems are related to excess uptake of sodium, chloride and boron. In the project area, only sodium levels have been noted to be high. ESP-values as high as 90% have been reported by Kanake (1982). Symptoms due to Na-toxicity appear as a burn or drying of tissues first appearing at the outer edges of leaves (Snedema & Rycroft, 1983). Table 2.9 gives the tolerence of some crops grown in the schemes to exchangeable sodium percentage (ESP) under non-saline conditions.

From the table, cotton and tomatoes stand out as possible choices in areas with ESP-values of less than 60%, under non-saline conditions. Fruits are extremely sensitive and would be restricted to areas with low ESP-values in Kamleza (Kanake, 1982).
Table 2.9: Tolerance of selected crops to exchangeable sodium percentage (ESP) under non-saline conditions.

<table>
<thead>
<tr>
<th>Tolerance to ESP and range at which affected</th>
<th>Crop</th>
<th>Growth response under field conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely sensitive (ESP = 2-10)</td>
<td>Citrus</td>
<td>Sodium toxicity</td>
</tr>
<tr>
<td></td>
<td>Avocado</td>
<td>symptoms are low</td>
</tr>
<tr>
<td></td>
<td>Deciduous</td>
<td>ESP-values</td>
</tr>
<tr>
<td></td>
<td>Fruits</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beans</td>
<td></td>
</tr>
<tr>
<td>Sensitive (ESP = 10-20)</td>
<td>Rice</td>
<td>Stunted growth at these ESP values</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>even though the physical condition of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the soil may be good</td>
</tr>
<tr>
<td>Moderately tolerant (ESP = 20-40)</td>
<td>Rice</td>
<td>Stunted growth due to both</td>
</tr>
<tr>
<td></td>
<td>Oats</td>
<td>nutritional factors and adverse</td>
</tr>
<tr>
<td></td>
<td></td>
<td>physical soil conditions</td>
</tr>
<tr>
<td>Tolerant (ESP = 40-60)</td>
<td>Cotton</td>
<td>Stunted growth usually due to</td>
</tr>
<tr>
<td></td>
<td>Tomatoes</td>
<td>adverse physical</td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>soil conditions</td>
</tr>
<tr>
<td></td>
<td>Barley</td>
<td></td>
</tr>
<tr>
<td>Most Tolerant (ESP &gt; 60)</td>
<td>Grass</td>
<td></td>
</tr>
</tbody>
</table>

Source: (Jensen, 1983; FAO, 1985).

So long as the ESP-values in affected scheme areas are not lowered, choice of crops will remain limited, mainly to cotton. In less affected areas, care should be taken to prevent the ESP-values from rising too high.
2.2.7.4. Dispersion effects

A high exchangeable sodium percentage (ESP) results in dispersion of clay particles. This causes the soil structure to deteriorate, leading to poor soil physical conditions (Smedema & Rycroft, 1983; Verhoeven, 1979; Shainberg & Oster, 1978).

That high ESP-values occur in the Taveta schemes is evident from results of both Asol (1984) and Kanake (1982). These high ESP-values have been particularly noted to occur in heavy textured soils of the schemes (Kanake, 1982). This is a major concern as problems due to dispersion are known to generally increase with the increase of easily dispersible clay (Michael, 1983; FAO, 1985; Smedema & Rycroft, 1983).

The poor physical soil conditions which result from dispersion of soil colloids include:

(i) low hydraulic conductivity due to a) blockage of pores by dispersed particles and b) also reduced size of soil pores due to swelling or wetting;

(ii) unfavourable soil consistency; soils are hard to work when dry and plastic-sticky when wet;

(iii) low resistance to slaking which leads to the formation of surface crusts hampering the infiltration of water into the soil and the mechanical strength of the crust is likely to hinder proper germination (irregular, patchy stands);

(iv) waterlogging, resulting from the general deterioration of the internal drainage characteristics of the soil associated with the above effects.
2.3. Water quality

The quality of both irrigation and groundwaters are of prime importance because of their influence on the amount and type of salts added to the rootzone. Waters of poor quality result in soil and cropping problems which reduce yields unless special management practices are adopted.

The suitability of water for irrigation is not only determined by its quality but also by other factors such as soil, crop, irrigation, leaching and drainage conditions (Van Hoorn, 1971). The quality of water may be considered as suitable for a certain type of soil or crop but as unsuitable for others.

The quality of both irrigation and groundwater are determined by the following chemical characteristics of the soil solution:

1. Total concentration of soluble salts, or salinity;
2. Concentration of sodium relative to other cations, or sodicity;
3. Anionic composition of the water, especially the concentration of $\text{HCO}_3^-$ and $\text{CO}_3^{2-}$ anions; and
4. Concentration of boron and other elements that may be toxic to plant growth.

It should be noted that this classification and the references for the above named four characteristics include Smedema & Rycroft (1983), Shainberg and Oster (1978), Van Hoorn (1971), FAO (1985).

The first three characteristics are briefly discussed below as they are the most relevant to the study.
2.3.1. **Total salt concentration**

Soluble salts in water principally include NaCl, CaCl$_2$, MgCl$_2$, Na$_2$SO$_4$, MgSO$_4$, NaNO$_3$, KNO$_3$, Na$_2$CO$_3$, NaHCO$_3$ according to FAO/UNESCO, (1973); Shainberg & Oster, (1978); and Smedema & Rycroft, (1983).

The total salt concentration may be expressed in g/l, me/l, ppm or by the electrical conductivity (EC) in mS/cm at 25°C and gives an indication of the salinity hazard. General classifications exist with regard to the salinity hazard namely:

- Classification of the U.S. Salinity Laboratory (Smedema and Rycroft, 1983);
- USSR classification (Van Hoorn, 1971);
- Classification of Durand for North Africa (Van Hoorn, 1971);
- Classification of FAO (FAO, 1976/85).

The classification of the U.S. Salinity Laboratory is the one employed in Kenya and therefore the salinity hazard of the waters in the project area will be classified in accordance with this classification. The salinity hazard under this classification is as shown in the Table 2.10.

It should be noted that this classification and the others mentioned can be utilized as a guide, but should not be used as a generalisation.

Waters of high salinity may be used for irrigation in highly permeable soils, where drainage is adequate, where irrigation water is applied in excess to provide considerable leaching and where very salt tolerant crops
<table>
<thead>
<tr>
<th>Salt concentration (EC&lt;sub&gt;1&lt;/sub&gt; (mS/cm))</th>
<th>Salinity hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.25</td>
<td>Low salinity (Class - C1)</td>
</tr>
<tr>
<td>0.25 - 0.75</td>
<td>Medium salinity (Class - C2)</td>
</tr>
<tr>
<td>0.75 - 2.25</td>
<td>High salinity (Class - C3)</td>
</tr>
<tr>
<td>&gt; 2.25</td>
<td>Very high salinity (Class - C4)</td>
</tr>
</tbody>
</table>

Source: Van Hoorn (1971) and Smedema and Rycroft (1983)

The sodicity hazard of irrigation (or groundwater) selected (Van Hoorn, 1971). This is the case in North African countries where irrigation waters may have salinity values of 2 mS/cm and above. In these countries, the classification of Durand for North Africa is used. However, this classification is not presented here as it is not used in Kenya. The USSR classification is also not presented for the same reason.

The classification of FAO is presented in Table 2.11 below. This classification sets higher limits than the U.S. Salinity Laboratory and is presented for comparison purposes only.

2.3.2. Sodicity hazard

The sodium content in water is very important, owing mainly to its effect on the soil. A high sodium content in the soil leads to high ESP-values and thus results in dispersion problems in other than sandy soils (see section 2.2.6.4).
Table 2.11: FAO Guidelines for irrigation water quality appraisal.

<table>
<thead>
<tr>
<th>Salinity EC$_i$ (mS/cm)</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.75</td>
<td>No problem</td>
</tr>
<tr>
<td>0.75 - 3.0</td>
<td>Moderate problem</td>
</tr>
<tr>
<td>&gt; 3.0</td>
<td>Severe problem</td>
</tr>
</tbody>
</table>

Source: Smedema and Rycroft (1983)

The sodicity hazard of irrigation (or groundwater) is given by the Sodium Absorption Ratio, (SAR - value) according to van der Molen (1979), Smedema and Rycroft (1983), Shainberg and Oster (1978).

$$\text{SAR} = \frac{\text{Na}^+}{((\text{Ca}^{2+} + \text{Mg}^{2+})/2)^{0.5}}$$ ...(2)

where Na$^+$, Ca$^{2+}$, Mg$^{2+}$ represent the concentrations of these elements in the irrigation water (me/l).

The relation between the ESP-value of the soil and the SAR-value is given below (van der Molen, 1979 and Van Hoorn, 1971).

$$\text{ESP} = 100(-0.0126 + 0.01475\text{SAR})/(1 + (-0.0126 + 0.01475\text{SAR}))$$ ...(3)

The classification of the sodicity hazard according to the US Salinity Laboratory system which is used by the Kenya Soil Survey is presented in Table 2.12.
Table 2.12: US Salinity Laboratory Classification (adopted from Smedema and Rycroft, 1978)

<table>
<thead>
<tr>
<th>Sodicity Hazard</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0 - 10</td>
</tr>
<tr>
<td>Medium</td>
<td>10 - 18</td>
</tr>
<tr>
<td>High</td>
<td>18 - 26</td>
</tr>
<tr>
<td>Very High</td>
<td>&gt; 26</td>
</tr>
</tbody>
</table>

2.3.3: The adjusted Sodium Adsorption Ratio ($\text{SAR}_{\text{adj}}$)

The adjusted sodium adsorption ratio can be expressed as:

$\text{SAR}_{\text{adj}} = \frac{\text{Na}^+}{[(\text{Ca}^{2+} + \text{Mg}^{2+}/2)]^{0.5}} \times (1 + (8.4 - \text{pH}_c)) \ldots (4)$

where \(\text{pH}_c = (pK'_2 - pK'_c) + p(\text{Ca}^{2+} + \text{Mg}^{2+}) + p(\text{AIK})\); and \((pK'_2 - pK'_c) = \text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+\);

\[ p(\text{Ca}^{2+} + \text{Mg}^{2+}) = \text{Ca}^{2+} + \text{Mg}^{2+} ; \]

\[ p(\text{AIK}) = \text{CO}_3^{2-} + \text{HCO}_3^- ; \]

\[ p = \text{concentration sum of; AIK = alkalinity.} \]

All units expressed in me/l. The adjusted SAR takes into consideration changes in soil water composition that are expected to result due to certain combinations of water salts which either dissolve lime ($\text{CaCO}_3$) from the soil (adding Ca) or deposit lime from the soil (reducing Ca). The
presence of $\text{CO}_3^{2-}$ and $\text{HCO}_3^-$ can increase the sodium hazard of irrigation water since they bring about the precipitation of Ca and to a lesser extent Mg in the soil, hence increasing the relative amount of sodium in the soil solution and therefore the RSP-value. (Smedema and Rycroft, 1983). Previously, the Residual Sodium Carbonate (RSC) was used to assess the risk of the concentration of $\text{HCO}_3^-$ and $\text{CO}_3^{2-}$ in water. The RSC is given as below:

$$\text{RSC} = (\text{CO}_3^{2-} - \text{HCO}_3^-) - (\text{Ca}^{2+} + \text{Mg}^{2+}) \quad \text{..................... (5)}$$

All concentrations in me/l. The ratings are as follows shown in Table 2.13 (adopted from Van Hoorn, 1971; Smedema & Rycroft, 1983).

Table 2.13: Classification of RSC-values

<table>
<thead>
<tr>
<th>RSC (me/l) 1976</th>
<th>Water Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1.25</td>
<td>Safe (no problem)</td>
</tr>
<tr>
<td>1.25 - 2.5</td>
<td>Marginal (moderate)</td>
</tr>
<tr>
<td>&gt; 2.5</td>
<td>Unsuitable (severe)</td>
</tr>
</tbody>
</table>

The general expression of a water balance equation, as such an inflow over time period, 6 days

$$\Delta \quad \text{inflow over time period, 6 days}$$

$$\Delta \quad \text{outflow over time period, 6 days}$$

$$\Delta \quad \text{change in water storage in 6 days}$$

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2.4 **Groundwater salt balance**

For areas with drainage problems, the assessment of a groundwater balance is of primary importance because:

(a) the assessment enables the cause(s) of the drainage problem to be determined in quantitative terms. This helps in the selection of the appropriate remedial measures e.g. if the cause is determined as seepage inflow, then a cut-off drain may be selected (Kessler & De Ridder, 1980 and Szabolcs, 1976).

(b) the assessment also enables predictions on the probable changes in drainage status (or groundwater table conditions) of a given area to be made. The changes may be due to influencing environmental factors such as rainfall or human interventions such as irrigation, drainage and control of flooding. Based on the predictions made, the most appropriate control measures(s) can be selected in advance (Szabolcs, 1976).

As the project area has drainage problems such an assessment for areas within the scheme is important.

2.4.1 **Groundwater balance equation**

The general expression of a water balance equation, as given by Kessler and De Ridder (1980) and Oosterbaan (1987) is:

\[ I - O = \Delta \]  \hspace{1cm} (6)

where, \( I \) = inflow over time period, \( t \) days

\( O \) = outflow over time period, \( t \) days

\( \Delta \) = change in water storage in \( t \) days
In terms of the various recharge and discharge components, a more detailed equation can be written as follows (see Fig. 2.5 for the various groundwater flow components):

\[(\text{Perc-Cap}) + (Q_{\text{inf}} - Q_{\text{dr}}) + (Q_{\text{up}} - Q_{\text{do}}) + (Q_{\text{lsi}} - Q_{\text{lo}}) = \Delta S_{\text{grw}} \ldots \ldots \ldots (7)\]

The recharge - discharge conditions determined by the position of the water level in relation to the water table: 

- \(Q_{\text{dr}}\) - the recharge - discharge conditions determined by the potential mean head in the underlying semi confined aquifer (see Fig. 2.5); 
- \(Q_{\text{lo}}\) - the recharge - discharge conditions determined by the lateral groundwater flow across the boundaries.

The components of the groundwater balance equation can be determined directly or indirectly to be able to solve the equation. Direct methods of determining the components are often expensive, especially for the vertical and lateral flow components, which require a lot of pumping and field work to find reasonable estimates of the transmissivity \(K\) - product of hydraulic conductivity of

\[\text{Fig.2.5: Flow components of a groundwater sub-system (Kessler & De Ridder, 1980).} \]
Where,

\( (\text{Perc} - \text{Cap}) \) = the recharge - discharge conditions determined by the water balance of the unsaturated zone.

\( (Q_{\text{inf}} - Q_{\text{dr}}) \) = the recharge - discharge conditions determined by the position of the water level in the stream channel and open water courses in relation to the water table.

\( (Q_{\text{up}} - Q_{\text{do}}) \) = the recharge - discharge conditions determined by the potential metric head in the underlying semi confined aquifer (see Fig. 2.5).

\( (Q_{\text{lsi}} - Q_{\text{iso}}) \) = the recharge - discharge conditions determined by the lateral groundwater inflow and outflow across the boundaries of the area under consideration, and

\( \Delta S_{\text{grw}} \) = change in groundwater storage.

The dimensions for the above flow quantities can be in discharge units of \( \text{mm}^3/\text{day}, \text{m}^3/\text{day}, \text{l/s}, \text{etc}, \text{or in units of discharge/area, mainly, mm/day.} \)

2.4.2 Solution of the groundwater balance equation

The components of the groundwater balance equation may be determined directly or indirectly to be able to solve the equation. Direct methods of determining the components are often expensive, especially for the vertical and lateral groundwater flow components, which require a lot of pumping tests and field work to find reasonable estimates of the transmissivity (KD - product of hydraulic conductivity of transmitting layer, K, and the depth of the layer, D).
Kessler & De Ridder (1980) have recommended the use of the indirect method as it is less expensive and still gives a good indication of the magnitude of the groundwater flow components. The principle of the indirect method is that the area and time are chosen in such a manner that the conditions of recharge, discharge and storage are uniform and quantitatively known, except for one flow component. This component can then be solved from the equation. The component thus found can subsequently be introduced into the equation for another unknown item provided the value of the component remains reasonably constant. In general, lateral groundwater terms remain rather constant for different time periods, whereas percolation and capillary rise usually vary during different parts of the hydrological year (Kessler and De Ridder, 1980).

It is recommended that calculations be made for more than one time period in order to have a check on the results obtained. Also, it is not always possible, nor necessary to solve all the individual members of the groundwater balance equation separately. Sometimes, depending on the problem under study, a number of members can be lumped, and the net value be taken (Kessler and De Ridder, 1980).

Through the indirect method, the various components may be determined as follows:

(a) \( \text{(Perc-Cap)} \)

This may be determined by solving the water balance equation of the unsaturated zone expressed as:

\[
(R + I_i - R_{off}) - ET - (P - Cap) = \Delta S_{sm} \ldots \quad (8)
\]

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where, $R = \text{precipitation}; I_i = \text{irrigation}; R_{\text{off}} = \text{surface runoff}; ET = \text{evapotranspiration};$ and $\Delta S_{\text{sm}} = \text{change in soil moisture storage}.$

During the rainy season, the following equation may be used;

$$P = R - ET - R_{\text{off}} \hspace{1cm} (9)$$

as $\Delta S_{\text{sm}} = 0$ (soil moisture at field capacity) and $\text{Cap} = 0$ (as there is percolation). For a short period of intense rainfall, covering only a few days, $\Delta S_{\text{sm}} = \text{Cap} = 0$ (as in eqn. (12) above) and ET can also be neglected during this short and wet period (Kessler and DeRidder, 1980), therefore,

$$P = R - R_{\text{off}} \hspace{1cm} (10)$$

The $(P - \text{Cap})$ term, may also be determined from the groundwater balance equation, as shown in (b) below.

(b) **Total net groundwater flow**

The groundwater flow components may be lumped together so that their total net effect can be found from the groundwater balance equation, provided all other members are known. The net effect may be expressed as,

$$I'ss = (Q_{\text{lsi}} - Q_{\text{lo}}) + (Q_{\text{up}} - Q_{\text{do}}) \hspace{1cm} (11)$$

where, $I'ss = \text{total net effect of the individual groundwater flow components}.$
A period or area may be selected such that \((Q_{\text{inf}} - Q_{\text{dr}})\) term (from eqn. 9), is zero, i.e. when the channel network is dry or far away and does not directly influence the groundwater table of the selected area. The \(I'\) term may thus be determined from:

\[
I' = \Delta S_{\text{gm}} - (P - C) \quad \text{..................}(12)
\]

For a period when \(\Delta S_{\text{grw}} = 0\),

\[
I' = (C - P) \quad \text{.................................}(13)
\]

If both \(P = C = 0\) (no rainfall or irrigation and a deep water table then):

\[
I' = \Delta S_{\text{grw}} \quad \text{..................................}(14)
\]

(c) **Determination of change in groundwater storage \((\Delta S_{\text{grw}})\)**

According to Kessler and De Ridder (1980),

\[
\Delta S_{\text{grw}} = \mu \Delta h \quad \text{..................}(15)
\]

Where \(\mu\) = drainage pore space (or effective porosity).

Through frequent recording of the groundwater table, i.e. from wells, the value of \(\Delta h\) may be determined. The effective porosity, \(u\), may be determined by:-

(i) **Estimation from the hydraulic conductivity, \(K\), of the particular soil according to Smecma and Rycroft (1983) as,**

\[
\mu = (K)^{0.5} \quad \text{..................}(16)
\]

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(ii) Estimation from tables, giving values of different soil textures from past experiments as below.

Table 2.14: Effective porosity ranges for different materials (after Johnson, 1966).

<table>
<thead>
<tr>
<th>Material</th>
<th>Range</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0 - 5</td>
<td>2</td>
</tr>
<tr>
<td>Silt</td>
<td>3 - 19</td>
<td>8</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>3 - 12</td>
<td>7</td>
</tr>
<tr>
<td>Fine sandy</td>
<td>10 - 32</td>
<td>21</td>
</tr>
<tr>
<td>Medium sandy</td>
<td>15 - 32</td>
<td>26</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>20 - 35</td>
<td>27</td>
</tr>
<tr>
<td>Gravely sand</td>
<td>20 - 35</td>
<td>25</td>
</tr>
<tr>
<td>Fine gravel</td>
<td>17 - 35</td>
<td>22</td>
</tr>
<tr>
<td>Medium gravel</td>
<td>13 - 26</td>
<td>23</td>
</tr>
</tbody>
</table>

Source: Kessler and De Ridder (1980)

(iii) Selecting a period of intense rainfall, such that,

\[
\mu = \frac{P}{(\Delta h)}
\]  \hspace{1cm} (17),

(all other terms being zero),

(iv) If both \( P = \text{Cap} = 0 \) (no rainfall or irrigation and a deep watertable), and the value of \( \mu'\text{ss} \) is known, then;

\[
\mu = \frac{\mu'\text{ss}}{(\Delta h)}
\]  \hspace{1cm} (18),

(v) If both \( \mu'\text{ss} \) and \( \mu \) are unknown, then they can be determined from two different periods for which the supply is known, assuming the values are constant over two periods, a condition which is satisfied if the water table during the two periods is at the same elevation. By solving the two
simultaneous equations below, the values of $I'ss$ and $u$ can be determined.

\[ I'ss = u \frac{\Delta h}{(\Delta t)_1} - (P - Cap)/(\Delta t)_1 \]  \[ I'ss = u \frac{\Delta h}{(\Delta t)_2} - (P - Cap)/(\Delta t)_2 \]  

These equations will be used during groundwater balance calculations in Chapter 7.

2.4.3 Salt balance and leaching requirement

A salt balance can be prepared for a given area and/or for a given soil layer and also for different periods of time. Quantification of the various components of a salt balance can serve to indicate if salinity is increasing or decreasing, if measures should be taken and, if so, to quantify such measures (mostly in terms of extra irrigation water and the drainage requirement).

As salinity problems exist in the crop rootzone of the project area, a salt balance assessment, for the crop rootzone, is of utmost importance. A salt balance equation of the crop rootzone can be derived from the water balance equation of the rootzone (unsaturated layer). Fig. 2.6 shows the various water flows into and out of the rootzone. The water balance of the rootzone can be written as:

\[ \text{Incoming water} = \text{Outgoing water} + \text{Change in moisture storage}, \]

\[ R + I_1 + G = ET + P + \Delta S_m, \]  \[ ............. (20) \]  

44
By affixing the salt concentrations of the various inflow and outflow water components above, the salt balance becomes:

\[ \frac{d}{dt} \sum c_s = - \sum_{i} T_i c_{si} + \sum_{o} T_o c_{so} + \Delta s_{sm} \]  

(21)

where \( c_s \) is the salt concentration of the water.

\[ (\text{rain}(R) \downarrow \text{transpiration} \uparrow \text{evapotranspiration (E)} \downarrow \text{irrigation (I)} \downarrow \text{evaporation} \uparrow \text{capillary flow from groundwater (G)} \downarrow \text{deep percolation (P)} \downarrow \text{groundwater} \downarrow \text{water table}) \]

Fig. 2.6: Water balance of irrigated land (Smedema & Rycroft, 1983)

Where, \( R \) = infiltrating rainfall, 
\( I \) = infiltrating irrigation water, 
\( G \) = groundwater rising by capillarity, 
\( ET \) = evaporation by crop or soil surface, 
\( P \) = percolation below the root zone,
\( \Delta s_{sm} \) = change in the soil moisture content (+ or -).

If the various components of the salt balance above remain constant, then the change in the salt content of the root zone can also be quantified. Under steady state conditions (for steady state), averaging over a period, sufficient excess water can be provided to keep excess salts, consequently, \( \Delta s = 0 \). Also \( c_x = 0 \).
By affixing the salt concentrations of the various inflow and outflow water components above, the salt balance equation becomes:

\[ R \cdot c_r + I_i \cdot c_i + G \cdot c_g = P \cdot c_p + \Delta S \]  \hspace{1cm} (21)

Where, \( c \) = salt concentration of the water (subscripts \( r, i, g, p \) referring to rainfall, irrigation, etc).

\( \Delta S \) = change in salt content of the soil solution in the rootzone.

If the various components of the salt balance above are known quantitatively, then the change in the salt content of the rootzone can also be quantified. Under steady state or equilibrium conditions, which is true for averages over annual periods (Smedema & Rycroft, 1983), the change in both moisture can be considered as zero. In order to achieve a constant salt content in the rootzone over a similar period, sufficient excess water can be provided to flush out excess salts, consequently, \( \Delta S = 0 \). Also \( c_r = 0 \) as rainfall contains very little salt; Equations 20 and 21 can therefore be written as (for steady state):

\[ I_i = (ET - R) + (P - G) \]  \hspace{1cm} (22)

\[ I_i \cdot c_i = P \cdot c_p - G \cdot c_g \]  \hspace{1cm} (23)

The term \((ET-R)\), represents the net crop irrigation requirement and \((P-G)\), is the leaching requirement or the additional irrigation water that must be applied to maintain the existing salt balance in the rootzone, i.e keep \( \Delta S = 0 \).
The salt concentration terms $c_i$, $c_g$, and $c_p$ can be replaced by $EC_i$, $EC_g$, and $EC_p$ respectively as they are linearly related. The salt concentration or electrical conductivity of the of the percolating water on average equals $1.5EC_e$ (Lenselink, 1988; Smedema & Rycroft, 1983). By incorporating the leaching efficiency factor, $f$, the salt balance of the rootzone, under steady state conditions can be expressed as:

$$fI_{\text{ET}} = \frac{(ET - R)1.5EC_e}{EC_g - 1.5EC_e} + \frac{G}{(1.5EC_e - EC_i)} = \frac{(1.5EC_e - EC_i)}{(1.5EC_e - EC_i)}.$$  

Values of the leaching efficiency factor, $f$, depend on the soil texture and structure, and the irrigation method. Table 2.15 gives $f$-values of different soil textures.

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>loam, sandy clay loam, silt clay loam</td>
<td>0.4 - 0.5</td>
</tr>
<tr>
<td>silt loam, sandy loam</td>
<td>0.5 - 0.6</td>
</tr>
<tr>
<td>(heavy)-clay</td>
<td>0.1 - 0.3</td>
</tr>
<tr>
<td>silt clay</td>
<td>0.6</td>
</tr>
<tr>
<td>fine sandy soil</td>
<td>0.7 - 0.8</td>
</tr>
</tbody>
</table>

Source: Van Der Molen (1979)
2.5 Calcic and petrocalcic horizons

(Petro)calcic layers are horizons of CaCO₃ accumulation which are mainly found in soil profiles of arid and semi-arid climatic environments. Calcic horizons are discontinuous accumulations of CaCO₃ i.e. - are uncemented, in mass, though nodules may be cemented (Wilding et al., 1983 and Ruellan, 1973). In the project area, these accumulations have been referred to as soft caliche by Kanake (1982).

Petrocalcic horizons are continuously cemented or indurated accumulations of CaCO₃ (Chorley, 1984; Brady, 1986; FitzPatrick, 1980; Flint et al., 1983; and USDA, 1969). The terms often used to describe this layer are caliche (in USA); Croute Calcaire (or encroûtement calcaire) in France with the English translation being calcareous crust (lime crusting or calcareous encrustation). As mentioned by Bear (1955) and Kanake (1982), most parts of the Kimorogo and Kamleza Schemes are believed to be underlain by this petrocalcic horizon.

2.5.1 Formation and development

These CaCO₃ accumulations are believed to be relicts from different climatic conditions in the Pleistocene to Recent Age as reported by Young (1976), Wilding et al.(1983) and Bear (1955).

There exists three different mechanisms which have been put forward to explain how the accumulations have been formed. These mechanisms are:-
(a) Downward leaching model;
(b) Upward movement of calcium (bi)-carbonate rich
groundwater; and

(c) Lacustrine sedimentation.

Not wholly true as the horizons have been found to weather and ground lowering is a very slow process

(a) Downward leaching model

This mechanism, as named by Young (1976), involves a process of salt movement and differentiation, occurring in two stages. The first stage is referred to as primary or undifferentiated salt movement (Chorley, 1984 and Wilding et al., 1983).

The primary salt movement is assumed to occur during periods of limited precipitation and a consequent shallow moisture penetration, when an undifferentiated movement of all soluble salts takes place from the upper horizons to the lower B- or C- horizons. These salts accumulate and eventually precipitate in solid forms as the soils dry out.

During periods of uncommonly wet years, which are accompanied by deeper soil moisture penetration, secondary salt movement is assumed to occur. This involves the leaching away of the most soluble solid phase precipitates and leaving the least soluble salts/components such as calcite (CaCO$_3$). In this way, an horizon rich in CaCO$_3$ is formed, whereas the more soluble salts of sodium, potassium and magnesium may accumulate at greater depth, or may be translocated vertically or laterally, or may be eventually leached away from the regolith (Wilding et al., 1983).

For the first mechanism to hold, there must be a readily available source of CaCO$_3$ either from a calcareous parent material (Flint et al., 1974; Ruellan, 1973; Wilding et al., 1983 and Young, 1976) or from a calcareous dust fall as in New Mexico (Wilding et al., 1983).
Objections to this first mechanisms are:

(i) Origination of CaCO$_3$ from calcareous parent material is not wholly true as the horizons have been found to occur over non-calcareous parent material (Ruellan, 1973).

(ii) Weathering and ground lowering is a very slow process in dry regions and therefore the carbonates are not likely to have originated from rock weathering (Young, 1976).

(iii) Leaching of soluble materials downwards is minimal in dry regions because of the absence of percolating water and hence the quantities of CaCO$_3$ could not possibly have been leached (FAO, 1973 and Young, 1976).

(b) Upward movement from a calcareous groundwater

This second mechanism which seems to have more general support, assumes that the carbonates originate from groundwater rich in calcium (bi) carbonate (calcareous groundwater) by capillary rise. So long as this water is replaced by inward seepage then more and more carbonates will be transported and accumulated near the top of the capillary fringe (Chorley, 1984; Flint et al; 1974; Jackson & Erie, 1973; Wilding et al., 1983 and Young, 1976).

Chorley (1984), supports this mechanism by asserting that (petro) calcic layers (or CaCO$_3$ rich horizons) appear to be formed in areas of carbonate-rich groundwater where sheet floods dry out, capillary rise occurs and the watertable oscillates close to the ground surface.
(c) Lacustrine sedimentation model

In this third mechanism, there is lacustrine sedimentation and evaporation, possibly with some subsequent redistribution by leaching. This is supported by the fact that many calcretes occur in basin like situations with very gentle slopes (0.2-0.4%) according to Young (1976).

2.5.2 Forms or types of the calcareous layer

The form of occurrence of the layer is important as it influences the movement of water through the soil (vertically and laterally) and hence the drainage status of an area.

According to Ruellan (1973) and Wilding et al. (1983), the CaCO₃ accumulations have been noted to occur in different forms or types although still falling under either a Calcic (discontinuous) or a Petrocalcic (continuous) horizon.

The different types are often related to the stage of the development process. According to Wilding et al. (1983), the development of the CaCO₃ rich horizons, in the presence of a ready source of CaCO₃, reportedly progresses in two evolutionary morphological sequences of four stages each. One sequence occurs relatively rapidly in materials of gravel and cobbles, the other occurs slowly in non-gravely, sandy or loamy material. Both sequences converge on their fourth stage on an indurated petrocalcic horizon with a laminated, almost pure carbonate, upper subhorizon. The stages of the development processes are as briefly discussed below;

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Stage (i):

This consists of a diffuse accumulation with or without pseudo-mycellium. The calcareous profile may be described as weakly differentiated (Ruellan, 1973). For gravelly material, this involves coating of pebble bottoms with carbonate and for non-gravelly material, there exists an horizon with a few filamentary deposits or thin ped coatings of carbonate (Wilding et al.; 1983).

Stage (ii):

This is an horizon of soft concretions or nodules (hard concretions) throughout the thickness of the profile for non-gravelly material (Ruellan, 1973 and Wilding et al., 1983). For gravelly material, all pebbles are surrounded by carbonate and there exists a discontinuous or uncemented carbonate accumulation.

In this second stage, the horizon may be referred to as a calcic horizon (Wilding et al., 1983) or a moderately differentiated calcareous profile (Ruellan, 1973).

Stage (iii):

This stage consists of a cemented layer (continuous accumulation) and is referred to as the Petrocalcic horizon (Ruellan, 1983). The thickness of the layer varies from 10 cm to more than 2 m. The calcareous profile at this stage can be said to be very well differentiated (Ruellan, 1973). The layer may be:

(1) non-platy;
(2) Platy, i.e. a crust normally surrounding a non-platy lime crusting; or
(3) a compact slab situated on a crust and on a non-platy lime crusting.

Stage iv:

This is the final stage and involves the disposition of one or more thick carbonate laminac on top of the petrocalcic layer (Ruellan, 1973 and Wilding et al, 1983).

2.5.3 Calcium carbonate content of the horizons

The calcium carbonate content of the layers is variable. According to Ruellan (1973), the carbonate contents are as given below:

i) weakly differentiated: the accumulation is diffuse with, sometimes pseudo-mycelium (carbonate content: < 40%);

ii) moderately differentiated: there exists diffuse and nodular carbonate; nodules can be soft or hard (carbonate content: < 60%).

iii) very well differentiated: there exists a calcareous crust, (carbonate content: > 60%).
3 METHODOLOGY

This chapter is divided into three sections. The first part (Sec. 3.1), explains how it was intended to achieve each of the four project objectives as outlined in Chap. 1, Sec. 1.3. In Sec. 3.2, details of the field investigations carried out are presented. The laboratory analyses of samples collected from the field are presented in Sec. 3.3.

3.1 Plan of action

It is imperative to have data on the soil salinity. In the following parts (i) to (iv), the plan of action for each of the four project objectives is given.

(i) and (ii) - Drainage and salinity data

The two objectives required that data be provided to describe the existing state, extent and degree of the drainage and salinity problems in the project area. To provide the data, it was planned to carry out investigations on the groundwater and soil conditions.

The data on groundwater conditions of the area consist of:

- water-table position relative to the ground surface;
- fluctuations in the watertable levels; and
- groundwater quality.

The depth to groundwater data help in identification of areas with drainage problems, i.e., they show where shallow groundwater tables occur. Data on groundwater table fluctuations help in identifying periods of high groundwater
table and thus show when drainage is required. The groundwater quality data are important with regard to soil salinisation, especially when shallow groundwater table conditions exist.

The data on soil profile conditions included:
- soil salinity and sodicity status;
- soil texture;
- soil hydraulic conductivity; and
- the calcareous layer (caliche).

It is imperative to have data on the soil salinity and sodicity levels due to the effect of the two on crop production. Information on the hydraulic conductivity of the soils gives an indication of the subsurface drainability, i.e., a low hydraulic conductivity indicates poor or low natural subsurface drainage capacity of the soils. Soil texture data was required for three main reasons, (i) it influences the rate of capillary rise from the groundwater table and thus the rate of salt transport to the surface or rootzone, (ii) the development of soil sodicity conditions is influenced by the soil texture, and (iii) soil texture differences down the profile have an influence on the movement of water through the soil i.e., vertical or horizontal drainage.

Information required on the calcareous layer was with respect to its depth below the ground surface, extent, slope, nature or form of occurrence and its thickness. These features are likely to influence the drainage depth; direction and slope of possible (field) drains and water movement through the soil (vertical or horizontal).
In addition to the investigations on the groundwater and soil conditions it was important to study the area's topography so as to:

- provide a topo-map combining both Kimorigo and Kamleza schemes on which to reference the soils and groundwater data. The existing topo-map at a scale of 1:10,000 only covers a small part of Kamleza scheme;
- get present ground levels which would help in derivation of groundwater and caliche levels (a.m.s.l.). This was to enable the production of the groundwater and calcareous layer contour maps;
- determine the location and adequacy of outlet conditions for evacuation of (possible) excess water and salts from the project area; and
- obtain additional information regarding ground slopes; location of canals and drains; current scheme boundaries; seepage areas, and relative levels between the Luwi river and the project area to check on the possible influence the river may have on the on the area's drainage.

(iii) Cause(s) of the drainage and salinity problems

The fulfillment of the third objective required that the possible cause(s) of the drainage problem (excess groundwater) and high soil salinity be quantitatively characterised. To do this it was decided to assess the groundwater and salt balances of the area within the schemes. It is only after the cause(s) have been identified and quantitatively characterised that appropriate remedial measures can be recommended, e.g. if the source of excess water causing the drainage problem is over-irrigation, the
solution may involve education of the farmers on water the
source of salts rise from the groundwater, then lowering of
the groundwater table or providing adequate water for
leaching to counteract salts brought to the rootzone by
capillarity flow may be the solution.

To determine the causes quantitatively meant the
solution of the groundwater balance equation. As mentioned
in Sec.2.4, the various terms of the equation which needed
to be determined were :–

- \(( P - \text{Cap})\),
- \(( Q_{\text{inf}} - Q_{\text{dr}})\),
- \(( Q_{\text{ap}} - Q_{\text{do}})\),
- \(( Q_{\text{lso}} - Q_{\text{lso}})\), and
- \(\Delta S_{\text{grw}}\).

The \((P - \text{Cap})\) term i.e. the supply to the
groundwater table from the unsaturated zone could be
obtained in two ways:
(a) through solving the water balance equation of the
unsaturated zone when all the other terms are
quantitatively known (see sec. 2.4 eqn. 11), and
(b) from the groundwater balance equation during periods
when the net groundwater flow, \(I_{\text{ss}}\) and the change in
groundwater storage \(S_{\text{grw}}\), are known (see sec.2.4, eqn.
10).

The data to be collected for solving the two water
balance equations above included :
- daily precipitation data,
- daily evapotranspiration data,
- change in the groundwater table height, \(h\), as a
measure of the change in groundwater storage,
The water balance equations were to be solved for periods when only one of the components of the equations is unknown. The unknown components included:

- net groundwater flow, $I$,
- amount of irrigation water applied at predetermined times; this would lead to estimation of irrigation efficiencies,
- amount of infiltrated flood water, and
- the drainage pore space, $y$.

The salt balance assessment is to be carried out assuming steady state conditions. The amount of extra irrigation water required to maintain favourable salt conditions in the rootzone will be used as an indicator of the possible salinisation without leaching (see Sec. 2.4.2). With information on the groundwater table and soil texture, it will be possible to determine the approximate rate of capillary rise and the leaching efficiency. Also the groundwater quality will be known from the groundwater quality investigations. Average rainfall and evapo-transpiration figures are to be obtained from Table 2.1.

(iv) The appropriate remedial measures

With data on the drainage and salinity status in the area and after identifying and quantitatively characterising the possible causes of the drainage problem, then appropriate remedial measures could be recommended, thus fulfilling the final project objective.
3.2: Field work

Field work comprised topographic surveys, ground- and surface water investigations, and soil investigations as detailed in the following sub-sections.

3.2.1: Topographic survey

The survey was carried out in 5 months from September, 1988 to January, 1989 with the help of 3 - Survey Assistants from the Ministry of Agriculture. The area was divided into a grid pattern of 100 m x 100 m, using a theodolite, ranging rods and two tape measures of 50 m length each. The elevations of the grid points were obtained by the use of two automatic levels and levelling staffs. The collimation method was used to find the reduced ground levels of the grid points.

The total area surveyed was approximately 1500 ha (see Fig. 4.1 for the survey boundary). The allowable misclosure during the topo-survey was 1 cm per km. As a check during the survey period, several cross-sections were drawn and a comparison made with the ground topography as seen in the field. Where doubts were cast on the survey result, a repeat was done.

3.2.2: Ground and surface water investigations

(a) Groundwater investigations

Wells were set up in the field at a grid of 1000 m x 500 m, the longer side running to the parallel North-West
to South-East road and the shorter length running perpendicular to this road from Kamleza Scheme towards the Lumi river as shown in Fig. 3.1.

The wells were designated by a letter and a number e.g. A2 as shown in Fig. 3.1. In a few cases, some wells do not fall under the grid of 1000 m x 500 m. This occurred when, (i) the well was previously existing, (ii) the well occurred towards the end of survey area and the distance remaining was less than 1000 m or 500 m, and (iii) when the well was set up later between two existing wells for further study of groundwater quality and depth.

A total of 50 open wells were dug in the area for the purpose of this study. In areas where the caliche layer was present, it was chiseled through. In addition to the open wells, 11 augerhole points were set up (5 along the G-line and the other 6 in the area close to the Ruvu swamp as shown in Fig. 3.1). The area covered by the wells and augerhole points in this study is approximately 2,250 ha. According to recommendations by De Ridder (1980), at least 40 wells should be set up for an area covering between 1000 - 10,000 ha and therefore the 61 measuring points are acceptable.

Most of the wells were set up between September, and December, 1988. The additional wells, in between the grid points, were set up at later dates.

Groundwater data collected from the wells were:-

1. Water level measurements:— these were measured on a weekly basis from 21/10/88 to 31/8/89, except during periods of rapid watertable fluctuations (rainy season or during heavy floods), when at least 2 measurements per week were taken. The depth to water level was measured in cm by use
Fig. 3.1: Well locations in the project area.
of a tape measure from a reference point at the top of the well. The groundwater level (a.m.s.l.) was found by subtracting the measured depth from the ground surface elevations known from the topo-survey.

2. Water quality measurements:– samples were taken from the wells and analysed for pH and EC (mS/cm) in the field by use of portable pH- and EC-meters. Measurements were made at least once a month to monitor the changes of salinity with time. More readings per week were taken whenever significant changes occurred in the salinity. The measurements were taken from November, 1988 to August, 1989.

(b) Surface water investigations

This mainly involved the following:

(i) Water quality measurement comprising the pH and EC of the water as in part (a) above. The measurements were taken 1) before the rains in April, 1989; 2) during the rains and 3) after the rains to see whether the rains caused any marked changes in the surface water quality. The waters were taken from the Lumi river and Kamleza canal. The swamp water quality was also checked in the month of June, 1989.

(ii) Flow measurement in the canals and drains: A 5 ft-Parshall flume (permanent) was installed at the head of Kamleza scheme in the main canal to measure the incoming flows. This was done in February, 1989. Flow measurements were taken every morning and evening. A photo of the flume is shown in Fig. 3.2.
Fig. 3.3: 5-ft. Parshall flume constructed in the main Kamleza canal.

3.2.3: Soil investigations

a) Investigation on the caliche layer:

Two sets of investigations were carried out on the layer. First, the depth to the calcareous layer from the surface was determined using Edelman soil augers (8 cm dia.). The augering was done at all the topo-survey grid points. The caliche level (a.m.s.l.) was obtained by subtracting the measured depth from the known grid point.
ground levels. This investigation covered the period October, 1988 to January, 1989.

The second investigation involved noting the form of occurrence of the layer i.e., whether pervious, slightly pervious or impervious. This was done during well construction.

In addition to the above two investigations, a total of 22 samples of the layer from 18 locations were collected for laboratory chemical analysis.

b) Hydraulic conductivity measurement

Hydraulic conductivity, K, was determined in the field using the auger-hole method (Van Beers, 1963, and Smedema and Rycroft, 1983). The equipment used for determination of the K-value in the field was obtained from Eijkelkamp Agrisearch Equipment, Netherlands.

The investigations were carried out in May-June 1989, when high groundwater tables existed in the area after the heavy rains and floods in April. The sites at which the measurements were taken are presented in Fig. 3.3.

c) Soil sampling for laboratory analysis:

The soils in the area have been investigated at a semi-detailed level by Kanake (1982). However, for this study further investigations were carried out to specifically note:

(i) the influence of groundwater depth and quality on soil salinity at various locations;
Fig. 3.3: Hydraulic conductivity points.
(ii) the influence of topography on soil salinity. This is with particular reference to areas which receive subsurface inflow (or seepage from higher areas);

(iii) the influence of the calcareous layer on soil salinity e.g. in areas with a perched groundwater table, soil salinisation may be more severe than in better or well drained areas;

(iv) the influence of soil texture on soil salinity-sodicity and drainage status, as differences in soil texture often influence the amount of salts retained in the soil (FitzPatrick, 1987). Infiltration of water into the soil is also influenced by soil texture and thus the drainage condition; and

(v) the differences in soil salinity levels in vegetated and fallow land.

Decisions of where to sample soils in the field were based on the above factors i.e. soils were sampled from areas of different groundwater depth and quality; different soil textures; different ground elevations (and slopes); and from cultivated and fallow lands.

A total number of 150 soil samples were collected from 24 locations in the project area indicated in Fig. 3.4. The 24 locations were considered representative of soil conditions around them. If a representative site was near a well, then the soil was sampled from the well.

For areas not near wells, a profile pit, measuring 1.5 x 1.0 m was excavated and thereafter soil samples were taken. In cultivated and high groundwater table areas, soil samples were obtained by use of augers.
Fig. 3.4: Soil sampling locations.
The sampling depth depended on the depth of occurrence of the caliche layer, and had a maximum of 3 m. Sampling down the profile was done according to recommendations by USDA (1954) and Elgabaly (1971).

The sampling intervals were determined as follows:

1. Salt crusts (0-5 cm) were sampled separately;
2. For underlying soil layers, intervals of 15-20 cm were used. However, there were a few cases in which intervals greater 15-20 cm were used mainly based on homogeneity in soil textural and/or colour conditions.

At least 1 kg of soil was sampled from each layer (or interval) in the soil profile and placed in plastic bags (the soil being well mixed) with the date, depth and site indicated on the bag. The samples were collected in March and June, 1989.

3.2.4: Rainfall data collection

Daily rainfall data were collected from the Kenya Malaria Research Station at Kivalwa at the head of the project area near Njoro Kubwa canal (see Fig. 4.1). The rainfall data were collected from October, 1988 to August, 1989.

Data on evaporation were not collected from the field as there was no evaporation measuring facility at the station. Existing data on evaporation for the period 1965 - 1982, i.e. 17 years, was obtained from a publication by Berger and Kalders (1983).
3.3: Laboratory investigations

The laboratory investigations comprised water and soil analysis as presented in the following sub-sections.

3.3.1: Chemical analysis of surface and groundwaters

To determine the cation and anion composition of the surface and ground waters, samples of 3 litres were collected from the field in November, 1988 and May, 1989 (after rains) for analysis at the Ministry of Water Development Quality Laboratories at Industrial Area in Nairobi. A total of 36 samples were collected and analysed. The samples were analysed for:

- pH, EC (mS/cm);
- Cations Ca$^{2+}$, Mg$^{2+}$, Na$^{+}$, K$^{+}$;
- Anions Cl$^{-}$, SO$_4^{2-}$, HCO$_3^-$, CO$_3^{2-}$.

3.3.2: Chemical analysis of the caliche layer

Samples of the caliche layer were analysed mainly to find the percentage content of Ca. The contents of Na, K, Mg, and Fe were also determined. Analysis of the samples was done at the Mines and Geology Laboratories of the Ministry of Environment and Natural Resources, Nairobi.

3.3.3: Soil chemical analysis

The soil samples from the field were analysed for:

- pH and EC (mS/cm) at 25°C;
- Exchangeable cations $\text{Na}^+$, $\text{K}^+$, $\text{Mg}^{2+}$, $\text{Ca}^{2+}$ (in me/100g soil);
- CEC (in me/100g soil).

(i) EC - determination:

The electrical conductivity, EC, was measured using a conductivity meter Bridge. A soil suspension of 1:2.5 (soil:water ratio) was prepared and EC readings taken after at least 15 minutes of settling. The reading obtained was recorded and the room temperature noted. The EC value was then converted to the standard temperature of $25^\circ\text{C}$ by a correction factor as recommended by USDA (1954).

(ii) pH-determination:

Soil pH-values were obtained from suspensions of soil samples in water (1:1 soil:water ratio) and in 0.01M CaCl$_2$ (1:2 soil:solution ratio). A Metrohm Herisar pH-meter, model E350B was used. Readings were taken after the mixture had been allowed to settle for 30 minutes.

(iii) Exchangeable cations

Samples weighing 5g were leached with 100 ml of ammonium acetate at pH 7.0, in stages of 25 ml each (4 leachings of 25 ml each).

A 100 ml of the soil leachate was then taken for the analysis of the exchangeable cations at the Mines and Geology Laboratories, Ministry of Environment and Natural Resources at Industrial area in Nairobi, with an Atomic
Absorption Spectrometer. The determinations of the exchangeable cations was done for single leachates only, i.e. not in duplicate.

(iv) CEC - determination

Since most of the soils in the area are alkaline, as found by Kanake (1982), the CEC of the soils was determined by leaching of 5 g soil samples with 100 ml of 1N sodium acetate at pH 8.2 as recommended by USDA (1954). During this leaching exchangeable cations are replaced by Na⁺-ions. This initial leaching was then followed by a second leaching with 100 ml of 96% ethyl-alcohol to wash out excess sodium ions from the soil. Finally the soil was leached with 100 ml of the 1N ammonium acetate at pH 7.0 during which the Na⁺-ions in the exchange complex are replaced by NH₄⁺-ions. The amount Na⁺-ions in the final leachate was then determined using the same AAS machine as for the exchangeable cations above. The CEC equals the Na-content determined in me/100g soil.

3.3.4: Soil textural analysis

This involved the analysis of the texture of the soil samples for the % clay, % sand, and % silt using the hydrometer method (Brady, 1984).
4.1 Topographical features and ground contours

Based on the topographical data collected, a topographical map of the project area has been prepared as shown in Fig. 4.1. The map covers the area stretching from the Njoro Kubwa canal in the north-west to the Jipe and Ruvu swamps in the south. The Lumi River runs along the Eastern side to the swamps in the South. On the Western side of the schemes lie the Eldoro and Kitogoto Hills and along the Kenya-Tanzania border, flows the Ruvu River from the swamps to Tanzania.

Between the Njoro Kubwa canal and Kimorigo village there occurs a swampy area shown by the dotted lines in the map. The size of the swamp varies, reaching a maximum during the rainy season and approximating the dotted area.

On the topo-map are shown ground contours with a vertical interval of 1.0 m covering an area of around 1200 ha. The area is nearly flat with ground slopes varying from under 0.1% in the Kimorigo, Block C and Ngutini areas to slightly over 1% in parts of Kamleza scheme on the hillslope of Eldoro and Kitogoto hills.

The contours show that the general direction of groundslope and hence surface drainage is from the hilly areas and the upper areas in the North-West towards the Block C area and eventually to the Jipe and Ruvu Swamps in the South.

The longitudinal profile in Fig. 4.2 also illustrates the variations in ground topography in the project area from the Njoro Kubwa canal (point N), along the North-West to South-East road to the edge of Ruvu swamp.
Fig. 4.2: Longitudinal profile from Nyoro Kubwa Canal (point N) to the edge of the Ruvu swamp (point S).

The Ngoro river is dam at 780 m. The main drain is dug at 150 m apart. To make use of the flood, a drainage system in the Kisoro scheme consists of an 8 km long main drain (the Siyungu) and 2.5 km secondary drain (the part above 780 m). The main drain is 200 m across at 150 m apart. The secondary drain is 90 m wide. The secondary drains are built at 150 m apart along the side of the secondary canals.
(point S). In this Fig. 4.2, it can be noted that i) the northern swampy area near Kivalwa occurs in a depression at 1500 - 2500 m, ii) the ground slope changes from 0.4 % before the depression (0 - 1500 m) to 0.1 % in the distance 2500 m to edge of Ruvu swamp at point S, iii) groundwater table slope varies almost the same as the topography (see Chap. 5 for details on watertable), and iv) the caliche layer covers the whole of Kimorigo scheme (see Chap. 6 for details).

From the longitudinal profile in Fig. 4.2, it can be deduced that the area can be drained by gravity as the outlet point is lower than the project area.

4.2 Irrigation and drainage system

(a) Kimorigo scheme

The Kimorigo scheme occupies an area of 140 ha. The main canal serving the scheme originates from the Lumi river. The total length of the main canal (including two branches) is about 7 km long. There are 31 secondary canals, spaced at 150 m apart. There is currently no irrigation in the scheme due to siltation and seepage problems in the main canal. The main canal section between the river and the dyke (approximately 200 m) gets silted annually after flood flows and has become difficult for farmers to maintain. The drainage system in the Kimorigo scheme consists of an 8 km long main drain (the old Kimorigo drain (see Fig. 4.1) and 21 secondary drains on the part above the road. The secondary drains are spaced at 150 m apart and are on the upper side of the secondary canals.
The old Kimorigo main drain starts from the swampy area near Kivulwa and discharges into the Ruvu swamp behind the Kitogoto hill as shown in Fig. 4.1. A longitudinal profile of this old drain from the end of Kimorigo scheme (point L1, near well D5) to the outlet at Ruvu swamp (point L2) is shown in Fig. 4.3. From this profile (Fig. 4.3), it can be noted that i) ground level at outlet is about 6.0 m below the ground level at end of Kimorigo scheme, and ii) the water level at outlet is about 4.0 m below the groundwater table at point L1 (near well D5). As the water level at outlet point is lower than both the ground elevation and groundwater table of the project area, drainage of the area by gravity is possible. The average groundwater table slope is about 0.1 % (also see Chap.5).

The bedslope of the drain is 0.1 % for a distance of 2600 m from the end of the scheme and 0.7 % for the remaining distance of 400 m to the outlet.

The New Kimorigo drain (8.9 Km), which is still under construction by Ministry of Water also discharges into the Ruvu swamp upstream of the old Kimorigo drain outlet. Out of the 8.9 Km, 3.4 Km are yet to be done (see Fig. 4.1).

Due to the inoperation of Kimorigo scheme for long (since 1966, see Chap.2), the irrigation and drainage systems are rarely maintained. All drains are in a poor state being heavily silted and/or vegetated in most parts. The photo in Fig. 4.4 shows a heavily silted part of the old Kimorigo drain (near the Kimorigo village).
Fig. 4.3: Longitudinal profile from end of Kimorigo Scheme
Fig. 4.4: Old Kimorogo drain at head of scheme. In the photo is a measuring weir under construction. (Photo taken end of March before floods).

(b) Kamleza scheme

From the topographical data, it has been found that Kamleza scheme presently occupies an area of 431 ha and not 314 ha as in Ministry of Agriculture records (an increase of 117 ha.). The main supply canal originates from the Njoro Kubwa canal and has a total length of about 9.5 km (including the two branches). There are 32 secondary canals along the main canal. Excess water drains into the old Kimorogo drain. However, as will be explained later in Chap. 5, little or no irrigation water is drained as it is insufficient.

There are no drains in Kamleza scheme and any excess surface water normally ponds until all of it has percolated
to the groundwater table. Any excess irrigation water in the Njoro Kubwa canal often results in high flows in the Kamleza canal, especially if it occurs at night and the control gate is not closed. The high flows overtop the main Kamleza canal and together with increased seepage losses, result in surface water ponding in the Kamaleza North scheme area (see Fig. 4.1). Such an incident was witnessed during the period December, 1988 to January, 1989 and this is as shown by the Photo in Fig. 4.5. This caused a lot of damage to crops as can be seen in the photo.

Fig. 4.5: Flooding of farms in Kamleza North due excess flow in the main canal.
There is a lot of surface runoff from around the Eldoro and Kitogoto hills into the Kamleza scheme. However, this surface runoff does not cause any damage as it gets into the main canal and is subsequently discharged into the Old Kimorigo main drain.

(c) Block C area

This is a formerly rice irrigated area of 400 ha. The irrigation and drainage infrastructure are still evident, only that they are silted and vegetated in most parts. However, during the flood flows, they channel floodwater into the Block C and Kimorigo area and are thus a menace. In Fig. 4.1, only two main drains have been indicated. The irrigation canals and other drains are not shown.

4.3: Flood problem

There exists a serious flood problem in the project area. The floods, as mentioned in Chap.2, originate from the Mt. Kilimanjaro area and occur during the short and long rains. The short rain floods are of low magnitude and do not cause much damage. However, the floods which occur during the long rainy season cause a lot of damage. These floods normally occur between the months of March and May, and for a few days only (flash floods). While there exists a flood control dyke on the project side of the river (see Fig. 4.1), this dyke is ill-maintained and so are the flood and storm drains on the river and landside of the dyke respectively. The floodwaters affecting the schemes pass through a breach (broken area) of the dyke in the upper
areas around Kivalwa (near Njoro Kubwa canal) as shown by the photo in Fig. 4.6. The whole Kimorigo scheme and the lower parts of Kamleza scheme are affected by these floodwaters. The floodwaters affecting the Block C area also originate from breaches in the lower parts of the dyke and are led into the area by existing old drainage canals and the storm water drain on the landside of the dyke (See Fig. 4.1)

Fig. 4.6: Flood flow through a breach near the head of the dyke (Photo taken on 5/4/89 on the day of floods).
As the old Kimorigo main drain is silted, its discharge capacity is reduced. The drain therefore overflows and the floodwaters spread onto the adjacent lands as seen in Fig. 4.7. These floodwaters cause a lot of damage as discussed later in Sec.4.5.

Fig. 4.7: Overflow of the old Kimorigo drain during floods.
(5/4/89)

4.4 Relative elevation difference between the river and project area

From the topographical data, it was found that the river lies at higher elevation than the adjacent lands of the project area as shown by the two longitudinal profiles.
Fig. 4.8: Longitudinal profiles from Kamleza Scheme to the Lumi river.
in Fig. 4.8, from points A2 and A5 in Kamleza Scheme to the Lumi River. The water level in the river is also higher than the adjacent lands. Consequently, it is expected that, i) there occurs overflow from the river to the adjacent lands; most sections between the river and the dyke were noted to be either waterlogged or swampy, except in areas where farmers have constructed open drains and do cultivation after subsidence of floodwaters, ii) there exists subsurface from the river into the adjacent low-lying areas, causing high groundwater tables (this is evident from the two profiles; also see Chap. 5), and iii) overflow of the river onto the adjacent lands during floods is inevitable as the river already runs full in the project area.

In the second profile (Fig. 4.8 (b)), there is a notably wide low area between the river and well E5; this was (is) probably the flood plain area before the dyke was constructed in the early 1970's. Also another low spot occurs between well A5 and D5. Floodwaters from the upper areas around Kivalwa normally pass through this low spot on the way to Ruvu swamp. The watertable and calcareous layer positions shown in the two profiles are discussed in Chaps. 5 and 6 respectively.

The height of the flood control dyke which is about 1.0 m above the ground surface appears to be sufficient; no floodflow was noted occurring over the dyke (see Fig. 4.6). It is probably due to poor maintenance of the dyke that floodwaters have managed to break through weak points in the dyke.
4.5: Discussion

4.5.1 Drainage situation in the area

The topographical results indicate that (i) surface drainage from the area would be low due to the low ground slopes (around 0.1 %), and (ii) the natural subsurface drainage or gravitational outflow from the area would be low as the drainage base is high (the area drains into the Lake Jipe and surrounding swamps).

The prolonged surface water ponding in Kamleza North scheme highlights the serious surface drainage problem in the project area (see Fig. 4.5).

Another important observation that was made during the study is the change in the swamp boundary. In the profile in Fig. 4.2 from Njoro Kubwa canal to the swamp edge, it was found that the current swamp edge is about 600 m further inland (point S instead of S1). This can only be true if the water levels in the lake are rising, encroaching on adjacent land (and encouraging swampy vegetation). Underhill (1955) and Farrant (1966) have in the past reported that water levels in the Lake are rising, due to high amounts of silt brought by the flood waters from the catchment areas of the Lumi River in the slopes of Mt. Kilimanjaro.

According to a report by Kalders (1986), the water level in the Lake Jipe has risen by 1.0 m in the period 1954 to 1986 (32 years); an average of 3 cm/year. Further reports by Farrant (1966), indicate that the swamp area has increased from approximately 259 ha in 1906 to 3627 ha in 1965. A rise in the area’s drainage base level will adversely affect the drainage situation.
4.5.2 **Causes of surface drainage problems in the project area.**

The sources of excess surface water in the project area include i) floodwater, ii) irrigation water, and iii) precipitation. Overflow from the river onto the adjacent land between the river and the dyke can also be considered as a source of excess surface water. By far floodwater can be considered as the major causative factor of the drainage problems, firstly, due to the wide area affected by floods and secondly, the amount of floodwater flowing over the area.

The flood results in siltation of canals and drains, destroys or washes away canals, and causes damage to farms and crops in the schemes. The roads in the project area also get destroyed. Villagers in Kimorigo often have to emigrate to higher ground in severe flood incidences as their houses become flooded (some get destroyed and have to be rebuilt).

After the flood flow over the farms which occurs in early part of the cropping season (mid-March to mid-April), replanting has to be done in most of the farms. Where the crops have not been washed away, the resulting waterlogged soil conditions retards growth and yellowing of crops occur as shown by the photo in Fig.4.9.

In conclusion, the investigations have shown the inadequacy of the existing surface drainage and flood control facilities in the project area and there is need to: (i) Maintain and repair the dyke and the existing drains so as to improve the control of floodwater and any surface flow from either rainfall and/or irrigation. Improvement of the surface drainage status will also reduce amount of percolated water to the groundwater table and thus a reduced
Fig. 4.9: Yellowing of cotton crop under waterlogged conditions in Kamleza South (May, 1989).

... burden for subsurface drainage requirement. The completion of the remaining 3.9 km of the New Kimorigo main drainage canal, with a discharge capacity of 2.5 m³/s will greatly alleviate the drainage problems in the area.

(ii) look into ways of improving the channel capacity of the Lumi river, especially in its lower reaches where the water level is at a higher elevation than the adjacent land (See Fig. 4.5). With continued siltation, both the lake and river water levels are bound to rise to even higher levels
in the future worsening the drainage problems in the area. There will be more flood incidences even at low flows and encroachment of adjacent land by swampy vegetation is bound to increase.

(iii) Improve soil conservation measures in the catchment of the Lumi River in the lower slopes of Mt. Kilimanjaro so as to reduce surface runoff. This may require the cooperation between the two neighbouring governments of Kenya and Tanzania.

The pH and electrical conductivity of the irrigation water (EC) in Kesileza canal and the Lumi River were monitored between March and June, 1989 to check on any variations due to annual occurrence of heavy rains and floods in April.

The results obtained are presented in Table 6.1 and indicate that no major variation occurred in the salt content of the waters during the period March to June, 1989. This occurred on 5 - 4 - 1989 and lasted 2 - 5 days.

The EC of the water sample from the Lumi River on day of the floods was found to be lower than in the days before and after the rains; this could be attributed to dilution of the river water by the flood waters with a lower salt concentration.
5. SURFACE AND GROUNDWATER RESULTS

5.1 Surface water investigation results

Investigations on the surface waters of the project area consisted of (i) monitoring of the variation of the pH and EC in (mS/cm) with time, (ii) determination of the cation and the anion composition of the waters, and (iii) flow measurement in the Kamleza canal (see Chap.3).

5.1.1: Variation in pH and EC of the surface waters

The pH and electrical conductivity of the irrigation water (EC) in Kamleza canal and the Lumi river were monitored between March and June, 1989 to check on any variations due to annual occurrence of heavy rains and floods in April.

The results obtained are presented in Table 5.1 and indicate that no major variation occurred in the salt content of the waters during the period March to June, 1989. Floods occurred on 5 - 4 - 1989 and lasted 3 - 5 days.

The EC of the water sample from the Lumi river on the day of the floods was found to be lower than in the periods before and after the rains; this could be attributed to dilution of the river water by the flood waters with a lower salt concentration.
Table 5.1: Variation of pH and EC (mS/cm) in the Kamleza canal and Lumi River.

<table>
<thead>
<tr>
<th>Place</th>
<th>Date</th>
<th>EC at 25°C</th>
<th>pH</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kamleza canal</td>
<td>27/3/89</td>
<td>0.25</td>
<td>7.4</td>
<td>8.3 before floods in April.</td>
</tr>
<tr>
<td></td>
<td>5/4/89</td>
<td>0.23</td>
<td>9</td>
<td>8.2 day of floods</td>
</tr>
<tr>
<td></td>
<td>22/5/89</td>
<td>0.32</td>
<td>1.3</td>
<td>8.7 after floods, light rains.</td>
</tr>
<tr>
<td></td>
<td>30/6/89</td>
<td>0.24</td>
<td>2.1</td>
<td>8.2 dry season (no rains)</td>
</tr>
<tr>
<td>Lumi River</td>
<td>20/3/89</td>
<td>0.22</td>
<td>7.2</td>
<td>7.9 before floods</td>
</tr>
<tr>
<td></td>
<td>27/3/89</td>
<td>0.20</td>
<td>0.5</td>
<td>8.1 before floods</td>
</tr>
<tr>
<td></td>
<td>5/4/89</td>
<td>0.3</td>
<td>0.9</td>
<td>8.2 day of floods</td>
</tr>
<tr>
<td></td>
<td>30/6/89</td>
<td>0.23</td>
<td>0.7</td>
<td>8.3 dry season (no rains)</td>
</tr>
</tbody>
</table>

5.1.2 Chemical analysis results (laboratory)

The results of the laboratory analysis of the surface waters are as shown in Table 5.2. The waters from Njoro Kubwa canal, Kamleza canal and Lumi river have medium salinity and low sodicity hazards according to the US Salinity Laboratory classification System (Chap.2, Table 2.4). The RSC-value for all the waters is zero, hence there is no danger of sodification from the use of the waters (Chap.2, Tab.2.7).

The swamp water has a high salinity hazard but a low sodicity hazard. Although the sodicity hazard is low, the RSC-value of 9.3 me/l is high (see Chap.2, Tab.2.7) indicating that there is a danger of sodification should the water be used for irrigation.
Table 5.2: Chemical analysis results of various surface waters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Njoro Kebwa canal</th>
<th>Lumi River canal</th>
<th>Kamleza canal</th>
<th>Ruuru swamp</th>
<th>Kimorigo Drain</th>
</tr>
</thead>
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<tr>
<td>pH</td>
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<td>7.4</td>
<td>7.4</td>
<td>8.6</td>
<td>9.2</td>
</tr>
<tr>
<td>EC, mS/cm</td>
<td>269</td>
<td>254</td>
<td>268</td>
<td>1696</td>
<td>2642</td>
</tr>
<tr>
<td>Ca, me/l</td>
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<td>0.9</td>
<td>0.9</td>
<td>2.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Mg, me/l</td>
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<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td>K, me/l</td>
<td>0.3</td>
<td>0.5</td>
<td>0.6</td>
<td>12.3</td>
<td>16.3</td>
</tr>
<tr>
<td>Na, me/l</td>
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<td>0.09</td>
<td>0.1</td>
<td>0.2</td>
<td>0.7</td>
</tr>
<tr>
<td>TH, me/l</td>
<td>2.0</td>
<td>2.1</td>
<td>2.1</td>
<td>3.4</td>
<td>1.0</td>
</tr>
<tr>
<td>TA, me/l</td>
<td>2.1</td>
<td>2.0</td>
<td>2.0</td>
<td>12.8</td>
<td>17.4</td>
</tr>
<tr>
<td>Cl, me/l</td>
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<td>0.3</td>
<td>0.08</td>
<td>2.5</td>
<td>8.3</td>
</tr>
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<td>SO4, me/l</td>
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<td>0.1</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>SOR</td>
<td>0.3</td>
<td>0.5</td>
<td>0.6</td>
<td>9.3</td>
<td>23.1</td>
</tr>
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<td>RSC, me/l</td>
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<td>0 (7)</td>
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<td>C2-S1</td>
<td>C2-S1</td>
<td>C3-S1</td>
<td>C4-S4</td>
</tr>
</tbody>
</table>

NB: TH = Total Hardness     TA = Total Alkalinity

The water from Kimorigo drain is of the poorest quality of all the surface waters, with a very high salinity hazard (C4) and a high sodicity hazard (S4); this shows that the drain helps in removing salts from the area. The RSC-value is also high, indicating the potential sodification danger.

5.1.3: Quantity of irrigation water in the main Kamleza canal

Water flows in the main Kamleza canal at the head of the scheme were measured by means of a 5 ft. Parshall flume. Flow data were collected from the second week of March, 1989 to end of July, 1989. The water depth measurements at the flume were converted into discharge units (l/s) by use of standard tables for a 5 ft. Parshall flume. The flows
obtained in l/s as average (from 2 daily readings) for a 24 hour duration are given in Table 5.3.

Table 5.3: Discharge in the main Kamleza canal at head of scheme (l/s) - 1989.

<table>
<thead>
<tr>
<th>Date</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
</tr>
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<tbody>
<tr>
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<td></td>
<td>156</td>
<td>43</td>
<td>136</td>
<td>236</td>
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<td>2</td>
<td>146</td>
<td></td>
<td>43</td>
<td>72</td>
<td>250</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>146</td>
<td>&lt; 43</td>
<td>63</td>
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<td>112</td>
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<td>104</td>
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<td>82</td>
<td>205</td>
<td>57</td>
<td>205</td>
<td>270</td>
</tr>
<tr>
<td>9</td>
<td>82</td>
<td>241</td>
<td>(71)</td>
<td>35</td>
<td>245</td>
</tr>
<tr>
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<td>186</td>
</tr>
</tbody>
</table>

NB: (47) = Flow determined assuming 96% submergence, otherwise actual submergence is 100%. For all other cases without the brackets, the submergence ratio is less or equal to 96%.
The bracketed flows correspond to periods of 100% submergence as a result of heavy growth in the canal causing water back-up up to the flume structure (see footnote at end of Table 5.3).

Irrigation mainly takes place in the months of June to October when there is very little or no precipitation (see Table C-1, Appendix C). Cotton, maize and vegetables are the main crops grown under irrigation between March to July/August. From September to December, only maize and vegetables are cultivated. From the data in Table 5.3, normal water flow in the canal occurred during the month of July, the average daily flow being 250 l/s. In the months of January to Mid-March, farmers carry out land preparation and any water in the canal is mainly for domestic and livestock consumption. From mid-March there is some irrigation but this halts with the onset of heavy rains in late March to May.

The graph in Fig. 5.1 shows the variations in the daily flows in the main canal. Peak flows of around 400 l/s occurred when there were floodflows in the main Kamleza canal. Two other high flows of around 350 l/s in May and June are due to excess flow in the canal, possibly as a result of high water levels in the Njoro Kubwa canal from where Kamleza scheme gets its water. Periods of zero flow in the canal correspond to times when there is canal maintenance and/or repairs.

The total scheme area of Kamleza was found to be 431 ha. However, the area under irrigation is lower than this due to either salinity or absentee farmers (see Chap. 6 for details on areas affected by salinity). The average discharge of 250 l/s is not sufficient for the 431 ha. Considering the month of October with the highest
evapotranspiration of 4.8 mm/day (see Table C-2, App.C), during the irrigation seasons, the scheme water requirement for a 24 hour daily irrigation with an average crop factor of 0.9 and overall irrigation efficiency of 50% is 0.9 l/s/ha. For 431 ha., the discharge required would be 388 l/s. The 250 l/s would be sufficient for 278 ha. Farmers normally complain of insufficient water, especially those at the tail end of the scheme, and the flow measurement results prove that this is so.
Fig. 5.1: Variations in canal flows at the head of Kamleza scheme.
5.2: Groundwater investigation results

Investigations on the groundwater conditions of the area comprised field measurement of the depth to the groundwater table and monitoring of the pH and electrical conductivity of the groundwater. Samples of the groundwater from the field were also analysed in the laboratory to determine its cation and anion composition.

The detailed results on the depth to groundwater measurements are presented in Tables A-1 and A-2, Appendix A for the period October, 1988 to August, 1989 (10 months). The pH and EC-values measured in the field are in Table A-4 while the cation and anion composition data are in Table A-5 of Appendix A.

Using the depth to groundwater data, two groundwater maps were prepared, namely, the groundwater table contour map and the depth to groundwater contour map. A salinity map has also been prepared using the EC-data from the field.

An analysis of the groundwater conditions employing the above mentioned data and maps is presented in the following sections.

5.2.1 Groundwater table contour

A groundwater table contour map has been prepared for the last week of July, 1989 by drawing lines of equal watertable elevation. The water table levels (a.m.s.l.), were obtained by subtracting the depth to water level measurements of 28/7/89 from ground surface elevations at the observation points (see Table A-3, Appendix A). A
total of 52 observations points (41 open wells, 6 auger holes, and 5 river water levels have been used in the preparation of the watertable contour map (Fig. 5.2).

The date of 28/7/89 was chosen as it had the maximum number of water table measurements. In addition, the date falls within the irrigation season; this makes it possible to see the influence of irrigation on the groundwater table contours of the area.

Groundwater flows from the Lumi river, higher areas around Njoro Kubwa canal and also from the irrigated areas of Kamleza North, and converges in the central part of Block C and thereafter flow southwards to the swamps as indicated by the flowlines in Fig.5.2. There is also direct flow of groundwater from Kamleza North towards the Ruvu swamp.

Groundwater slopes along the flowlines have been calculated, the highest slopes being found close to the Lumi River, averaging 0.4%. Lowest groundwater slopes, ranging between 0.08 - 0.12 % occur in the Block C and Ngutini areas, and also in the upper parts of Kimorogo scheme and the adjacent areas of Kamleza scheme. The central to lower areas of the schemes have groundwater slopes of around 0.2 %.
5.2.2: Depth to groundwater table

5.2.2.1: Depth to groundwater table data analysis

Using data on the depth to groundwater table (Table A-1, Appendix A), a depth to watertable contour map and 10 well hydrographs (App.A), have been prepared. The depth to groundwater table contour map is to help in identifying areas with drainage problems since it shows the relative watertable depths in various parts of the project area. The well hydrographs enable identification of periods with critically high watertables, when additional drainage may be required. In addition, by noting the dates when there is precipitation, irrigation, floods etc, on the hydrographs, it is possible to relate the change in groundwater table to one or more of the possible causes, such as excess precipitation and derive certain characteristic values such as the drainable pore space.

5.2.2.2 Depth to groundwater table contour map

From the depth to groundwater table contour map in Fig.5.2, the relative watertable depths in various places in the project area during the last week of July, 1989 can be described. In the northern areas close to the Lumi river and around the swamp between Kivalwa and Kimorigo scheme, the watertable depth is under 0.5 m. Between the swampy area and the upper parts of Kimorigo and Block C areas, the watertable varies from 0.5 - 1.0 m.
Fig. 5.3: Depth to groundwater table contour map.
In most parts of Block C area, the watertable at this period lies in the range 1.0 - 1.5 m, except in areas closer to the river where watertable depths under 1.0 m occur.

In Kimorigo scheme, the watertable depth varies from under 1.0 m in the upper areas to 1.5 m in the central areas. Towards the end of the scheme and in the adjacent Ngutini area, the watertable depth is greater than 2.0 m. The depth to the groundwater decreases closer to the swamps and becomes less than 0.5 m from the surface at the swamp edge.

Watertable depths in Kamleza scheme vary from under 0.5 m around well B2 in Kamleza North to over 2.0 m in the higher areas around the Eldoro and Kitogoto hills. In most parts of the scheme, ranging from the northern to southern areas, the watertable depth lies between 1.0 and 1.5 m.

5.2.2.3: Variation of groundwater table depth with time

Well hydrographs representing 10 locations are presented in Figs. A-1 to A-10, appendix A. The hydrographs represent different parts of the project area.

In the upper areas around Well E0, (Fig. A-1), groundwater tables remain close to the ground at around 0.25 m almost throughout the year. This is attributed mainly to subsurface groundwater supply from the river and from the higher areas around the Njoro Kubwa canal, as shown by the flowlines in the watertable contour map, Fig. 5.1. Similarly, subsurface inflow from the river maintains the groundwater table in most parts of the Block C area at 1.0 m before and after the rains. In April, the groundwater table
rises to the surface and remains under 0.5 m from the surface for up to two months (see Fig. A-10).

In Kimorogo scheme, flooding and precipitation causes high groundwater tables in the months of April and May. Subsurface inflow from the irrigated areas of Kamleza North, particularly in the months of June to August, causes a groundwater table rise during this period (see Figs. A-2 and A-3, App.A).

In Kamleza scheme, groundwater table changes are influenced mainly by irrigation water and excess precipitation in the months of April and May. The highest groundwater tables are however caused by percolation of excess irrigation water. Notable periods are the months of December – January and June to August (see Figs. A-6 to A-9, App.A). In the southern parts of the scheme, subsurface inflow from the upper irrigated areas often causes high groundwater tables and this is particularly the case in the months of July and August when the groundwater table stays at a constant level of 1.0 m from the surface (see Fig. A-8, App.A). In the lower parts of Kimorogo and Ngutini, deep groundwater tables greater than 2.0 m often occur. Changes in the groundwater table are mainly caused by excess precipitation and to a lesser extent by floods as in the lower parts of Kimorogo scheme (see Fig. A-4). The partly constructed New Kimorogo drain prevents flood flow over the areas in Ngutini and thus the little change in water table position after the floods.

The lowest groundwater tables in the whole of the project area occurred in the months of February and March, a period of low precipitation and little if any irrigation as it is mostly land preparation that is being undertaken.
5.2.3: **Groundwater quality**

Groundwaters from different parts of the project area were sampled and analysed for the salinity level (EC); pH, cation and anion contents of Na⁺, Ca²⁺, Mg²⁺, K⁺, Cl⁻, SO₄²⁻, HCO₃⁻ and CO₃²⁻; and also the total hardness (TH). Analysis of the data obtained is presented in the next two paragraphs.

The groundwater salinity data monitored at different periods (times) are presented in Tables A-4 and A-5, Appendix A. A study of these tables reveals the wide variations in salinity occurring in the project area. The EC-value varies from 0.34 mS/cm at well B2 in January, 1989 (Kamleza Scheme) to 88.6 mS/cm at well E4 in July, 1989 (between Kimorigo Scheme and Block "C" area).

The relative variation in salinity with place is illustrated by the groundwater salinity map (Fig.5.4). Average salinity values for the period Oct., 1988 to July, 1989 have been used in preparing the salinity map. Low groundwater salinities under 2 mS/cm occur in most parts of Kamleza scheme and also in areas close to the Lumi river. Towards Kimorigo and the Block C areas, there is a notable increase in the groundwater salinity level. The groundwater salinity level in most parts of Kimorigo for the period averages 8 mS/cm and above with extremely high salinity levels of above 30 mS/cm around well E4 between the Block C and Kimorigo area. The higher salinity of the groundwater in the Kimorigo and the Block C area can be attributed to a possible net inflow of groundwater (and salts). The water table contour map in Fig.5.1 shows that the two areas (Block C and Kimorigo) receive groundwater inflow from the Lumi.
river and Kamleza scheme).

In the southern parts of Kamleza scheme and the Ngutini area, salinity levels are also high, being over 30 mS/cm around wells A5, A6 and B6. These areas also receive seepage inflow from the higher areas and Figs. 4.1 and 4.5 (Chap. 4) show that this is so.

The sodicity levels of the groundwaters also vary as shown by the SAR-values of 24 wells in Table 5.4. Low sodicity levels of under 10 occur in the areas with low groundwater salinities such as Kamleza scheme. The SAR-values range from 0.5 at well D4 to 410 at well F5 in the Block C area. The cause of the high sodicity levels are discussed later in Sec.5.4.
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</table>
5.3: Discussion

5.3.1 Irrigation water and possible influence on soil salinity in the project area.

Investigations on the quality of the canal and river waters reveal that the waters have low salt content and are therefore suitable for irrigation. Provided that there is sufficient leaching and drainage in the irrigated areas, no salinity problems associated with the river and canal waters are expected in the long run. However, leaching and drainage are inadequate as has been mentioned in the literature review (Chap.2). It is therefore possible that since the inception of the Kimorogo and Kamleza schemes, salinisation due to irrigation could have occurred. An estimate of salt deposited by irrigation water can be estimated once the cropping pattern, crop water requirement and effective rainfall in the project area are known. This has been done below as follows:

(a) Cropping pattern:

Crop production is mainly in the months of March – July when mainly cotton and maize are cultivated. During August, there is harvesting and land preparation for the second season, which starts from September – December and the main crops grown are maize and vegetables. January and February are periods of harvesting and land preparation.
(b) **Crop water requirement:**

The potential evapotranspiration can be obtained from Table 2.1 through multiplication of the potential evaporation by 0.8. For the cropping seasons, the ETP's are:

March - July : 974 mm
September - Dec. : 1120 mm
Total ETP : 2094 mm

Considering an average crop factor of 0.9, the crop water requirement becomes 1885 mm for the two cropping seasons. The effective rainfall as calculated by Berger and Kalders, (1983), for Taveta are given in Table 5.5 below:

**Table 5.5: Effective rainfall for Taveta.**

<table>
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<th>Month</th>
<th>J</th>
<th>F</th>
<th>M</th>
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</table>

Taking into account the effective rainfall for the two cropping seasons, the irrigation water requirement after applying an efficiency of 0.5 becomes:

\[
\text{Crop water requirement} = \frac{(1885 - 370)}{0.5} = 3030 \text{ mm}.
\]

The amount of salts brought by irrigation water per year can thus be estimated. Considering irrigation water
quality of 0.25 mS/cm (≈ 160 ppm ≈ 160 mg/l), the amount of salts deposited in the soil per ha. is 4848 kg (4.848 tonnes). If these salts are not removed from the soil, they will accumulate and eventually result in salty soil conditions unfavourable for crop growth. Kamleza irrigation scheme has been in existence for 27 years (1963 - 1990). The total amount of salts brought by irrigation water over this period and deposited in the soil approximates 130 tonnes/ha.

From field investigations at different sites of the schemes, it was found that the rootzone depth never exceeds 50 cm, whether for cotton or maize. Considering an average bulk density of the soil as 1400 kg/m³, the increment in salt content over the 27 years in the 50 cm depth would be 1.8%.

According to reports by Elgabaly (1971), and El-Dujaili and Ismail (1971), salt content of 1% in the soil is equivalent to 23.1 mS/cm. Therefore, a salt content of 1.8% would be equivalent to 42 mS/cm and this salinity level would be unfavourable virtually for all crops. This is supported by Arar (1971), who mentions in the same report that a salt content of 0.5% in the soil rootzone is too high for most crops. The soil results presented in Chap. 6 indicate that higher soil salinity levels do actually exist in the scheme.

5.3.2 Causes of high groundwater table in the project area.

From the results on groundwater table conditions, it can be said that most parts of the project area are poorly drained. Groundwater tables remain high or close to the ground for long durations indicating that natural subsurface drainage outflow from the area is low. The low groundwater slopes of around 0.1% in most parts of the area confirm the low natural or gravitational outflow from the area.
The sources of excess water supply to the groundwater table in the project area are precipitation, irrigation, floodwater and seepage inflow from the Lumi river and also from high to low groundwater table areas. Groundwater supply from precipitation and floodwater occurs mainly in the months of April and May. Supply from irrigation happens normally during the irrigation seasons, with a peak in the months of June and July when there is very little precipitation.

Subsurface inflow from the river occurs throughout the year to all the adjacent low lying areas on the project side. This inflow from the river is the cause of the swampy conditions between Kivulwa and Kimorigo (the northern swamp). Fig. 4.4 shows high groundwater table conditions starting at around well D0, the edge of the swamp. The water table contour in Fig. 5.2 also shows flowlines from the river into this swampy area. In Fig. 4.5, the water elevation at the river is seen to be higher than the watertable elevation of the adjacent lands in the Block C area, confirming that there is subsurface inflow from the river. In Chapter 2, it was reported that the failure of the Block C scheme was due to waterlogging and salinity problems. Knowing that there exists seepage inflow from the river, waterlogging was inevitable in the absence of adequate drainage.

Groundwater balance assessment presented in Chap. 7, gives an estimate of the net subsurface inflows, especially within the Kimorigo and Kamleza schemes. The influence of floodwater on the groundwater water table can be said to most pronounced. Immediately after floodwater flow over the area, groundwater tables remain high for long durations as already reported. Flood control is therefore important to reduce its influence on the areas groundwater system.
5.3.3: Causes of high groundwater salinity in project area

As mentioned in Chap.2, high groundwater salinity in irrigated areas is often associated with i) low rainfall and high evapotranspiration and thus little percolation to cause groundwater refreshment, ii) seepage inflow which inevitably brings with it some salts, and iii) poor drainage conditions which result in low salt efflux. In the project area, low rainfall and high evapotranspiration conditions exist, thus promoting the development of high groundwater salinity conditions. Differences in groundwater salinity in the project area can be attributed to differences in seepage inflows, amount of leaching by irrigation water and drainage conditions (rainfall and evapotranspiration being the same).

In the irrigated areas, relatively low groundwater salinities occur and this is due to regular refreshment by percolating irrigation water and also sufficient groundwater discharge away from these irrigated areas causing evacuation of excess salts. Similarly, low groundwater salinity in the sections closest to the river can be attributed to constant fresh sufficient groundwater discharge from the river and hence excess salts (see Fig. 5.2, watertable contour). However, with increasing distance away from the river towards the low-lying and nearly flat area of Block C area, there is a notable increase in the groundwater salinity. As can be seen from the watertable contour map in Fig. 5.2, there is seepage inflow into the Block C area and this possibly brings in more salts than what is discharged away, resulting in the noted high salinity levels. The relatively lower groundwater slope in the Block C area than at the river, is an indication that the outflow from the area is less than the inflow, high capillary rise occurs and salts
may accumulate on the surface and in the groundwater. Similarly, the low groundslope in the Block C area also indicates low natural drainage outflow and would encourage accumulation of salts in the groundwater.

In the central part of Kimorigo scheme between wells D3 and D4, groundwater salinity is relatively lower than in adjacent areas which also receive seepage inflows e.g., the upper areas of Kimorigo scheme (see sec.5.3). This means that the drainage discharge from the central area is better than in the other adjacent areas. On the other hand, there could be some fresh groundwater supply from below (a deeper aquifer). This is possible as the groundwater salinity remains low whether or not there is precipitation or seepage from the irrigated areas of Kamleza North.

The high groundwater salinity around well C3 in the central part of Kamleza scheme, despite regular refreshment from excess irrigation water, can only be true if there is impeded drainage. The underlying calcareous layer is impervious and perched groundwater occurs (see Chap.6). Accumulation of salts in-situ is therefore possible resulting in high groundwater salinity. Similarly, in the southern areas of Kamleza scheme around wells B5 and C5, the high groundwater salinities can be attributed partly to accumulation of salts in-situ due the occurrence of an impervious calcareous layer at shallow depth (see Chap.6), and partly to seepage inflow from higher irrigated areas bringing with it salts. In the Ngutini area around wells A6 and B6, the high groundwater salinities can be attributed to seepage inflow from higher areas and to poor drainage conditions, and thus low salt efflux from the area (see Fig. 5.2).
5.3.4: Possible influence of high groundwater table and salinity on soil salinisation in project area.

As the salty groundwater occurs at shallow depth, capillary salinisation is expected to be substantial, especially in unirrigated areas where for most parts of the year there is very little rainfall and thus minimal leaching. After the rains and floods, groundwater tables remain at high levels for long durations and thus re-salinisation from groundwater may occur, negating the leaching effect of the rains. A salt balance assessment, incorporating capillary rise from the groundwater is presented in Chap.7.

In Chap.2, it was mentioned that salty groundwater should not stay in the rootzone for more than 48 hours to prevent injury to crops. The results on the watertable depths show that it takes up to 2 months for the watertable to fall below 0.5 m as shown by the well hydrographs. Injury to crops will therefore be inevitable. While it was mentioned in Chap.2, that the critical salinity for groundwater should lie between 2.3 - 4.7 mS/cm, it can be seen from the results presented that higher groundwater salinities do occur and at depths less than the critical depth of between 2.5 - 3.0 m. It is for certain that substantial capillary salinisation occurs.

5.3.5: Factors promoting capillary salinisation in project area.

Among the factors which can be considered as influencing capillary salinisation include seepage inflow, leaching and drainage and the high evapotranspiration over rainfall in the area. Seepage inflow from the river into the
low-lying adjacent areas on the project side ensure maintenance of high groundwater tables for most parts of the year, promoting upward capillary flow and hence salinisation. Inadequate leaching, especially in unirrigated parts as in Kimorigo scheme allows accumulation of salts in the soils. Poor or inadequate drainage result in low salt efflux from the area, and this is evident from the high groundwater salinities in various parts of the project area. High groundwater table conditions for long durations are also indicative of poor or inadequate drainage. Re-salinisation is therefore certain to occur in the area under the prevailing drainage conditions.

The high evapotranspiration rate over rainfall (1900 mm and 600 mm respectively), certainly ensures a net upward salt movement by capillary rise, especially in areas with high groundwater tables as already mentioned, thus promoting capillary salinisation.

5.3.6 Possible remedial measures

In order to improve the drainage conditions in the project area, it is important that measures to either reduce the groundwater recharge and/or increase the discharge of excess groundwater from the project area should be undertaken. The groundwater recharge components include i) subsurface inflow from higher areas, ii) percolating rain, iii) percolating floodwater, and iv) percolating irrigation water.

Of the four mentioned groundwater recharge components, influence of floodwater on the groundwater table is the most widespread, covering many parts of the project

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area (see sec. 5.2). The resultant high groundwater tables for long durations promote capillary salinisation. This calls for the need to control the floodwater flow over the area to reduce the recharge to the groundwater table as mentioned in Chap. 4. Surface drainage in the project area is also inadequate, with ponding surface water being common, thus causing high recharge to the groundwater system. The need to install additional surface drainage canals to enable quick discharge of excess surface water from the area is thus recommended. The completion of the main Kimorogo drain will greatly help in alleviating the surface drainage problems.

Measures to improve the subsurface drainage conditions in the schemes include provision of adequate subsurface drainage facilities for rapid removal of excess groundwater, and also to lower the groundwater table to below the critical water table depth. A means of demineralisation of the groundwater to lower its salinity level can also be considered.

The depth to which the groundwater table in the schemes can be lowered depends on the water level at the outlet (Ruvu swamp). For the month of November, 1988, the water level at the outlet was found as 706.8 m (a.m.s.l.). At well B5, the water level was 708.8 m (a.m.s.l). The distance between the two points is 1800 m, and the groundwater slope then was 0.1%. As the groundwater levels at well B5 are known for all the other months up to August, 1989 (see Tables A-1 and A-2, App.A), the water levels at the outlet can be approximated by subtracting 1.8 m from the groundwater levels of well B5. The results are as shown in Table 5.6 (also see watertable contour map in Fig.5.2 for location of well B5 and the outlet point, L2). The surface elevation of well B5 is 711.55 (see Table A-3, App.A).
Table 5.6: Average monthly watertable levels at well B5 and Outlet (L2).

<table>
<thead>
<tr>
<th>Month</th>
<th>Watertable at B5 (m)</th>
<th>Watertable m(b.g.)</th>
<th>Water elevation depth at B5</th>
<th>Water elevation at B5</th>
<th>Water elevation at outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.92</td>
<td>710.6</td>
<td></td>
<td></td>
<td>708.80</td>
</tr>
<tr>
<td>Feb</td>
<td>0.89</td>
<td>710.7</td>
<td>710.5</td>
<td></td>
<td>708.9</td>
</tr>
<tr>
<td>Mar</td>
<td>1.24</td>
<td>710.3</td>
<td></td>
<td></td>
<td>708.11</td>
</tr>
<tr>
<td>Apr</td>
<td>0.63</td>
<td>710.9</td>
<td></td>
<td></td>
<td>709.1</td>
</tr>
<tr>
<td>May</td>
<td>0.12</td>
<td>711.4</td>
<td></td>
<td></td>
<td>709.6</td>
</tr>
<tr>
<td>Jun</td>
<td>0.6</td>
<td>711.0</td>
<td></td>
<td></td>
<td>709.2</td>
</tr>
<tr>
<td>Jul</td>
<td>0.7</td>
<td>710.8</td>
<td></td>
<td></td>
<td>709.0</td>
</tr>
</tbody>
</table>

The highest water level at the outlet occurred during the month of May, 1989 and was 709.6 m (a.m.s.l.). This water level can be compared with the desired water levels in the main drain for parts of Kimorogo and Kamleza schemes at points D5 (end of Kimorogo scheme), D2 (start of Kimorogo scheme). The ground surface elevations at wells D5 and D2 are 712.94 and 715.77 m respectively. Applying the minimum slope of 0.05 %, water levels in the drain can be determined. The results are shown in Table 5.7.

The water elevations in the drain become 3.27 m at site D2, 1.94 m at D5 and 1.05 m at B5. The results indicate that it is possible to have deep field drains greater than 2.5 m depth around site D2 in the upper areas of Kimorogo and Kamleza schemes. In the lower areas, the field drain depth will be less than 1.9 m around well D5 and less than
Table 5.7: Water levels in main drain along D2 to L2

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance (m)</th>
<th>Elevation (m a.m.s.l)</th>
<th>Slope %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet (L2)</td>
<td>0</td>
<td>709.6</td>
<td>0.05</td>
</tr>
<tr>
<td>B5</td>
<td>1800</td>
<td>710.5</td>
<td>0.05</td>
</tr>
<tr>
<td>D5</td>
<td>2800</td>
<td>711.0</td>
<td>0.05</td>
</tr>
<tr>
<td>D2</td>
<td>5800</td>
<td>712.5</td>
<td></td>
</tr>
</tbody>
</table>

1.0 m around well B5. Control of capillary rise through installation of deep drains in the lower areas of Kamleza scheme is therefore difficult due to lack of sufficient head. The recommended water table depth for preventing capillary rise into the rootzone lies between 2.5 - 3.0 m. (D5) and 1.05 m (B5).

The recharge to the groundwater table due to excessive irrigation can be reduced through improved water distribution and application. Only the correct amount of water at the right time should be applied to avoid over-irrigation and thus high recharge to the groundwater table. Enough water should also be applied to ensure that sufficient leaching of salts occurs.
6. SOIL ANALYSIS RESULTS

Results of soil investigations in the field are presented here in three sections. The first section is on the calcareous layer, the second on the soil chemical and textural analysis and the third section is on hydraulic conductivity.

6.1 The calcareous horizon

Investigations on the calcareous layer comprised determination of the nature of the layer (whether petrocalcic or calcic (see Chap. 2)). A chemical analysis of the layer was also carried out to give indications of the carbonate content and relate to the percentages represented in Sec. 2.5.3, Chap. 2. In addition to determining the nature of the layer, the depth of occurrence of the layer too was determined. The results are presented in the next two subsections.

6.1.1 Types of horizon in the project area

Two main types of the calcareous layer were found to exist in the project area, namely, calcic and petrocalcic horizons. The calcic horizon occurs mostly outside the scheme areas, especially in areas towards the swamps and River Lumi, and in the Block C and Ngutini areas. However, close to the river and near the southern swampy areas, no calcic or petrocalcic horizon exists.

The petrocalcic horizon is found in almost all parts of Kamleza and Kimorigo schemes, occurring in different forms. Some horizons are pervious while others are
completely impervious.

In the areas around Kitogoto hill, no calcic or petrocalcic horizon was found at depths of 3 - 4.5 m (around well A5). However, calcareous nodules and small concretions do occur in the profile.

Eight different forms were distinguished. In Table 6.1, the wells at which the various forms occur are given.

Table 6.1: Types of the calcareous horizons in the project area.

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Form of occurrence</th>
<th>Well no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>discrete nodules</td>
<td>D3, D4</td>
</tr>
<tr>
<td>II</td>
<td>cemented nodules with holes</td>
<td>B2</td>
</tr>
<tr>
<td>III</td>
<td>cemented layer of nodules (impermeable)</td>
<td>A2, B5, C3</td>
</tr>
<tr>
<td>IV</td>
<td>massive encrustation of well B3 to D3</td>
<td>C2, D1, D2, E2</td>
</tr>
<tr>
<td></td>
<td>with fine pores (single layer), semi-permeable</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>massive encrustation with fine pores of 2-3</td>
<td>C1, C4, C6, D5</td>
</tr>
<tr>
<td></td>
<td>distinct layers, s-permeable</td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>massive encrustation with no pores (single layer), impermeable</td>
<td>B4, C5</td>
</tr>
<tr>
<td>VII</td>
<td>earthy CaCO₃ layer (calcic horizon)</td>
<td>D6, D7, E4, F</td>
</tr>
<tr>
<td>VIII</td>
<td>earthy CaCO₃ horizon underlain by a layer of sands and pebbles</td>
<td>E5, E6, E7, F5</td>
</tr>
</tbody>
</table>
(A) : Discrete nodular layer (Form I)

This type of CaCO₃ accumulation is found in the central part of Kimorogo scheme from well D3 to D4. It consists of discrete calcareous nodules (hard concentrations). These nodules resemble calcareous tuffaceous grits obtained around the lower slopes of Mt. Kilimanjaro. Fig. 6.1 shows the nodules obtained from well D3 at a depth of about 1.7 m.

The nodules have holes in them. The shape can be described as botryoidal (bears resemblance to a bunch of grapes).

Porosity of the layers is very high at the two wells due to the discontinuity of the nodular horizon. As can be seen in Fig. 6.1, the nodules have minimal earth between them or within the holes. Deepening of well D3 to find out what occurs further down the profile was prohibited by too much water at shallow depth (=1.0 m).

At well D4, the nodules were coated with more earth, as opposed to the nodules found at well D3 mentioned above. The nodules started at a depth of about 1.0 m and as the depth increased to 2.4 m, there was a notable increase of soft concentrations of CaCO₃ or nodules. In addition, the proportion of sand and gravel particles increased between 1.0 - 2.4 m.

The CaCO₃ content of the nodules is 49% at well D3 and 55% at well D4. The general carbonate contents for nodular concentrations was mentioned in Chap. 2 as less than 60%, which agrees with the contents obtained.
Fig. 6.1. Discrete nodules, obtained from well D3 (Type I).

(B): **Nodular layer with holes (Form II)**

This form was found at depths of around 1.0 m at well B2 in Kamleza scheme. It consists of a cemented layer of nodules with holes in them. The porosity of the layer is as high as for Type I. Pieces of the layer also bear resemblance to those of Type I. As at well D3, it was not possible to investigate what lies at greater depths due to too much water below 1.0 m.

The CaCO$_3$ content of this layer is 67% which is in agreement with other values for a cemented layer, which are normally greater than 60% (see Chap. 2).
**Nodular layer with no holes (Form III)**

This type occurs in Kamleza scheme around wells A2, C3 and B5. It consists of nodules cemented together forming a continuous impermeable crust (nodular encrustation). Perched water occurs on top. At well A2, the layer started at a depth of 2.1 m; at C3, 1.5 m and at B5, 1.8 m. Fig. 6.2 shows pieces of the chiselled layer from well C3 in Kamleza scheme. From the photo, it can be seen that some reddish earth appears on the surfaces of the nodules. This is an indication that previous to the development of the cemented layer, some earth was present and this was not completely displaced during the cementation process.

The thickness of the layers varied; 50 cm at well A2; 75 cm at well C3 and 65 cm at well B5. The CaCO$_3$ contents were 64% at well A2 and 55% at well B5.

Concretions and nodules occur both above and below the layer. The ones above the layer are covered by a mixture of whitish CaCO$_3$ and reddish brown earth. Underneath, the nodules are coated with whitish CaCO$_3$. Water occurs immediately underneath the cemented layer in all these wells. Deeper down the profile, smaller and softer nodules are more abundant as are gravel and sand particles.

Fig. 6.3 shows pieces of the encrustation from well B5 in Kamleza scheme.

Due to the fine pores filled with soil, these two layers are pervious, though not as pervious as type III. In places where the layer occurred within the table area such as in the upper areas of Kisorigo and the adjacent parts of Kamleza scheme, water was allowed to ooze as the layers were chiselled through.

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Fig. 6.2: Pieces of the nodular cemented calcareous layer from well C3 in Kamleza scheme (Form III).

(D) : Massive encrustation with fine pores (Forms IV and V)

Types IV and V are similar in that they are both massive encrustations with fine continuous pores filled with soil. Type V occurs in layers of 2 or 3, while Type IV occurs as a single continuous horizon. Fig. 6.3 shows chiselled pieces of the encrustation from well D5 in Kimorogo scheme.

Due to the fine pores filled with soil, these two types of layers are pervious, though not as pervious as types I and II. In places where the layer occurred within the water-table zone such as in the upper areas of Kimorogo scheme and the adjacent parts of Kamleza scheme, water was observed to ooze as the layers were chiselled through.
This type of layer was found to occur at depths between 0.8 m at well C1 to 1.75 m at well C6. The thickness of the Type IV petrocalcic layer varied from 45 cm at C2 to 100 cm at wells D1 and D2. Each layer of the layered petrocalcic horizon (Type V) was between 10 - 30 cm thick.

Below the layer there is a discontinuous accumulation of nodules in a thick paste of whitish CaCO₃. Deeper down the profile softer concretions, sand and gravel particles are found, as e.g. at wells C4 and D5.

The CaCO₃ content was 65% at well D1 and 59% at well D5.

Fig. 6.3: Pieces of massive encrustation from well D5 (Form IV).
**Massive encrustation with no pores (Form VI)**

This type occurs around well C5 in Kamleza scheme close to the main drain. This is a massive encrustation with no pores and is therefore impervious. When chiselling through, it breaks into large pieces of solid rock as shown in Fig. 6.4.

There are nodules occurring above and below the layer, those below being covered with a thick whitish coating of CaCO$_3$. The nodules above also have coatings of CaCO$_3$ but not as much.

![Image of massive encrustation from well C5 (Form VI).](image.jpg)
Due to the impermeability of the layer, a perched watertable is often found (see Chap. 5). Immediately below the layer there exists confined groundwater. The CaCO$_3$ content was 62% at well B4 and 44% at well C5.

(G) : Earthy CaCO$_3$ (Calcic horizon) - Type VII

This type of calcium carbonate accumulation consists of discontinuous soft and hard concentrations (nodules) in a layer of whitish - yellowish - brown earth as shown in Fig. 6.5.

Fig. 6.5: Whitish - yellowish - brown calcareous earth (Type VIII).
The top soil in most places with such calcic horizons is black heavy clay. The earthy layer starts at about 1.0 m at wells E4 and F2. The thickness of these layers was 75 cm (E4) and 100 cm (F2). An indurated nodular layer of about 10 cm occurs at the bottom of the calcic horizons at depths of 1.5 m at E4 and 2.9 m at F2. A water table often occurs within this calcic horizon.

Similar horizons are found around wells D6 and D7 with an indurated layer of nodules below the horizon. The thickness of the calcic horizon at the two wells is 120 cm and 70 cm, respectively.

Below the indurated nodular horizon, discontinuous accumulations of nodules are found which give way to a profile with more sand and gravel, particularly around wells D6 and D7.

(H): Earthy CaCO₃ horizon underlain by a sandy/pebbly layer (Form VIII).

This type bears resemblance to type VII in that both have a similar calcic horizon. The only difference is that the calcic horizon is not underlain by an indurated nodular layer. Instead, this calcic horizon gives way to a zone composed of sand particles and smooth rounded pebbles which are mainly black in colour at wells E5 and F5 and whitish at wells E6 and E7.

Groundwater mostly occurs in this pebble and sandy horizon. The overlying soil is predominantly black heavy clay at wells E6, E7 and F7 with deep cracks of up to 50 cm below the surface. Around well E5, the soil overlying this calcic horizon has a dark grey colour and is loamy.
The presence of the smooth rounded pebbles is an indication that at one time in the past sediments or rock fragments were transported from some other location, either by water or wind, and deposited here. In the process of transportation, the rock fragments became smooth and rounded (Flint et al., 1974).

6.1.2: Depth to the calcareous horizon

The depth to the calcareous layer was determined at the grid of 100 m x 100 m mentioned in Chap. 3. From the collected data, two maps were prepared; firstly, a contour map of the elevation of the layer and, secondly, a contour map showing the depth to the calcareous layer below the ground surface. It should be noted that:

(i): In some places, there was no petrocalcic horizon or caliche, but an accumulation of discontinuous nodules as at D3 and D4 (See Sec. 6.1.1).

(ii): In some other places also, the layer of discontinuous nodules occurred above a petrocalcic (caliche) horizon. Where the nodules were large or close together, the recorded depth was less than the actual depth. At wells A2, C3, and C5, the recorded depths were found to be less by 0.45, 0.50 and 0.35 m, respectively. Large nodules measured up to 30 cm long x 20 cm wide. It would have been therefore fitting to add these to recorded depths; but; (a) the auger may miss hitting such nodules, and hence get actual depth, and (b) there was no way to find out whether the auger had hit a nodular layer or a petrocalcic, except at the well points. The creaking sound produced when the auger hits a hard obstacle is similar in
such cases.

Outside the Scheme areas, most parts were observed to have a calcic horizon (an earth layer composed mainly of soft concentrations and relatively few nodules or hard concentrations). While augering, it was assumed that there could be a petrocalcic horizon underneath. However, this was only found to occur around wells F2 and E4 as mentioned in Sec.6.1 (F). The depths measured in most places were therefore erroneous and only presented the depth to which the auger could penetrate depending on the hardness or compactness of the underlying layers. The maximum augered depth at which no hard layer was struck was 4.26 m. The areas with calcic horizon have therefore been left out while making a contour map.

The other area left out, but which occurs within the scheme is in Kamleza South around well A5 and other section close to the two hills. At well A5, no hard layer was found at a depth of 4.3 m, although sparse nodules were found. The augering depths, in most parts ranged from 2.5 - 3.5 m. Greater depths were prevented by the hardness of the soil (black clay soils). No petrocalcic horizon was encountered at these depths.

Two contour maps have been drawn: (1) Depth to calcareous layer (Fig. 6.6) and (ii) the surface contour of the layer (Fig. 6.7). Longitudinal profiles in Fig.4.2 and 4.8 (Chap. 4) also show the relative depth of this layer at various points.

The depth to the calcareous layer contour map in Fig.6.6 reveals the following:-

(i) The layer is deepest in areas near the hills where depths of 2 m and above occur. Other places where the layer
Fig. 6.6: Depth to the calcareous layer contour.
occurs beyond are at wells A2 (2.5 m) and the section between wells C3-D3-D4 (2.30 m).

(ii) In Kamleza Scheme, the layer is mostly found at depths of 1.0 - 2.0 m, with upper parts having large areas with the layer between 1.0 - 1.25 m. In the Central part the layer varies between 1.50 - 1.75 m, except around well C4, where the layer occurs at depths between 1.0 m and 1.25 m. The lower parts have the layer occurring in the range 1.50 - 1.75 m.

(iii) In Kimorigo Scheme, the upper parts are mostly underlain by the layer at depths less than 1.0 m. The shallowest depth in this part of the scheme is 0.5 m. Along the road, the layer has been found to occur at a depth of 0.35 m (See profile in Fig. 4.2). In the central parts of the scheme the layer is found at depths of 1.0 - 1.5 m, with depths greater than 1.75 m occurring in a section between C3-D3-D4 (See (i) above). In the lower parts, the layer occurs from under 1.0 m to 1.25 m, the shallowest depth being 0.70 m, in this part.

The contour map shows that the layer slopes away from the hilly and higher areas towards Kimorigo and the swamps. The slope direction is therefore the same as for the topography. The contour lines are rather rugged around well C3 in Kamleza Scheme (Central Part). This is probably due to the existence of nodules on top of the calcareous layer.

The slopes of the layer have been calculated and found to average 0.25 % in the upper parts of Kimorigo and Kamleza Scheme. The central and lower parts have slopes averaging 0.06 %. The lower parts of Kamleza scheme have slopes of about 0.3 %. Higher slope values of up to 2.5 % occur in some parts where great difference in depth to the calcareous layer occur within short distances.
Fig. 6.7: Calcareous layer contour.
Profiles in Fig. 4.2 and 4.8 show that the elevation of the layer varies in a similar manner as the topography, except in a few cases. One of these can be seen in the profile of Fig. 4.2 as a dip in the calcareous layer. However, the explanation here is that a calcic horizon is found here and has been made very soft by the presence of high groundwater table throughout the year (this portion forms the Northern swamp). Where the dip or valley occurs, the depth of augering was 4.30 m and no hard layer was struck. The calcic horizon commences at 1.50 - 1.70 m and extends beyond 4.30 m (maximum augered depth). The sand fraction increased with depth.

The other two profiles in Fig 4.8 also show the layer occurring deeper beyond the scheme towards the river. The same explanation as above applies, except that at well F2, a thin petrocalcic horizon was struck at 3.0 m. There is no hard layer at E5 and F5. Only sand and black pebbles are found underneath the calcic horizon. (see Sec.5.2.1). Between A5 and B5, the layer was not struck at depths between 2.5 - 3.5 m. Penetration was prevented by soil hardness. At A5, no layer was found at a depth of 4.3 m depth of well A5).
6.2 Soil salinity and sodicity conditions

6.2.1 Soil salinity groups

A total of 150 soil samples from 24 locations in the project area were analysed to determine the soil pH, EC, CEC, exchangeable Ca, Mg, Na, and K, and the soil texture. The results obtained are presented in Table B, Appendix B. The location where the soils were collected are shown in Fig. 3.5, Chap. 3.

From the results obtained, soils with similar salinity and sodicity conditions have been grouped together. Average EC-values (1:2.5) have been calculated considering a rootzone depth of between 50 to 70 cm. The depth range was chosen after finding that the two major crops in the area, cotton and maize, had rooting depths of under 50 cm. The weighted average EC-value in the rootzone has been calculated using the sampling intervals as weights. In the same manner, average ESP-values over the rootzone have been calculated. The soil salinity classification has been done in accordance with Table 2.2, Chap. 2, while soil sodicity classification is in accordance with Table 2.1 of the same chapter.

In all, four groups were made, namely; I) Non-saline, non-sodic soils, II) Non-saline, but sodic in depth, III) Slightly - moderately saline and sodic, IV) Saline - sodic soils.

The soil profiles in each group are represented in Table 6.2. For each group, except group IV, a representative profile has been selected and discussed in the text under this section. In group IV, three subgroups have been formed. Each subgroup shows a distinct variation.
of salinity with depth down the profile. The first subgroup, (a), consists of soils showing a maximum salt concentration at the surface followed by a sharp drop down the profile. The second subgroup, (b), consists of soils also depicting maximum salt concentration at the top, but the decrease down the profile is gradual. The final subgroup, (c), consists of soils having a maximum salt concentration at mid-depth.

### Table 6.2: Soil salinity and sodicity groups.

<table>
<thead>
<tr>
<th>Soil group no.</th>
<th>Soil profile</th>
<th>Representative pit no.</th>
<th>Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Non-saline, 2, 6, 15</td>
<td>2</td>
<td>Non-sodic (close to Lual River).</td>
</tr>
<tr>
<td>II</td>
<td>Non-saline, 1,7,8,18,20,23</td>
<td>8</td>
<td>Sodic in depth</td>
</tr>
<tr>
<td>III</td>
<td>Slightly-moderately saline and sodic, 10,14</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Saline-sodic (a) 0.2, 11,12,13,4,24</td>
<td>12</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>(b) 0.2, 5,9,16,17</td>
<td>16</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>(c) 0.2, 19,21,22</td>
<td>22</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Groundwater depth at 3.5 m (March, 1983)

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6.2.2 Non-saline, non-sodic soils – (group I)

These soils occur close to the Lumi river (levee soils), in areas of Kamleza scheme close to the main irrigation canal and in the southern parts of Kimorigo scheme around well D5 (also see Fig. 3.5 for soil sampling locations). Both the EC- and ESP-values of the soils are low, indicating non-saline, non-sodic soil conditions as shown in Table 6.3.

Fig. 6.8 indicates that Ca$^{2+}$ and Mg$^{2+}$ ions are the dominant cations in these soils, a condition which is characteristic of non-saline soils (See Chapter 2). These soils are intensively cultivated as shown in Fig. 6.9, the main crop being bananas.

Table 6.3: Soil salinity and sodicity at profile No. 2 (close to Lumi River).

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>EC mS/cm</th>
<th>ESP</th>
<th>pH 0.01 M CaCl$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 50</td>
<td>0.3</td>
<td>5.3</td>
<td>8.1</td>
</tr>
<tr>
<td>50 - 74</td>
<td>0.2</td>
<td>3.1</td>
<td>7.9</td>
</tr>
<tr>
<td>74 - 120</td>
<td>0.2</td>
<td>2.2</td>
<td>7.7</td>
</tr>
<tr>
<td>120 - 160</td>
<td>0.3</td>
<td>2.4</td>
<td>8.0</td>
</tr>
<tr>
<td>160$^4$</td>
<td>0.6</td>
<td>2.5</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Note: Groundwater depth at 1.5 m (March, 1989).
### Fig. 6.8: Exchangeable cations in soils close to the Lumi river (Profile no. 2).

![Image of Lumi river area]

### Fig. 6.9: Intensive cultivation of bananas and other crops close to the main Kamleza canal (Kamleza scheme).
6.2.3: **Non-saline soils, but sodic at some depth in the profile (group II)**

These soils occur in the upper project area around the Njoro Kubwa canal; in northern and southern parts of Kamleza scheme and in some areas close to the Ruvu swamp (see Fig. 3.5).

The soils are non-saline as shown by the EC-values in Table 6.4. Non-sodic soil conditions occur in the top 60 cm depth. Beyond which they are sodic up to a depth of 160 cm, as shown in Table 6.4.

The depths at which the high ESP -values occur have a relatively higher clay content than the overlying soil layers, as shown in Table 6.4.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>EC (mS/cm)</th>
<th>ESP (%)</th>
<th>pH (0.01 M CaCl₂)</th>
<th>% Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>0.2</td>
<td>0.8</td>
<td>7.4</td>
<td>9</td>
</tr>
<tr>
<td>5 - 20</td>
<td>0.4</td>
<td>2.0</td>
<td>7.4</td>
<td>9</td>
</tr>
<tr>
<td>20 - 40</td>
<td>0.1</td>
<td>2.0</td>
<td>7.1</td>
<td>31</td>
</tr>
<tr>
<td>40 - 60</td>
<td>0.3</td>
<td>2.0</td>
<td>7.2</td>
<td>36</td>
</tr>
<tr>
<td>60 - 80</td>
<td>0.3</td>
<td>18</td>
<td>7.5</td>
<td>27</td>
</tr>
<tr>
<td>80 - 100</td>
<td>0.3</td>
<td>20</td>
<td>7.8</td>
<td>33</td>
</tr>
<tr>
<td>100 - 120</td>
<td>0.3</td>
<td>21</td>
<td>7.7</td>
<td>30</td>
</tr>
<tr>
<td>120 - 140</td>
<td>0.3</td>
<td>23</td>
<td>7.6</td>
<td>16</td>
</tr>
<tr>
<td>140 - 160</td>
<td>0.3</td>
<td>25</td>
<td>7.8</td>
<td>25</td>
</tr>
<tr>
<td>160 - 180</td>
<td>0.3</td>
<td>5</td>
<td>7.9</td>
<td>28</td>
</tr>
<tr>
<td>180 - 200</td>
<td>0.4</td>
<td>5</td>
<td>8.2</td>
<td>39</td>
</tr>
</tbody>
</table>

Note: Groundwater: Average depth = 2.5 m and average EC = 0.7 mS/cm (Oct. 1988 to July, 1989).
A high clay content favours the accumulation of Na⁺-ions (see Chapter 2). It is therefore possible that over the years, Na⁺-ions have been retained in the clay-enriched layers after coming into contact with either irrigation or groundwater.

The dominant cations are Ca²⁺ and Mg²⁺ as indicated in Fig.6.10. As favourable soil conditions exist in the topsoil (top 60 cm depth), these soils are also intensively cultivated, like the soils of Group I above.

![Graph showing cation content across different soil depths](image)

**Fig.6.10 :** Exchangeable cations at profile no.8 (Kamleza North).
6.2.4: Slightly-moderately saline and sodic soils (III).

These soils occur in the unirrigated parts of central Kamleza and Kimorigo schemes, and also in Ngutini area adjacent to the lower parts of Kimorigo scheme. The representative soil profiles are nos. 10 and 14 in Fig.3.5.

In most of the central sections of the two schemes, strongly saline conditions exist in the top 10 cm layer of the soil below which slightly to moderately saline conditions are found. At profile no.10, the EC-value decreases from 11.6 mS/cm in the top 10 cm to under 5 mS/cm in the underlying layers as shown in Table 6.5. Similarly strong sodic conditions exist in the top 10 cm, which decrease to moderately sodic conditions in the subsoil, as also indicated in Table 6.5.

Table 6.5: Variation of ESP (%), pH and texture with depth (profile No. 10, Kimorigo Central).

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>EC (1:2.5)</th>
<th>ESP %</th>
<th>0.01M CaCl₂</th>
<th>Texture Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 5</td>
<td>11.6</td>
<td>20</td>
<td>6.8</td>
<td>Silt loam</td>
</tr>
<tr>
<td>5 – 30</td>
<td>4.9</td>
<td>11</td>
<td>7.3</td>
<td>Loam</td>
</tr>
<tr>
<td>30 – 50</td>
<td>4.1</td>
<td>10</td>
<td>6.9</td>
<td>Silt loam</td>
</tr>
<tr>
<td>50 – 70</td>
<td>3.6</td>
<td>12</td>
<td>7.5</td>
<td>Loam</td>
</tr>
<tr>
<td>70 – 90</td>
<td>2.3</td>
<td>12</td>
<td>7.6</td>
<td>&quot;</td>
</tr>
<tr>
<td>90 – 110</td>
<td>1.6</td>
<td>12</td>
<td>7.9</td>
<td>&quot;</td>
</tr>
<tr>
<td>110 – 130</td>
<td>1.0</td>
<td>12</td>
<td>7.8</td>
<td>&quot;</td>
</tr>
<tr>
<td>130 – 150</td>
<td>0.8</td>
<td>11</td>
<td>8.0</td>
<td>Clay loam</td>
</tr>
<tr>
<td>150 – 170</td>
<td>0.6</td>
<td>12</td>
<td>8.0</td>
<td>&quot;</td>
</tr>
<tr>
<td>170 – 190</td>
<td>0.5</td>
<td>10</td>
<td>8.1</td>
<td>&quot;</td>
</tr>
<tr>
<td>190 – 210</td>
<td>0.5</td>
<td>12</td>
<td>7.8</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Groundwater: Av. depth = 1.1 m and Av. EC = 1.3 mS/cm (Oct., 1988 – July, 1989).

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The occurrence of a maximum salt concentration at the surface points at a net upward movement of salts towards the surface, which then get deposited as water is lost through evapotranspiration, i.e. there is salinisation from groundwater by capillary action (see Chap. 2). The groundwater salinity is under 2 mS/cm in this central to lower area of the two schemes. With the groundwater table at an average depth of 1.1 m below the surface, it is possible for capillary rise to reach the surface for a loam soil (for a loam soil, maximum height of capillary rise is in the range of 1.0 - 1.5 m; see Chap. 2).

The cation composition in the soil profile is illustrated by the bar chart in Fig. 6.11. As in the previous two cases both Ca\(^+\) and Mg\(^+\) ions are dominant, although there is a notable increase in the Na\(^+\) ion content in the top layer.

Patchy growth of cotton and white salt crusts are a common feature in these slightly-moderately saline/sodic soils as exhibited by the photo in Fig. 6.12.

6.2.5: Strongly saline and sodic soils (group IV)

As earlier mentioned, these soils have been divided into three subgroups of distinctly different salinity profiles; they are presented below as (a) to (c).

(a) Very high surface salinity only (maximum salinity at the surface followed by sharp a drop in the subsoil)

These soils occur in parts of Kimorigo and Kamleza schemes and at the swamp edges. The EC-value at the surface was found to be above 60 mS/cm for all the soil samples
Fig. 6.11: Exchangeable cations at profile no. 10 (Kimorigo Central).

Fig. 6.12: Patchy and stunted cotton in central Kimorigo scheme (note the white salt crusts).
analysed, the maximum EC-value being 92 mS/cm at profile no. 3 (near well D0 at the swamp edge).

The sharp drop in salinity below the surface crust is illustrated by the EC-values presented in Table 6.6 for profile no.16 in Kamileza South scheme. Similarly, the ESP-value of these soils is highest in the top 3 cm and suddenly decreases to a more or less constant value lower down, as shown in the Table 6.6. The very high concentration of salts at the surface is indicative of capillary salinisation as already mentioned in Sec.6.2.3, and this is possible as the average groundwater level occurs at 1.0 m and capillary rise can reach the surface for either clay loam or silt loam texture for which the height of capillary rise is greater than 1.0 m.

Table 6.6: Variation of pH, ESP and soil texture with depth (cm) (profile No. 16, Kamileza South).

<table>
<thead>
<tr>
<th>Depth</th>
<th>EC (1:2.5)</th>
<th>pH</th>
<th>ESP</th>
<th>%S</th>
<th>%Si</th>
<th>%C</th>
<th>CLASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 3</td>
<td>63</td>
<td>9.2</td>
<td>100+</td>
<td>46</td>
<td>37</td>
<td>13</td>
<td>SiL/CL</td>
</tr>
<tr>
<td>3 - 20</td>
<td>8.9</td>
<td>9.0</td>
<td>35</td>
<td>35</td>
<td>32</td>
<td>13</td>
<td>SiL</td>
</tr>
<tr>
<td>30 - 40</td>
<td>2.3</td>
<td>8.7</td>
<td>36</td>
<td>34</td>
<td>35</td>
<td>31</td>
<td>CL</td>
</tr>
<tr>
<td>40 - 60</td>
<td>2.1</td>
<td>8.9</td>
<td>42</td>
<td>34</td>
<td>35</td>
<td>31</td>
<td>CL</td>
</tr>
<tr>
<td>60 - 80</td>
<td>2.4</td>
<td>8.9</td>
<td>41</td>
<td>38</td>
<td>35</td>
<td>27</td>
<td>L</td>
</tr>
<tr>
<td>80 - 100</td>
<td>2.5</td>
<td>9.0</td>
<td>40</td>
<td>35</td>
<td>35</td>
<td>25</td>
<td>L</td>
</tr>
<tr>
<td>100 - 120</td>
<td>2.2</td>
<td>9.0</td>
<td>43</td>
<td>38</td>
<td>34</td>
<td>28</td>
<td>CL</td>
</tr>
<tr>
<td>120 - 130</td>
<td>2.4</td>
<td>8.9</td>
<td>38</td>
<td>34</td>
<td>27</td>
<td>39</td>
<td>CL</td>
</tr>
</tbody>
</table>

Groundwater: Av. depth = 1.0 m; Av. EC = 7.6 mS/cm and SAR = 36

The Na⁺-ion content of these soils is much higher than in the soils already discussed. In Fig.6.13, the Na⁺-ion is dominant throughout the profile. This situation is true for saline and/or sodic soils (see Chap.2). The high pH -
values indicate the sodic or alkaline conditions of these soils (Table 6.8).

In all these areas with strongly saline and sodic soils, the groundwater salinity is greater than 2 mS/cm, e.g. at profile no.16, the average EC-value of the groundwater was 7.6 mS/cm during the project period (see footnote in Table 6.6 above). With groundwater tables often occurring at shallow depth e.g. at an average depth of 1.0 m for profile no.16, capillary rise is able to reach the surface, resulting in considerable amounts of salt transport to the surface from the salty groundwater and thus the high soil salinities results can be easily understood (see Table B-3, App.B for soil analysis results).

Fig.6.13: Exchangable cations at profile no.16 (Kamleza South).
The result of the high saline and sodic conditions is barren patches covered with white salt crusts and exuberant salty vegetation, mainly Suaeda monoica (See photo in Fig. 6.14). These are black heavy clay soils which occur mainly in Cultivation is rare in these areas, although some farmers try cultivating cotton, despite the stunted and patchy growth. There is no irrigation in this area, and thus leaching of salts is only by rainfall and floodwater. - value of the top layer is lower but still high decreases gradually down the profile: from 26 ms/cm in topsoil to 16 ms/cm at 120 cm depth as shown in Table...

Fig. 6.14: Surface covered with white salt crusts. (near well C5, profile No. 16, Kamleza South).
(b) **Saline-sodic soils with a gradual decrease in salinity down the profile.**

These are black heavy clay soils which occur mainly in the Block C area and in the adjacent areas of Upper Kimorigo scheme. In contrast to the saline-sodic soils discussed under (a) above, these soils have relatively higher ESP-value, which remain fairly constant throughout the profile (Table 6.7). The EC-value of the top layer is lower but still high and it decreases gradually down the profile: from 26 mS/cm in the topsoil to 16 mS/cm at 120 cm depth as shown in Table 6.7.

Table 6.7: The ESP, pH and texture of soil sample from profile No. 12 (Block C, area)- Group IV(b) soils.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>EC(1:2.5)</th>
<th>ESP</th>
<th>pH</th>
<th>% 0.01 M CaCl₂</th>
<th>%Si</th>
<th>%C</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>26.0</td>
<td>98</td>
<td>8.5</td>
<td>23</td>
<td>48</td>
<td>29</td>
<td>CL</td>
</tr>
<tr>
<td>5 - 20</td>
<td>20.5</td>
<td>100+</td>
<td>9.1</td>
<td>43</td>
<td>37</td>
<td>20</td>
<td>L</td>
</tr>
<tr>
<td>20 - 40</td>
<td>19.5</td>
<td>100+</td>
<td>9.4</td>
<td>25</td>
<td>20</td>
<td>55</td>
<td>C</td>
</tr>
<tr>
<td>40 - 60</td>
<td>20.0</td>
<td>100+</td>
<td>9.5</td>
<td>31</td>
<td>35</td>
<td>34</td>
<td>CL</td>
</tr>
<tr>
<td>60 - 80</td>
<td>17.0</td>
<td>100+</td>
<td>9.6</td>
<td>42</td>
<td>22</td>
<td>36</td>
<td>CL</td>
</tr>
<tr>
<td>80 - 100</td>
<td>16.5</td>
<td>95</td>
<td>9.6</td>
<td>26</td>
<td>26</td>
<td>52</td>
<td>C</td>
</tr>
<tr>
<td>100 - 120</td>
<td>16.5</td>
<td>100+</td>
<td>9.6</td>
<td>25</td>
<td>23</td>
<td>52</td>
<td>C</td>
</tr>
<tr>
<td>120 - 140</td>
<td>7.5</td>
<td>99</td>
<td>9.6</td>
<td>26</td>
<td>16</td>
<td>56</td>
<td>C</td>
</tr>
<tr>
<td>140 - 165</td>
<td>6.8</td>
<td>59</td>
<td>9.2</td>
<td>29</td>
<td>5</td>
<td>66</td>
<td>C</td>
</tr>
<tr>
<td>165⁺</td>
<td>2.0</td>
<td>58</td>
<td>9.2</td>
<td>64</td>
<td>14</td>
<td>22</td>
<td>SIL</td>
</tr>
</tbody>
</table>

Groundwater: Av. depth = 1.2 m and Av. EC = 43 mS/cm and SAR = 162 (Oct., 1988 - July, 1989).

In Fig. 6.15, the dominance of Na⁺-ion throughout the profile is evident. The likely source of the Na⁺-ions is the sodic groundwater which has a high SAR-value as shown by the footnote below Table 6.7.

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Figure 6.15: Exchangeable cations at profile no.12 (Block C area) for group IV (b) soils.

The surface soil condition is often characterised by a puffy or fluffy crust of white salt. In some places white salt crusts can be seen occurring between short grass as shown in Fig. 6.16. Soil pits also often have their sides covered with white salt crusts as illustrated by the photo in Fig. 6.17; this is a clear indication of the extreme salinity and sodicity conditions in this area.
Figure 6.16: White salt crusts in between short grass growth (Block C area).

Figure 6.17: White salt crusts on the side of well K4 (Block C).
(c) **Saline-sodic soils with maximum salinity** at mid-depth depth.

These soils are predominant in the Ngutini area to the south of the schemes. The soils are characterised by a maximum salt concentration at some depth in the profile. This is shown by the EC-values in Table 6.8, for the soil from profile No. 22. The ESP-values are relatively low in the top soil, as also indicated in Table 6.8. Similarly, the cation contents are highest at this same depth of maximum salt concentration (Fig.6.18).

The occurrence of higher salt concentration at a particular depth is normally an indication of the depth to which salts are leached, or the depth to which capillary rise from the groundwater reaches. In this Ngutini area, the groundwaters occur at depths between 2.0 - 3.0 m, except in areas close to the swamps (Sec Chapter 5, Section 5.2).

**Table 6.8: Variation of ESP, pH and texture for soil from profile pit No. 22 (Ngutini).**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>EC(1:2.5) mS/cm</th>
<th>ESP</th>
<th>pH</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
<td>0.4</td>
<td>3.8</td>
<td>7.6</td>
<td>27</td>
</tr>
<tr>
<td>10 - 60</td>
<td>4.0</td>
<td>79.0</td>
<td>8.0</td>
<td>29</td>
</tr>
<tr>
<td>60 - 105</td>
<td>14.</td>
<td>100t</td>
<td>8.1</td>
<td>21</td>
</tr>
<tr>
<td>105 - 140</td>
<td>8.3</td>
<td>100t</td>
<td>8.5</td>
<td>21</td>
</tr>
<tr>
<td>140 - 160</td>
<td>3.8</td>
<td>100t</td>
<td>8.4</td>
<td>37</td>
</tr>
<tr>
<td>160 - 200</td>
<td>1.7</td>
<td>83.0</td>
<td>8.9</td>
<td>53</td>
</tr>
<tr>
<td>200 - 250</td>
<td>1.2</td>
<td>100t</td>
<td>8.6</td>
<td>73</td>
</tr>
</tbody>
</table>

Groundwater: Av. depth = 2.5 m; Av. EC = 8.1 mS/cm and SAR = 46 (Oct., 1988 - July, 1989).
A height of capillary rise of 1.0 m will therefore possibly cause salt accumulation at around 1.5 m depth below the surface.

**Fig. 6.18:** Exchangeable cations at profile no. 22 (Ngutini).

### 6.3: Hydraulic conductivity

The results of the hydraulic conductivity (K) tests from 39 locations are presented in Fig. 6.19. Two sample calculations of how the K-values have been obtained are presented in App. D. The first sample calculation is for a homogenous soil profile while the second is for a layered soil (heterogenous). The augerhole and water table depths, depth of saturated layer and the depth to the impervious layer indications are also given in Table D-1, App.D. Augerhole depths varied between 100 cm at site D2-5 to 293 cm at site D3 (see Fig. 6.19).

In Fig. 6.19, the K-values can be seen to vary from as low as 0.009 m/day to 17.4 m/day at site D9. Low K-
values occur where the transmitting layer is clay texture as in parts of Block C and the upper areas of Kimorigo scheme. In Table 6.9, the K-value and the soil texture of the transmitting layer are given (see Sec. 6.2 for the details on soil texture).

Table 6.9: K-value and soil texture of transmitting layer

<table>
<thead>
<tr>
<th>Location</th>
<th>Texture of salt layer</th>
<th>K-Values m/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>E2 (profile pit no.4)</td>
<td>clay</td>
<td>0.06</td>
</tr>
<tr>
<td>D0 (profile pit no.3)</td>
<td>clay</td>
<td>0.2</td>
</tr>
<tr>
<td>C3 (profile pit no.9)</td>
<td>loam/clay</td>
<td>0.03</td>
</tr>
<tr>
<td>E4 (profile pit no.12)</td>
<td>clay</td>
<td>0.8</td>
</tr>
</tbody>
</table>

At sites E2, D0 and C3, the K-values lie within the recommended range for clay soils (See Table D-11 App D).

At site E4, the K-value of 0.8 m/day appears out of the range for clay soils. However, at this site, calcareous nodules are present in the soil profile, which may increase the porosity and hence the permeability.

At site C3, the saturated layer is partly loamy and partly clayey, which may explain the low K-value. Also, the soils around this site have high ESP values, which could have caused dispersion of the clay particles and thus poor permeability.

Towards the river and near the southern Jipe and Ruvu swamps, the heavy clay soils are underlain by a black sandy layer of high permeability. The K-values were found to vary between 2.7 and 17.4 m/day (See Fig. 6.19).

In the scheme areas, where loam and silt loam soils are predominant, the K-values obtained lie within the normal range as shown in Table D-1, App D. In Table 6.10, K-values at sites with known soil textures are presented.
The high K-value at site C5, which is out of range for either clay loam or loam soils, can be attributed to the presence of calcareous nodules in the soil profile above the impervious calcareous layer. The porosity of the soil around this area is therefore high (see Sec 6.1 also).

Table 6.10 : Soil texture and K-values at selected sites (in the schemes).

<table>
<thead>
<tr>
<th>Location</th>
<th>Texture</th>
<th>K-Values (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3-5 (profile no. 10)</td>
<td>loam</td>
<td>0.6</td>
</tr>
<tr>
<td>C2-D2 (profile no. 5)</td>
<td>loam</td>
<td>1.7</td>
</tr>
<tr>
<td>B5 (profile pit no. 17)</td>
<td>Clay/silt loam</td>
<td>1.2</td>
</tr>
<tr>
<td>C5 (profile pit no. 10)</td>
<td>Clay-loam/loam</td>
<td>11</td>
</tr>
</tbody>
</table>

Differences in K-values within short distances can also be seen at site B5 in Fig.6.19. The K-value differed appreciably within a distance of 20 m, e.g. 0.16 m/day at well B5 and 1.2 m/day. At 80 m away, the K-value was found as 1.9 m/day.

6.4: Discussion

6.4.1: The calcareous layer

From the presented data on the calcareous layer, some ideas can be formulated with respect to origin, influence on groundwater flow, and groundwater quality. In Chap.2, sec.2.2.6, three possible mechanisms explaining the
formation of the calcareous layer were given. Of the three, the second mechanism can possibly explain how the calcareous layer in the schemes was formed. As summarized by Chorley (1984), calcareous layers can be formed in areas of carbonate rich groundwaters where sheet floods dry out, where capillary rise occurs and where the water table oscillates close to the ground surface. From investigations on the surface and groundwater conditions in the Kimorigo and Kambaleza schemes it was noted that:

i) sheet floods do occur in the area,

ii) the groundwaters are rich in the (bi)-carbonate salts,

iii) the groundwaters do occur at shallow depth and capillary rise can reach the surface as evidenced by pronounced capillary salinisation of the soils (see Sec. 6.2),

iv) There is seepage inflow from higher areas which replaces water lost from the groundwater table by capillary rise.

The semi-arid climate in the area ensures that evaporation exceeds rainfall, so that there is, on the long run, a net upward flow of water and salts from the watertable below. In addition, as the area is close to the volcanic Kilimanjaro mountain, it is possible that calcareous dustfall has been a major source of CaCO₃, as was noted in New Mexico (Wilding et al., 1983).

Bears (1955), also supposed that the calcareous layers in the Taveta area originated from the groundwater through capillary rise. He further noted that the maximum thickness of the layers was between 2 - 3 ft, i.e. 60 - 90 cm. Our observations on the thickness of the layer in Sec.6.1.2 are
within this range.

The influence of the layer on groundwater flow varies with the type of the layer. Where the layer is pervious, as in the central parts of Kimorogo scheme, drainage conditions are good and groundwater salinity is low (see Chap. 5). Where the layer is completely impervious as in the central and lower parts of Kamleza scheme, perched groundwater is found. As drainage is restricted, the groundwater salinity in these areas is high (see Chap. 5). Waterlogged conditions also result after heavy rainfall or floodflow as vertical drainage is restricted as shown by the hydrograph for well B5, in Fig. A-8, App. A.

It should be noted that while the layer is bound to restrict both vertical and horizontal groundwater flow and thus possibly result in shallow groundwater tables, groundwater depth position in the area is generally low even in areas without the petrocalcic horizon. This is because the drainage base is set mainly by the swamp levels.

Spacing of field drains is dependent amongst other factors, on the depth of the underlying impervious layer. The shallower the depth, the closer the drain spacing (Smedema and Rycroft, 1983). To avoid too close a spacing of drains, the impervious layer should occur at a depth of at least 1.5 m from the surface (MOA, 1984). In the schemes the layer occurs at depths of even less than 1.0 m and this may be an obstacle to the installation of field drains as a high number of drains will be expensive to construct and maintain (see Chap. 8).
6.4.2: Salinity conditions and salinisation

Before carrying out investigations on soil salinity in the Kimorogo-Kamaleza area, it was mentioned that the main objective was not to show that salty soils exist, as this is already known (see Chap.2), but to relate the soil salinity in different parts of the area to influencing factors like:

- groundwater depth and quality,
- rate of capillary rise,
- groundwater flow,
- soil texture,
- calcareous layer,
- leaching and internal drainage conditions.

The soil salinity conditions at the surface are given in Table 6.11 for various soil textures and under known groundwater conditions of depth and salinity (average watertable depth and salinity between Oct.1988 to July, 1989). The topsoil depths are shown in the table.

In Chap.2, Sec.2.2.5, it was mentioned that the extent of capillary salinisation and the depth at which salts accumulate is governed by the rate and height of capillary rise and the groundwater salinity, counteracted by the leaching intensity. In the non-irrigated areas, the very high salinity at the surface suggests that there is capillary salinisation (see Tables 6.5, 6.6, and 6.7). This shows that leaching by rainfall is insufficient and thus a net upward movement of salts occurs.
Table 6.11: Variation of soil salinity at the surface for various soil textures with groundwater table depth and salinity.

<table>
<thead>
<tr>
<th>Profile no.</th>
<th>Soil Depth (m)</th>
<th>GW Depth (m)</th>
<th>GW Salinity (mS/cm)</th>
<th>EC(1:2.5) at soil surface (mS/cm)</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0-2</td>
<td>0.3</td>
<td>3.3</td>
<td>92</td>
<td>clay</td>
</tr>
<tr>
<td>5</td>
<td>0-2</td>
<td>1.0</td>
<td>8.0</td>
<td>72</td>
<td>loam</td>
</tr>
<tr>
<td>9</td>
<td>0-3</td>
<td>1.0</td>
<td>2.7</td>
<td>72</td>
<td>loam</td>
</tr>
<tr>
<td>10</td>
<td>0-10</td>
<td>1.4</td>
<td>1.3</td>
<td>12</td>
<td>loam</td>
</tr>
<tr>
<td>11</td>
<td>0-3</td>
<td>1.3</td>
<td>12.9</td>
<td>22</td>
<td>clay loam</td>
</tr>
<tr>
<td>12</td>
<td>0-5</td>
<td>1.2</td>
<td>46.0</td>
<td>26</td>
<td>clay</td>
</tr>
<tr>
<td>13</td>
<td>0-5</td>
<td>1.0</td>
<td>9.0</td>
<td>14</td>
<td>clay</td>
</tr>
<tr>
<td>15</td>
<td>0-30</td>
<td>1.9</td>
<td>3.2</td>
<td>0.4</td>
<td>loam</td>
</tr>
<tr>
<td>16</td>
<td>0-3</td>
<td>1.2</td>
<td>7.6</td>
<td>63</td>
<td>loam</td>
</tr>
<tr>
<td>17</td>
<td>0-5</td>
<td>1.0</td>
<td>3.6</td>
<td>68</td>
<td>silt/clay</td>
</tr>
<tr>
<td>22</td>
<td>0-10</td>
<td>2.5</td>
<td>9.0</td>
<td>0.4</td>
<td>clay loam</td>
</tr>
</tbody>
</table>

Where the groundwater table is less than 1.5 m from the surface, maximum salinity exist at the soil surface as shown in Table 6.11 or at least within the top 0 - 50 cm, indicating that capillary rise is able to reach the rootzone or the surface. As the groundwater table falls to beyond 1.9 and 2.5 m, soil salinity at the surface is considerably lower, as shown in the table. The zone of maximum soil salinity instead occurs deeper in the profile (see Table 6.10), showing that at the two depths of 1.9 and 2.5 m, capillary rise is not able to reach the surface or, if it does, the rate of rise is so small that insignificant amounts of salt get transported to the surface. These two depths are close to the recommended critical water table depth of 2.5 - 3.0 m (see Chap.2).

The highest salinity at the surface within the project area occurs where there is waterlogging, like in the
swamp edges, and this can be attributed to relatively high rates of capillary rise and hence salt transport to the surface (see Table 6.11, profile no. 3). Soil texture also causes differences in capillary salinisation at the surface. At about the same groundwater table depths, medium textured soils exhibit higher soil salinity at the surface than fine textured soils, even with lower groundwater salinities. This can be seen by comparing soil salinity results of profile nos.16 and 12, 11 and 10 and also 17 and 13 in Table 6.11. The higher salinities at the surface can be attributed to higher rates of capillary rise for medium textured soils than for finer textured soils.

For soils of the same texture, groundwater table depth, and hence the rate of capillary rise, appears to contribute more to soil salinity at the surface than the groundwater salinity level (cf. results for profile nos.5, 9, 16 and 17). Differences in groundwater salinity do not necessarily result in higher or lower salinity conditions at the surface. Similar results have been obtained by Elgabuly (1971).

High soil salinity in the area is generally associated with seepage inflows which maintain high groundwater tables for prolonged periods and thus enhance capillary salinisation. The Block C area, the Upper and Central parts of Kimorogo scheme and the southern areas of Kamleza scheme and the adjacent Ngutini areas, where high soil salinity conditions exist, all receive seepage inflow from areas with higher groundwater tables.

Where the groundwater table is perched due to an impervious calcareous layer, as at profile no.9 in Kamleza scheme, poor salt efflux conditions result in higher
groundwater salinities than similarly irrigated areas in Kamleza scheme. Salinisation therefore occurs in between irrigations and this has led to high soil salinity despite possibly sufficient leaching by irrigation water. Perched groundwater also occurs in the southern parts of Kamleza scheme (see Sec. 6.2).

Where non-saline soils occur, both leaching and internal drainage can be said to be sufficient. This is the case in the irrigated areas of Kamleza scheme where excess irrigation water causes sufficient leaching of salts. Adequate internal drainage ensures evacuation of excess salts in the groundwater and, as reported in Chap.5, groundwater salinities in most parts of Kamleza scheme are low. Under inadequate leaching, capillary rise from even water of relatively low salinity, as at profile no.10 (Kimorogo Central), can lead to high soil salinity levels (see Table 6.11). Where drainage conditions are poor, as in the Block C area, groundwater tables remain high for long durations after a sudden groundwater table rise. As noted in Chap.5, the Block C area continually receives subsurface inflow from the river throughout the year, which ensures maintenance of high groundwater table conditions.

The soil salinity results obtained by Asol (1984), for the central part of Kimorogo scheme (near profiles no.10 and 11), also reflect the presence of capillary salinisation, although his salinity levels are lower. This indicates that salinity levels have risen, which could be true as no measures have been taken since then to prevent salinisation, i.e. there have been no improvements in the leaching and drainage conditions.
The soil salinity boundaries drawn by Kanake (1982) no longer hold, because some of the areas indicated as having non-saline or slightly saline soils, particularly in the southern parts of Kamleza scheme and the adjacent Ngutini areas, now have strongly saline and sodic soils, as illustrated by profile nos. 16, and 17 (see map in Fig. 6.20). This too indicates that soil salinity levels have risen. Similarly, in parts of Kimorigo scheme, like around profile nos. 10 and 12, the salinity levels are considerably higher. The rise in salinity levels can be attributed partly to irrigation and partly to upward movement of salts from the shallow and saline groundwater (see Chap. 5).

6.4.3: Soil salinity/sodicity effects on crop growth

EC-values in the rootzone can be obtained by multiplying the weighted averages in the rootzone by a factor of 3 (see Sec. 6.2 and Chap. 2). The rootzone depth considered is in the range 50 - 70 cm. Tables 6.12 and 6.13 give the ECe- and ESP-values in the rootzone depth. The discussion on the effects of the soil salinity and sodicity conditions on crop growth is presented in two parts:

(i) Kimorigo and Kamleza Schemes;
(ii) Ngutini, Block C and swamp edges.

(i) Kimorigo and Kamleza Scheme

The ECe- and ESP-values for Kimorigo Scheme in Table 6.12 reveal that only in the lower areas the salinity and sodicity levels are low enough to enable cultivation of a
Fig. 6.20: Soil salinity changes indicated on the soil salinity map.
wide variety of crops, except sensitive ones (see Table 2.9). However, as there is no irrigation in Kimorigo Scheme, only the relatively drought tolerant cotton is cultivated in this lower part of Kimorigo scheme, which forms approximately 18% (25 ha) of the total scheme area.

The remaining areas of the scheme in the upper and central portions have too high ECe- and ESP-Values in the rootzone, such that even the salt tolerant cotton would produce little or no yield (see Table 2.8 and 2.9). These upper and central areas of Kimorigo scheme are largely uncultivated and only short grasses are found. In a small portion of the central area around profile no.10, it is possible to cultivate cotton, but with a reduction of some 50% in the yield (see Table 2.8). Cotton is actually grown in these areas, and a patchy growth does occur as shown by the photo in Fig. 6.12.

It is possible that with leaching, resulting from rainfall and floodwaters during the rainy season (March-May), lower ECe-values may temporarily occur in the rootzone. However, high groundwater tables for long durations after the rainy season increase soil re-salinisation and the benefit of leaching may be lost.

In Kumlcza scheme, areas with high ECe- and ESP-values which would significantly affect crop growth, occupy approximately 25% (= 75 ha) of the total scheme area. ECe-values are as high as 60 mS/cm in the rootzone and no crop growth would be expected.
Table 6.12: ECe- and ESP-Values in the rootzone
(Kimorigo and Kamleza Schemes)

<table>
<thead>
<tr>
<th>Area</th>
<th>Average</th>
<th>ESP</th>
<th>Possible crops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ECe mS/cm</td>
<td>ESP %</td>
<td></td>
</tr>
<tr>
<td>Kimorigo Scheme</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>24.6</td>
<td>77</td>
<td>No crop</td>
</tr>
<tr>
<td>Central</td>
<td>18</td>
<td>12</td>
<td>cotton</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>47</td>
<td>No crop</td>
</tr>
<tr>
<td>Lower</td>
<td>3</td>
<td>6</td>
<td>All except sensitive</td>
</tr>
<tr>
<td></td>
<td>crops</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kamleza Scheme</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>0.8</td>
<td>2</td>
<td>All crops</td>
</tr>
<tr>
<td></td>
<td>14.3</td>
<td>43</td>
<td>cotton with</td>
</tr>
<tr>
<td>Central</td>
<td>42</td>
<td>39</td>
<td>no crop</td>
</tr>
<tr>
<td>South</td>
<td>21</td>
<td>41</td>
<td>no crop</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>58</td>
<td>no crop</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>9</td>
<td>all crops</td>
</tr>
</tbody>
</table>

Salt tolerant bushes and grasses are predominant in these areas. The remaining 75% of the scheme area have low ECe- and ESP-values in the rootzone such that even sensitive crops can be grown. Crops which were observed in these areas include fruit crops (lemon, avocado, mango), food crops (maize, bean, cowpea); vegetable (cabbage, kale, onions, tomatoes) and cotton as a fibre crop.

In the section close to the river and also the areas adjacent to the Njoro Kubwa canal (profile nos. 2 and 1 respectively), salinity and sodicity levels are low enough to enable cultivation of even sensitive crops.
(ii) Ngutini, Block C and Swamp Edges

In the upper areas of Ngutini cotton can be cultivated as the ECe-value in the rootzone is 10 mS/cm. However, the high ESP-Value of 66% may cause stunted growth. Fig. 6.21 shows stunted cotton and maize growth in a saline and/or sodic patch.

The areas abounding Kimorogo Scheme have similar soil conditions as in the lower areas of Kimorogo and cotton does very well (see Table 6.12).

Fig.6.21: Stunted maize and cotton growth in a salt affected patch in Marodo.
The lower parts of Ngutini adjacent to Kamleza Scheme have soils with very high ECe- and ESP-values which cannot allow any crop growth. Salt bushes and grasses dominate in these lower areas of Ngutini.

The Block C area also has soils with very high ECe- and ESP-values in the rootzone that would prohibit cultivation of crops. As in the lower areas of Ngutini, the predominant vegetation are salt bushes and grasses.

On the swamp edges, extreme salinity and sodicity conditions also exist and the waterlogged condition appear to favour the growth of Wild date and Doum palms.

Table 6.13: ECe and ESP-Value and influence on crop growth (other areas).

<table>
<thead>
<tr>
<th>Area</th>
<th>ECe</th>
<th>ESP</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ngutini</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper: Profile no. 22</td>
<td>10</td>
<td>66</td>
<td>cotton can be grown</td>
</tr>
<tr>
<td>Lower: Profile no. 19</td>
<td>55</td>
<td>80</td>
<td>no crop</td>
</tr>
<tr>
<td><strong>Block C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper: As for Upper Kimorigo Scheme</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central: Profile no. 12</td>
<td>61</td>
<td>100</td>
<td>no crop</td>
</tr>
<tr>
<td>Lower:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Swamp Edges</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Profile no. 3</td>
<td>60</td>
<td>86</td>
<td>no crop</td>
</tr>
</tbody>
</table>

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6.4.4: Hydraulic conductivity discussions

The data in Sec. 6.3 on hydraulic conductivity give a pointer to the varying internal drainage conditions in the area. In the Block C area, the low hydraulic conductivities of less than 0.1 mm/day reflect poor internal drainage conditions. The salty conditions of the soil and groundwaters in the Block C area can be attributed to the poor internal drainage (due to low hydraulic conductivity) coupled with the low groundwater slope in the area, leading to low salt efflux. In terms of reclamation of the soils in the Block C area and the upper parts of Kimorigo scheme, the low K-values would result in i) very close spacing of drains, and ii) low leaching efficiency and thus very high amounts of water required for leaching.

In the central parts of Kimorigo scheme and most parts of Kamleza scheme, the K-values are higher than in the Block C and the upper areas of Kimorige scheme, indicating relatively better internal drainage conditions.
7.1: Introduction

Groundwater balance calculations in this chapter are to enable quantification of the various sources of excess groundwater in the project area. The theory and pertinent formulas have been considered in Chap. 2. Once the sources are quantitatively known, then appropriate remedial measures can be recommended as earlier mentioned in Chap. 2.

Four areas within the two schemes have been selected for the groundwater balance assessments, namely: Central and Southern areas of Kamleza scheme around wells C3 and B5 and the Upper and Lower areas of Kimorogo scheme around wells E2 and D3.

The main sources of groundwater supply in the area, which are often the causes of high groundwater tables or drainage problems, are excess irrigation and precipitation, floodwater and seepage inflows (see Chap. 5). Changes in watertable levels, $\Delta h$, for the four selected areas are represented by well hydrographs in Figs. 7.1 to 7.4 at wells C3, B5, E2, and D3, respectively.

In order to relate the groundwater table changes either rainfall or irrigation, 10-day rainfall totals have been plotted above the hydrographs. Arrows have been included in the figures to illustrate dominant percolation or capillary rise.

The precipitation data used in the waterbalance calculations are in Table C-1, App. C and the evapotranspiration data in Table C-2, App. C.
The unknowns to be determined from the water balance calculations are net subsurface inflows (I_{ss}), amount of percolated water (Perc), amount of irrigation water ( Irr) and the drainable pore space (u). Irrigation efficiency estimates have been made by comparing the expected crop water requirement for a given period with the amount of irrigation water calculated from the water balance for the same period.

For none of the four selected areas, there is direct interaction between the water level in the Lumi river and the groundwater table. Consequently, the discharge term, \( Q_{inf} - Q_{dr} \) in the Groundwater Balance Equation (eqn. 10), is zero. Also, due to the nearly flat topography (low ground slope) surface runoff is considered negligible in the following calculations.

A sample calculation has been presented for the area around Well C3 in Central Kamleza scheme. For the other areas, calculated values or results have been given in tables. However, for every area, a brief explanation is given of how the results have been obtained.

7.2: Sample calculation for Kamleza Central

Five different cases of groundwater balance assessment, using the indirect method, have been selected. The first case involves the determination of the net subsurface inflow, I_{ss}, and the drainable pore space, u, which are both unknown. In the next three cases, the calculated values of I_{ss}, and u are substituted in the groundwater balance equation to enable determination of the other unknowns as explained later. In the final case, the
net subsurface inflow, \( I_{ss} \), is determined from the groundwater balance equation, all other terms being known.

Case 1: Calculation of net subsurface inflow, \( I_{ss} \) and the drainable pore space, \( \mu \).

The net subsurface inflow and the drainage pore space have been calculated for two periods during which the supply (Perc - Cap) and the change in water table (\( \Delta h \)) are known. The two periods are 10/4 - 14/4/89 and 8/5 - 15/5/89. The groundwater table at the start of the two periods is at a depth of 90 cm below the surface (see Fig. 7.1).

For the two periods there is percolation due to excess precipitation over evapotranspiration causing a groundwater table rise. The soil is supposedly at field capacity, hence there is no change in the soil moisture content (\( \Delta S_{ss} = 0 \)). Capillary rise is zero as there is percolation of water to the groundwater table. There is no irrigation, hence \( \text{Irr} = 0 \) and runoff is negligible as already mentioned.

For the first period of 4 days from 10/4 - 14/4/89, the amount of percolation can be found by using eqn. (8) or (9) and substituting \( \text{Pr} = 37.5 \text{ mm} \) (from Table C-1, App. C) and \( \text{Et} = 16 \text{ mm} \) (from Table C-2, App. C). One thus obtains: \( \text{P} = \text{R} - \text{ET} = 21.5 \text{ mm} \).

Applying eqn. (18), and substituting \( \text{Perc} = 21.5 \text{ mm}, \Delta h = 225 \text{ mm} \) und \( \Delta t = 4 \text{ days} \) from Fig. 7.1, one finds:

\[ I_{ss} = 225 \mu /4 - 21.5/4 \quad \ldots \ldots \quad (i) \]
The period considered for the water balance is 4 / 12 = 1 / 3. There is percolation due to rainfall and irrigation.
For the second period of 7 days from 8/5 - 15/5/89, Pr = 41.0 mm and Et = 25.2 mm, and by substituting these values into either eqn.(8) or (9) one finds; P = 15.8 mm

By applying eqn. 18 and substituting Perc = 15.8 mm, Δh = 150 mm and Δt = 7 days (from Fig. 7.1) one finds for this second period;

\[ I'_{ss} = \frac{150 \mu}{7} - \frac{15.8}{7} \ldots \ldots \ldots \ldots (ii) \]

As the watertable elevations are similar during the two periods, the values of the drainable pore space and the net subsurface inflow are assumed constant (see Chap. 2, Sec. 2.4). The two equations (i) and (ii) can therefore be solved simultaneously, giving:

\[ \mu = 9 \% \text{ and } I'_{ss} = -0.32 \text{ mm/day} \]

At well C3, the soil texture in the range of watertable fluctuation during the two periods is silt loam (see Table A-2, App. A). From Table 2.4.1, the value of the drainage pore space for silt loam is in the range 3 - 19%. The calculated value of 9% therefore looks acceptable. The negative \( I'_{ss} \) is an indication that the outflow from the area is more than the inflow. This soon causes a fall in watertable as can be seen in Fig.7.1.

**Case 2:**

The period considered for the water balance assessment is 4/12-9/12/88. There is percolation due...
to excess irrigation. The amount of percolated water, Perc, can be determined by using eqn (15). By substituting, \( \mu = 9\% \), \( I_{ss} = -0.32 \text{ mm/day} \), \( \Delta h = 800 \text{ mm} \) and \( \Delta t = 5 \text{ days} \) (from Fig. 7.1) and Cap = 0 one obtains, \( P = 73.6 \text{ mm} \).

Applying eqn.(8), and substituting Perc = 73.6 mm, and ET = 22.5 mm (all other terms = zero), we get,

\[
I_i = P + ET = 96.1 \text{ mm}.
\]

For the 5 days (4/12 - 9/12/89), the crop water requirement would be about \( 5 \times 0.9 \times 4.5 = 20.25 \text{ mm} \), where 0.9 is the average crop coefficient factor, \( K_c \), and 4.5 is the average monthly evapotranspiration for the month of December.

The irrigation application efficiency, \( E_a \), can be calculated as

\[
E_a = 20.25/96.1 \times 100 = 21\%.
\]

Normally \( E_a \) is about 40 - 50\% for many surface irrigation methods (Michael, 1983). The calculated efficiency is therefore about half of the normal figure, an indication of poor water management (or excess irrigation).

**Case 3:**

The period considered here is 7/7 - 14/7/89. There is percolation resulting from irrigation. By substituting \( I_{ss} = -0.32 \text{ mm/day} \), \( \mu = 9\% \) and \( \Delta h = 350 \text{ mm} \) and \( \Delta t = 7 \text{ days} \) into eqn.(12), one finds, \( P = 33.7 \text{ mm} \). The amount of irrigation water can be found by applying eqn (11), and
substituting \( P = 33.7 \text{ mm} \) and \( ET = 24.5 \text{ mm} \) (all other terms being zero) and one finds, \( I_{i} = 58.2 \text{ mm} \)

The calculated irrigation efficiency in this case is 38%.

**Case 4:**

The period considered here is 21/7 - 4/8/89, and similar conditions apply as in case (3), except \( ET = 49.6 \text{ mm} \) and \( \Delta h = 150 \text{ mm} \) and \( \Delta t = 14 \text{ days} \). The calculated, Perc and Irr. - terms and the application efficiency, \( E_a \), are presented in Table 7.1 using eqs. 8 and 12, respectively.

**Case 5:**

This covers the period from 4/8 - 31/8/89. The groundwater table is constant, \( \Delta h = 0 \). The lateral subsurface inflow, I'ss, must therefore be equal to the capillary rise which in turn equals the ET - rate (all other terms being zero), which is 3.7 \text{ mm/day} for the month of August.

**Table 7.1:** Summary of results of groundwater balance calculations (Kamleza Central).

<table>
<thead>
<tr>
<th>Period</th>
<th>( \mu )</th>
<th>I'ss ( \text{mm/day} )</th>
<th>P ( \text{mm} )</th>
<th>Cap ( \text{mm/day} )</th>
<th>(P-Cap) ( \text{mm/day} )</th>
<th>( I_{i} ) ( \text{mm} )</th>
<th>( E_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/4-14/4/89</td>
<td>9</td>
<td>-0.32</td>
<td>21.5</td>
<td>0</td>
<td>5.4</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>8/5-15/5/89</td>
<td>9</td>
<td>-0.32</td>
<td>15.8</td>
<td>0</td>
<td>2.3</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>4/12-9/12/88</td>
<td>9</td>
<td>-0.32</td>
<td>73.6</td>
<td>0</td>
<td>14.7</td>
<td>96.1</td>
<td>23</td>
</tr>
<tr>
<td>7/7 14/7/89</td>
<td>9</td>
<td>-0.32</td>
<td>33.7</td>
<td>0</td>
<td>4.8</td>
<td>58.2</td>
<td>38</td>
</tr>
<tr>
<td>21/7-4/8/89</td>
<td>9</td>
<td>-0.32</td>
<td>18</td>
<td>0</td>
<td>1.4</td>
<td>68.3</td>
<td>65</td>
</tr>
<tr>
<td>4/8-31/8/89</td>
<td>3.7</td>
<td>0</td>
<td>3.7</td>
<td>-3.7</td>
<td>0</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

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7.3: **Groundwater balance calculations (Kamleza South).**

In Kamleza South (around well B5) marked changes in groundwater table occurred due to irrigation and precipitation, as illustrated by hydrograph of well B5, Fig. 7.2.

The values of the drainable pore space, \( u \) and the net subsurface inflow, \( I'_{ss} \), have been estimated for periods 7/4-10/4/89 and 9/12-23/12/88. These two values have subsequently been used in groundwater balance calculations for other periods, where they are assumed to be about the same. The results are presented in Table 7.2.

### Table 7.2: Groundwater balance calculation results (Kamleza South)

<table>
<thead>
<tr>
<th>Period</th>
<th>( \mu )</th>
<th>( I'_{ss} )</th>
<th>( P )</th>
<th>( \text{Cap} )</th>
<th>( P - \text{Cap} )</th>
<th>( I_i )</th>
<th>( E_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/4-10/4/89</td>
<td>9.1</td>
<td>0</td>
<td>100.5</td>
<td>0</td>
<td>33.5</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>9/12-23/12/88</td>
<td>-</td>
<td>1.7</td>
<td>0</td>
<td>1.7</td>
<td>-1.7</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>13/1-27/1</td>
<td>9.1</td>
<td>1.7</td>
<td>69.5</td>
<td>0</td>
<td>5.0</td>
<td>100.5</td>
<td>56</td>
</tr>
<tr>
<td>11/8-18/8/89</td>
<td>9.1</td>
<td>1.7</td>
<td>24.5</td>
<td>0</td>
<td>3.5</td>
<td>50.4</td>
<td>47</td>
</tr>
<tr>
<td>23/6-3/7</td>
<td>-</td>
<td>3.6</td>
<td>0</td>
<td>3.6</td>
<td>-3.6</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>14/7-28/7</td>
<td>9.1</td>
<td>5.3</td>
<td>0</td>
<td>3.5</td>
<td>-3.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(a) **Estimation of the drainage pore space \( u \).**

To calculate the drainable pore space, \( u \), a period of heavy rainfall, 7/4 - 10/4/89 was selected. Eqn. 16 applies
Fig. 7.2: Hydrograph for well B5 (Kamleza south).
and, \( u = \frac{P}{\Delta h} \), where \( \Delta h = 1025 \text{ mm} \) (from Fig. 7.2), and \( P = Pr \) for the period (see Table C-1, App. C).

During the period 23/6 - 3/7/89, the groundwater flow, \( I'_{ss} \), is due to the capillary rise which in turn equals the ET -

The period considered was 9/12 - 23/12/88. During this period the groundwater table is constant. The net subsurface inflow is found using Eqn.13, i.e., \( I'_{ss} = (\text{Cap} - P) \).

The \( (\text{Cap} - P) \) term is determined by using Eqn. 9 where, \( (P - \text{Cap}) = (R - \text{ET}) \), the values of \( R \) and \( \text{ET} \) being obtained from Tables C-1 and C-2, App. C. There is no change in the soil moisture content as water lost from the soil is replaced from below by capillary rise.

(c) Estimation of \( P \) and \( I'_{i} \)

Using the \( u - \) and \( I'_{ss} - \) values from (a) and (b) respectively, the amount of percolated water, \( \text{Perc} \) and irrigation water applied, \( \text{Irr} \), have been estimated for the periods 13/1-27/1/89 and 11/8-18/8/89. Application efficiencies, \( E_a \), have been calculated by comparing the expected crop water requirements with estimated amounts of irrigation water applied during the two periods.

The amount of percolated water is determined from Eqn. 12 and the irrigation water applied from eqn. 8. There is no change in the soil moisture content, \( \Delta S_{sm} = 0 \) and since there is percolation, \( \text{Cap} = 0 \) too.
(d) **Estimation of I'ss**

During the period 23/6 - 3/7/89, the groundwater table stays constant and the net subsurface inflow, I'ss, is equal to the capillary rise which in turn equals the ET rate over the period.

(e) **Estimation of I'ss**

For the period 14/7 - 28/7/89, there is a rise in groundwater table attributed to subsurface inflow. For the groundwater table to rise, the subsurface inflow must be greater than the evapotranspiration rate and consequently the capillary rise. The soil moisture content remains unchanged as any water lost from the soil is replaced from below by capillary water.

By assuming that the ET-rate approximates the capillary rise over the period of groundwater table rise, an estimate can be made of the net subsurface inflow, I'ss by using eqn. 12, and substituting $u = 9.1\%$, $\Delta h = 275$ mm (from Fig. A-7, App. A), $\text{Cap} = \text{ET} (= 3.5$ mm/day for July) and $P = 0$.

7.4: **Groundwater balance calculations for upper Kimorigo**

In this area, the main sources of excess groundwater are subsurface inflow, floodwaters and excess precipitation in the months of April and May. The variation in groundwater table position is shown in Fig. 7.3. Groundwater balance calculations have been done for two periods; 3/2 - 24/2/89 and 4/8 - 15/9/89.
Fig. 7.3: Hydrograph for well E2 (Upper Kimorogo scheme area).
For both periods, the net subsurface inflow equals the difference between precipitation and evapotranspiration. The results are shown in Table 7.3.

Table 7.3: Groundwater balance calculations Upper Kimorigo

<table>
<thead>
<tr>
<th>Period</th>
<th>I'ss</th>
<th>(P − Cap)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/2 - 3/8/89</td>
<td>4.3</td>
<td>-89.4</td>
</tr>
<tr>
<td>4/8 - 31/8/89</td>
<td>3.6</td>
<td>-100.6</td>
</tr>
</tbody>
</table>

7.5: Groundwater balance calculations (Kimorigo Central)

The central area of Kimorigo receives subsurface inflow from the irrigated areas of Kamleza North (See Fig. 5.1, Chap.5). This seepage inflow causes the groundwater tables in this area to rise and stay at around 1.0 m depth from the surface for long periods (see Fig. 7.4).

Changes in groundwater depth also result from excess precipitation and floodwater, during the months of April and May. Four groundwater balance calculations have been done to find estimates of net subsurface inflow, the drainage pore space, percolated floodwater. Results are presented in Table 7.4. The following notes relate to the calculation of the data presented in the Table.
Fig. 7.4: Hydrograph for well D3 (Kimorigo Central).
Table 7.4: Summary of results on groundwater balance calculations (Central Kimoriigo)

<table>
<thead>
<tr>
<th>Period</th>
<th>$\phi$ (%)</th>
<th>I' ss (mm/day)</th>
<th>P (mm)</th>
<th>Cap (mm/day)</th>
<th>(P-Cap) (mm/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/7-31/8/89</td>
<td>-</td>
<td>3.5</td>
<td>0</td>
<td>3.5</td>
<td>-3.5</td>
</tr>
<tr>
<td>23/12/88-6/1/89</td>
<td>-</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
<td>-2.0</td>
</tr>
<tr>
<td>7/4-10/4/89</td>
<td>9.6</td>
<td>0</td>
<td>88.5</td>
<td>0</td>
<td>29.5</td>
</tr>
<tr>
<td>23/6-10/7/89</td>
<td>9.6</td>
<td>5.9</td>
<td>0</td>
<td>3.6</td>
<td>-3.6</td>
</tr>
</tbody>
</table>

(a) The drainage pore space, $u$.

This has been calculated for a period when there is intense rainfall (7/4-10/4/89). The $\phi$ value is calculated using eqn. 14, i.e. $u = P/\Delta h$.

The amount of percolation is obtained from eqn. 8 or 9 and equals precipitation, all other terms being zero. The value of $\Delta h$ can be read off from Fig. 7.4. The 9.6% shown in Table 7.4 agrees rather well with the 9% for Kamleza Central and the 9.1% for Kamleza South.

(b) Net subsurface inflow, I' ss.

Three periods have been considered. During the first period (7/7-31/8/89), the groundwater table remains at the same level, and for this to happen, the net subsurface inflow, I' ss, should be equal to the capillary rise which in turn equals the ET-rate (all other terms being zero), which is 3.5 mm/day.

During the second period, 23/12/88-6/1/89, the groundwater table also remained constant. The net subsurface inflow therefore equals the difference between the
percolation and capillary rise, \((\text{Perc} - \text{Cap})\), which in turn equals the precipitation minus evaporation \((R - ET)\), all other terms being zero.

For the third period, 23/6 - 10/7/89, there is subsurface inflow from Kamleza scheme causing a groundwater table rise. Going by the same argument as in Sec.7.3 (e), an estimate is found of the net subsurface inflow by using eqn. 12 and substituting the \(u\) value, from (a) above, \(\Delta h = 400 \text{ mm} \) (from Fig. 7.3) and \(\text{Cap} = RT\) (from Table C-2, App. C).

7.6: Discussion

From the groundwater balance calculations, it is evident that there often is substantial subsurface inflow from higher irrigated areas to lower lying areas i.e., from Kamleza North to Upper and Central areas of Kimorigo, as also shown qualitatively by the arrows in the watertable contour map in Fig. 5.2. The net subsurface inflow is initially higher than the evapotranspiration rate and causes a rise in the groundwater table. As the water table rises, the subsurface inflow reduces until it equals the evapotranspiration rate and the groundwater table becomes constant.

The subsurface inflows are undesirable as the resulting high groundwater tables promote capillary salinisation. With estimates of the inflows made and the groundwater flow directions and slopes known (see Chap. 5, Sec. 5.2), it is possible to design cut-off drains and properly locate them. For example, in the case of subsurface inflow from Kamleza scheme to Kimorigo scheme, a cut-off
drain can be located along the road between the two schemes. This cut-off drain may also serve the purposes of discharging excess surface flows or as a main drain for Kamleza scheme.

Although some acceptable estimates of the irrigation efficiencies were made (around 40%), the very low irrigation efficiency of 23% in Kamleza Central indicates that there is no strict irrigation water management in the scheme. In Chap. 4, flooding of farms in Kamleza North was reported (see photo in Fig.4.8) which too is a pointer to poor irrigation water management. During the investigations it was not uncommon to come across irrigation water flowing even in uncultivated plots, an example being the area around Well B5 in Kamleza South.

A low irrigation efficiency means high amounts of water lost to the groundwater table, the consequence of which is a groundwater table rise in the irrigated and adjacent areas and an enhanced capillary salinisation. The water management in the scheme therefore needs to be improved and this will not only result in reduced recharge to the groundwater table but the irrigation water thus saved can be used in other non-irrigated areas. Where additional irrigation water is required for leaching, low irrigation efficiency is inevitable. However, in such cases, there should be provision of adequate drainage to ensure the evacuation of the extra leaching water. As already noted in the previous chapters, drainage is inadequate in the project area and the low efficiencies, at the moment, though desirable for leaching of salts, only exacerbate the drainage situation.

Percolation from excess precipitation and floodwater is high due to low run-off. When there is intense rainfall over a short period as occurred in April, 1989, percolation
is high causing groundwater tables to rise to the surface. The percolation to the groundwater table can be reduced through construction of surface drains to channel away ponded water. The influence of floodwater on the groundwater table can be reduced through flood control measures (see Chap. 4).

In Chap. 2, Sec. 2.2.1, it was mentioned that Berger and Kalders (1983) never considered subsurface inflow in their field drainage design as they assumed that it was negligible. The results obtained in this chapter prove that subsurface inflow is substantial and cannot be neglected in the design of field drainage, except when it is prevented from entering the field through installation of cut-off drains as mentioned above. Although no groundwater balance has been made for the areas close to the river, it is evident from the groundwater table contour map in Fig.5.2 that there is subsurface inflow from the river to the adjacent low-lying areas. The high groundwater tables in areas close to the river, as shown by the hydrograph in Fig.A-1, App. A, is due to this subsurface inflow (also refer to Chap. 5).

The values of the drainable pore space calculated (9 - 10 \%) lie within the expected range for silt loam soils as indicated in Table 2.15, Chap. 2.

Values have been calculated of the capillary rise ranging from 1.7 mm/day to 3.7 mm/day. The rate of capillary rise as mentioned in Chap. 2, decreases with increase in depth of the groundwater table below the surface. The soil texture also influences the rate of rise. The values calculated appear to be within acceptable limits.
8. SALT BALANCE ASSESSMENTS

8.1. Salt balance calculations

In Chap. 6, it has been shown that capillary salinisation exists in various parts of the project area. This a net upward salt movement could be counteracted by leaching water, washing salts down again. In Chap. 7, it has been shown that capillary rise may be as high as the evapotranspiration rate in areas with shallow groundwaters and a net positive subsurface inflow (seepage). It could thus be useful to have an idea of the magnitude of the leaching requirement, so that one can assess if leaching as a management practice can solve the problem. If so, quantification would provide a basis for drainage design at the same time.

Considering steady state conditions, a salt balance can be made to determine the extra irrigation requirement in various locations needed to maintain favourable salt conditions in the rootzone by using equation 24 (Chap. 2). The parameters which are required for the water balance are Et-rate (E); the rainfall amount (R); the rate of capillary rise (G); the groundwater quality (ECg); the irrigation water quality (ECi); the allowable soil salinity level in the rootzone (ECe); and the leaching efficiency factor (f).

The values of the evapotranspiration used (E) and rainfall (R) have been obtained from Tables C-1 and C-2 in App.C. The rate of capillary rise (G), has been determined by reference to Fig. 2.3 and Table C-3, App. C, which show the rate of capillary rise for different soil textures at different depths. Information on the soil textures is in Table B, App. B. For our case, the maximum rate of capillary
rise, on average, is taken as the maximum average
evapotranspiration, which is 4.23 mm/day (annual average).
Average water table depths have been obtained by reference
to Tables A-1 and A-2, App. A. The groundwater salinity
averages have been obtained by reference to Table A-4, while
the leaching efficiency factors have been obtained from
Table 2.15 (Chap.2). The rootzone depth considered is 50 cm
(see Chap.6).

Right sites have been considered for the assessment
and the details of the average groundwater quality, ECg,
average water table depth (W), soil texture (st.) above the
water table, the estimated capillary rise, G, based on the
water table depth and the soil texture, and finally the
leaching efficiency factor, f, are presented in Table 8.1.
The height of the rootzone above the water table (H) is also
indicated.

Three sample calculations of salt balance, considering steady state conditions are presented below for sites E3, D3 and C5.

Sample calculation (1) - site E3

Data

- Average annual ET = 1544 mm (from Table 1.1)
- Average rainfall, R = 595 mm (from Table 1.1)
- Capillary rise, G = 3.5 mm/day = 1277.5 mm/yr
  (from Table 8.1)
- Average groundwater quality, ECg = 13 mS/cm (from Table 8.1)
- Allowable ECe (crop rootzone) = 4 mS/cm *
NB: * - the allowable ECe for 75% yield potential for maize and some vegetables as shown in Table 2.3, Chap. 2.
Substituting the above figures and \( f = 0.4 \) (from Table 8.1), into eqn. (24), as below,

\[
(1544 \text{ mm/yr} - 23 \text{ mm/day}) \times \frac{1}{365} = 4.2 \text{ mm/day} \]

Using \( (24) \), we get: \( I = 604 \text{ mm} \) and \( P = 323 \text{ mm} \).

Table 8.1: Sites for water and salt balances and their characteristics.

<table>
<thead>
<tr>
<th>Site</th>
<th>ECg (mS/cm)</th>
<th>Texture</th>
<th>W (m)</th>
<th>H (m)</th>
<th>G (mm/day)</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5 (pit no.17)</td>
<td>3.8</td>
<td>Sil/C</td>
<td>0.9</td>
<td>0.4</td>
<td>4.2</td>
<td>0.4</td>
</tr>
<tr>
<td>C3 (pit no.9)</td>
<td>2.7</td>
<td>L</td>
<td>0.9</td>
<td>0.4</td>
<td>4.2</td>
<td>0.45</td>
</tr>
<tr>
<td>C5 (pit no.16)</td>
<td>7.6</td>
<td>L</td>
<td>1.0</td>
<td>0.5</td>
<td>4.2</td>
<td>0.4</td>
</tr>
<tr>
<td>D3 (pit no.10)</td>
<td>1.3</td>
<td>L</td>
<td>1.1</td>
<td>0.6</td>
<td>4.2</td>
<td>0.45</td>
</tr>
<tr>
<td>E2 (pit no.4)</td>
<td>11.5</td>
<td>C</td>
<td>0.85</td>
<td>0.35</td>
<td>0.3</td>
<td>0.25</td>
</tr>
<tr>
<td>F3 (pit no.11)</td>
<td>13</td>
<td>CL</td>
<td>1.3</td>
<td>0.8</td>
<td>3.5</td>
<td>0.4</td>
</tr>
<tr>
<td>E4 (pit no.12)</td>
<td>43</td>
<td>C</td>
<td>1.2</td>
<td>0.7</td>
<td>4.0</td>
<td>0.4</td>
</tr>
<tr>
<td>F3 (pit no.13)</td>
<td>7.9</td>
<td>C</td>
<td>0.8</td>
<td>0.3</td>
<td>4.0</td>
<td>0.25</td>
</tr>
</tbody>
</table>

\[
\frac{(E-H) \times 1.5 \text{ECe}}{G \times (\text{ECg} - 1.5 \text{ECe})} \]

onc obtains; \( I = 6363 \text{ mm} \) and \( P = 5086 \text{ mm} \) (from eqn.22).
Sample calculation (2) - site D3

The data is the same as above except that $\text{EC}_g = 1.3$ mS/cm, $f = 0.45$ and $G = 4.23$ mm/day $= 1544$ mm/yr. Using eqn. (24), we get; $I = -604$ mm and $P = 323$ mm.

This shows that irrigation water is not needed as there is already enough water brought from the groundwater table by capillary rise. There is also no need for leaching as $(P \cdot G)$ is negative. The results for other sites are given in Table 8.2 below.

Sample calculation (3) - site C5

Data is same as for the two cases above except that $\text{EC}_g = 7.6$ mS/cm, $G = 4.2$ mm/day, and $f = 0.4$. By substituting these figures into eqn. 24, one obtains; $I = 3549$ mm, and by using eqn. 22, $P = 4144$ mm.

The results of the salt balance calculations for the above and 5 other sites are given in Table 8.2 below. Also shown in the Table are the leaching ratio $(100 \times P/I)$ and the leaching requirement $(100 \times (P-G)/I)$. 

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Table 8.2: Results of salt balance calculations (steady state)

<table>
<thead>
<tr>
<th>Site</th>
<th>I</th>
<th>P</th>
<th>P-G</th>
<th>P/1x100</th>
<th>(P-G)/1x100</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5</td>
<td>998</td>
<td>1593</td>
<td>49</td>
<td>160</td>
<td>4.9</td>
</tr>
<tr>
<td>C3</td>
<td>231</td>
<td>826</td>
<td>-718</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C5</td>
<td>3549</td>
<td>4144</td>
<td>2600</td>
<td>117</td>
<td>73</td>
</tr>
<tr>
<td>D3</td>
<td>-604</td>
<td>-9</td>
<td>-1535</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>E2</td>
<td>9546</td>
<td>10141</td>
<td>8597</td>
<td>106</td>
<td>90</td>
</tr>
<tr>
<td>E3</td>
<td>6363</td>
<td>5085</td>
<td>3808</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>F4</td>
<td>25962</td>
<td>26473</td>
<td>25013</td>
<td>102</td>
<td>96</td>
</tr>
<tr>
<td>F3</td>
<td>5890</td>
<td>6401</td>
<td>4961</td>
<td>109</td>
<td>84</td>
</tr>
</tbody>
</table>

NB: I = infiltrating irrigation water (mm/year)  
P = total deep percolation (mm/year)  
G = capillary rise from groundwater (mm/year)

8.2: Discussion

From the salt balance calculations, it can be seen that the amount of (extra-)irrigation water depends on the salinity level of the groundwater, the rate of capillary rise, and the leaching efficiency (other factors being equal). In the area between Block C and the lower parts of Kimorogo scheme around well E4, where the groundwater salinity is very high, the amount of irrigation water required for maintenance of favourable salt conditions in the rootzone is enormous; 25,962 mm/year. Without this amount of water applied, then capillary salinisation is bound to occur. However, such annual amounts of water are out of the question; proper measures would include lowering
of the groundwater table, improving the drainage and a
rigorous reclamation programme, after which more normal
annual leaching requirements would be needed.

In the upper areas of Kimorigo scheme where both the
groundwater salinity and the leaching efficiency are high,
irrigation water requirements are high, although less than
at well E4 due to the lower groundwater salinity level. In
areas where the groundwater salinity is less than 1.5ECE,
irrigation water requirements are relatively lower and as at
well D3 in the central part of Kimorigo scheme, where the
groundwater salinity is 1.3 mS/cm, no irrigation water is
required; the capillary rise from below can be considered as
"rainfall from below" providing the net irrigation water
requirement. It was noted maize and banana crops did well in
this area despite there being no irrigation. At wells C3 and
B5 in the central and southern parts of Kamleza scheme,
irrigation water requirements are also low as the
groundwater salinity is less than 1.5ECE.

In the central area of Kimorigo scheme, towards the
old Kimorigo drain around well E3, the increase in
groundwater salinity results in higher amounts of irrigation
water for maintenance of favourable salt conditions in the
rootzone. From the groundwater salinity map in Fig.5.4 show
that most parts of the central and upper areas of Kimorigo
scheme have ECg- values greater than 8 mS/cm. The watertable
depths are also often less than 1.5 m from the surface ( see
Table A-2, App.A). As there is no irrigation, salinisation is
expected to be pronounced and the high soil salinity
conditions at profile no.11 ( around well E3), prove that
this is so ( see Chap.6).
In conclusion, it can be said that salinisation is bound to continue in most parts of the area unless there is adequate leaching and drainage. Groundwater tables need to be lowered to reduce capillarity into the rootzone and as noted from the information provided in Chapters 4 to 7, remedial measures can be recommended to solve the problem. The remedial measures may include: (1) the installation of an irrigation lift for the soil zone, (2) the installation of an irrigation lift for the soil zone, (3) the installation of an irrigation lift for the soil zone, and (4) the installation of an irrigation lift for the soil zone. In Chap. 4, two problems were identified: flood and surface drainage problems (which lead to surface water ponding for long durations). In Chap. 5, surface drainage problems were noted to exist in many areas of the scheme; high groundwater tables do occur for long durations; water at times is present for up to 3 months in the rootzone. The groundwaters were also noted to be very hard and/or sodic and their occurrence at shallow depths or within the rootzone leads to capillary salinisation as reported in Chap. 6. In Chap. 7, groundwater balance calculations have indicated that seepage inflow from higher order areas, excess precipitation and irrigation, and higher waters are the major sources of excess groundwater in the scheme. The salt balance assessment further points to the need of providing other measures in addition to extra irrigation water (leaching requirement), especially in areas where shallow and salty groundwater, because too high amounts of irrigation water would be needed to maintain favourable conditions in the rootzone. Moreover, any extra water needs to be removed to prevent the further rise of the groundwater table.

The measures recommended in order to help alleviate the drainage and salinity problems in the area are given in the following sub-sections.
9.1 Identified problems

From the information provided in Chapters 4 to 7, some remedial measures can be recommended to solve the problems afflicting irrigation development in the Kimorogo/Kamleza area. In Chap. 4, two problems were identified; flood and surface drainage problems (which lead to surface water ponding for long durations). In Chap. 5, subsurface drainage problems were noted to exist in many parts of the schemes; high groundwater tables do occur for long durations; water at times is present for up to 3 months in the rootzone. The groundwaters were also noted to be saline and/or sodic and their occurrence at shallow depths or within the rootzone leads to capillary salinisation as reported in Chap. 6. In Chap. 7, groundwater balance calculations have indicated that seepage inflow from higher to lower areas, excess precipitation and irrigation, and floodwaters are the major sources of excess groundwater in the two schemes. The salt balance assessment further points to the need of providing other measures in addition to extra irrigation water (leaching requirement), especially in areas with shallow and salty groundwater, because too high amounts of irrigation water would be needed to maintain favourable salt conditions in the rootzone. Moreover, any extra water needs to be removed to prevent the further rise of the groundwater table.

The measures recommended in order to help alleviate the drainage and salinity problems in the area are given in the following sub-sections.

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9.2 Flood control

Flood flow over the area was noted to originate from the Lumi river, through broken parts or breaches in the river's flood dyke and also around the dyke. It was also noted that the flood and storm drains adjacent to the dyke are vegetated and silted. Based on these findings, the measures which need to be undertaken to prevent flood flow over the area would include:

(a) Repair of all broken parts of the dyke, especially the main broken part at the head of the dyke (see Chap. 4);

(b) Desilting and clearing of vegetation in the flood and storm drains so as to increase evacuation of floodwater and also to prevent backing up of floodwater, which finds its way around the dyke;

(c) Extending the dyke further north to reduce chances of flood flow around the dyke. This may involve the construction of a further 500 to 1000 m length of dyke.

The height of the flood dyke, which varies between 1.0 - 2.0 m along its course, appears to be sufficient as no flood flow was noted to occur over the dyke. However, with the many broken parts, a firm decision on the adequacy of the dyke height cannot be made at the moment.

While the above may be the immediate measures to be undertaken to solve the surface flooding problem, further investigations may need to be carried out to:
(a) find ways of increasing the Lumi river channel capacity in its lower reaches where the water level in the river is at a higher elevation than the adjacent land (see Chap. 4). This may involve desilting and clearing of swampy vegetation. This will result in a higher channel capacity and thus a possible reduction in flood flow onto adjacent land.

(b) find ways of increasing the discharge from lake Jipe through the Ruvu swamp to Tanzania. A higher discharge will lead to possible lowering of the lake water level (and hence the drainage base of the project area). This will in turn result in improved drainage of adjacent areas. A clear channel of the Lumi river in its lower reaches will reduce flood flow.

(c) find ways of diverting some flood waters to either flow directly to the Ruvu swamp by-passing Lake Jipe or divert the flood water to the Lake Jipe through a channel before the Njoro Kubwa springs. However, this may in turn result in flood problems in other areas.

9.3 Surface drainage

Surface water ponding is common in the project area after occurrences of flood flows, high precipitation, excessive irrigation or canal overflows. Measures which need to be undertaken to avoid these surface ponding problems, apart from those mentioned in Sec. 9.2 are:

(a) Completing the Now Kimorigo drain; the remaining length is 3.4 km. The drain is designed to carry a peak discharge
of 2 m$^3$/s at a slope of 0.05 % and is 2.5 m deep (Berger and Kalders, 1983). This drain was intended to serve an area of 2000 ha stretching from the Njoro Kubwa canal area to Ngutini in the south (also to collect water from field drains). 

(b) If the above drain may not be possible in the next one or two years, due to lack of funds, then the old Kimorogo drain can be desilted and cleared of vegetation to help in discharge of excess surface water. Over the occurrence of the unsaturated zone layer at shallow depths, less than 1.5 m in many

(c) Installation of a main drain between Kimorogo and Kamleza schemes (along the road, see Fig.8.1) for disposal of excess surface and subsurface water from Kamleza scheme. This drain should start from around well D2 upto well D5, a length of 3 km, before joining the old Kimorogo drain (see Fig.8.1). As noted in Chap. 5, there is sufficient head between point D2 and the outlet at Ruvu swamp and this main drain can be as deep as the New Kimorogo drain (2.5 m).

(d) Installation of collector drains in the schemes for disposal of excess surface and subsurface water from the schemes and discharging into the main drain. The collectors will also receive water from field drains (see next section).

9.4: Field drainage

Capillary salinisation as already mentioned in chapter is pronounced in many parts of the project area. In order to prevent capillary salinisation, a net downward movement of excess water and salts should be ensured. This
can be achieved through provision of adequate water for leaching (see Chap. 8). The excess water and salts must then be evacuated out of the soil by providing adequate field drainage. The amounts of extra irrigation water required as already estimated through salt balance assessment calculations (Table 8.2, Chap. 8) are extremely high for some locations. In order to reduce the amount of salts transported to the surface by upward capillary flow, the groundwater table should be maintained at depths greater than 1.5 m from the surface as shown in Chap. 6. However the occurrence of the calcareous layer at shallow depths, less than 1.5 m in many places may be hindrance to maintaining the water table at 1.5 m below the surface.

From the investigations and the groundwater and salt balance assessments, the following information needed for design of field drainage system is available:

i) depth of the calcareous layer within the schemes,

ii) K-values at several locations,

iii) drainable pore space,

iv) leaching requirements (for current situation),

v) estimate of irrigation efficiencies and thus an estimate of expected irrigation losses, and

vi) net subsurface inflows.

However, before carrying out a field drainage design, more investigations are necessary to establish:

i) the depth to the impermeable layer, especially where the underlying calcareous layer is pervious as in the central parts of Kimorogo scheme.

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ii) the K-value of the semi-pervious calcareous layer (any design at the moment in places where the semi-pervious layer exists will assume that the layer is impervious or has a K-value less than 1/10th of that of the overlying soil).

iii) K-values in many other places in the scheme as the determined K-values only give an indication at a few locations. Differences may exist within short distances as was witnessed around well B5 (see Sec. 6.3). A K-map would be advisable.

The main sources of excess surface water are floods, irrigation and overflowing water from irrigation canals.

The main sources of excess groundwater supply (and the causes of the drainage problems) are floodwater, seepage, irrigation and seepage or subsurface drainage.

Surface and subsurface drainage are poor as used by various water ponds and high groundwater levels.

The area situation, calling for the need to install suitable surface drainage channels.

The main system of the soils originates from the water i.e. there is salinisation from groundwater (or salinisation from drainage channels).
10. CONCLUSION AND RECOMMENDATIONS

The results obtained of the drainage and soil investigations in the project area lead to the following conclusions:

i) Due to the low ground slopes, both surface and subsurface drainage of excess water is slow. This often leads to surface water ponding and high groundwater tables for long periods.

ii) The main sources of excess surface water are floods, precipitation and overflowing water from irrigation canals.

iii) The main sources of excess groundwater supply (and thus the causes of the drainage problems) are floodwater, precipitation, irrigation and seepage or subsurface groundwater flow.

iv) Both surface and subsurface drainage are poor as witnessed by surface water ponding and high groundwater tables for long duration, calling for the need to install more surface and sub-surface drainage channels.

v) The high salt content of the soils originates from the groundwater i.e there is salinisation from groundwater (capillary salinisation).

vi) A low irrigation efficiency of 21% as estimated from groundwater balance assessment is an indication of poor water management, especially in areas where salinity is not
yet a serious problem, where extra irrigation water is required for leaching.

vii) Where the calcareous layer is impervious, vertical penetration is restricted, leading to perched water tables. The groundwaters in such areas are saline and capillary salinisation is pronounced.

viii) There is enough head between the end of the scheme and the outlet at Ruvu swamp to enable evacuation of excess surface and subsurface waters.

In order to alleviate the drainage and salinity problems in the area, the following recommendations are given:

a) Repair of the flood control dyke and the adjacent drains is necessary to prevent flood flow into the area. Without the control of flood flow over the area, the drainage problems will persist.

b) The surface drainage problems, particularly in the Kimorogo and Kamleza schemes, can be solved through installation of additional surface drains and proper maintenance of the existing ones.

A cut-off cum storm drain is required between Kamleza and Kimorogo scheme close to the Kimorogo canal. This drain will cutoff seepage flow from Kamleza scheme towards Kimorogo. In the two schemes, collector drains will be required.
c) The northern swampy area between Kivalwa and Kimorigo should be drained to reduce seepage inflow into the upper areas of Kimorigo scheme. The New Kimorigo drain on completion will be able to drain this swamp.

d) Subsurface drains/open drains are needed in the schemes for groundwater table control and evacuation of excess water and salts from the area. At the moment, there are no such drains in the schemes.

e) Water management in the schemes needs to be improved. The right amount of water at the right time should be applied to avoid excessive losses to the groundwater. Some extra leaching water may be needed, but this should be done in a planned way. This will require an irrigation schedule.

f) A strong scheme committee is required to ensure that canals and drains are maintained properly. In the case of the dyke and the main drains, either the government should provide funds for maintenance or farmers also pay some fee to offset part of the maintenance expenses.

g) Reclamation of the upper areas of Kimorigo scheme and the Block C areas are not advisable due to i) the high EC- and ESP-value of the soils, ii) low hydraulic conductivity and shallow depth of the calcareous layer which both would result in very closely spaced drains and very high leaching requirements as shown in Chap. 8.

h) Due to fairly good drainage conditions in the central part of Kimorigo scheme, the soils can be reclaimed through
REFERENCES

Leaching and ensuring that field drains are provided to evacuate the excess salts out of the area.

i) In Kamleza scheme, the affected areas in the northern area adjacent to Kimorogo scheme are not recommended for reclamation due to the high ESP-values and the shallow depth of the calcareous layer which would require closely spaced drains. Similarly in the lower areas around wells C5 and B5, both soil salinity and sodicity conditions are very high in the rootzone and thus reclamation would be difficult and expensive.

j) In the central areas of Kamleza scheme, where salty patches are found as a result of the impervious calcareous layer, further salinity problems can be prevented through regular leaching of salts and provision of field drains to evacuate the excess salts from the area.


REFERENCES


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USDA, 1954. Diagnosis and improvement of saline and alkali soils. USDA Publication No. 60, USDA, Washington.


**DEPTH TO WATER LEVEL MEASUREMENTS**

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### WATER ANALYSIS REPORT

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### WATER ANALYSIS REPORT Con't

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WATER ANALYSIS REPORT
24-Jul-89

WATER ANALYSIS REPORT
04-Jan-89
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Fig. A-1: Hydrograph for Well Eo (Northern Swampy area).
Fig. A - 3: Hydrograph for Well D3 (Kimorigo Central)

Fig. A - 4: Hydrograph for Well D5 (Lower Kimorigo)
Fig. A - 5: Hydrograph for Well B2 (Kamleza North)
Fig. A - Hydrograph for Well B5 (Kamleza South)
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## APPENDIX C

Table C - 1: RAINFALL DATA AT KIVALWA MALARIA RESEARCH STATION

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1988
Table C-1  RAINFALL DATA
1989

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58.6 15.6 56.2 225.1 107.4 5.6 0 3.5
### TABLE C-2: AVERAGE EVAPORATION DATA (mm) - TAVETA.

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Source: Berger and Kalderas (1983)

### TABLE C-3: MAXIMUM DISCHARGE OF CAPILLARY RISE IN MM/DAY FROM GROUND WATER

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<th>Soil</th>
<th>Distance to ground water level (cm)</th>
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<td>Clay</td>
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<tr>
<td>Clay loam</td>
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<tr>
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<td>Sandy loam</td>
<td>&gt;5.0</td>
</tr>
<tr>
<td>Sand</td>
<td>&gt;5.0</td>
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</tbody>
</table>

Source: MOA (1984)
APPENDIX D - HYDRAULIC CONDUCTIVITY

where:

\( r \) = radius of auger hole, (cm),
\( H \) = depth of hole below the groundwater table,
\( \text{dy/dt} \) = the average level of the water in the hole for time interval \( dt \),
\( \text{dy/dt,avg} \) = the average level of the water in the hole for time interval \( dt \),

(A) Hydraulic conductivity determination

Hydraulic conductivity was determined in the field using the augerhole and the inverted augerhole methods. With the augerhole method, the hydraulic conductivity may be calculated for three different cases:

(i) In areas where the augerhole reaches the petrocalcic or caliche layer as shown in Fig.1-1, the formula used according to Van Beers (1963) and Eijkelkamp (1983) is:

\[
K = \frac{3600 \cdot r^2 \cdot \text{dy/dt}}{(H + 10r)(2-y/H) \cdot y} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (22)
\]

(ii) In areas where the impermeable layer is at a depth \( S > 1/2H \), the formula used is:

\[
K = \frac{4000 \cdot r^2 \cdot \text{dy/dt}}{(H + 20r)(2-y/H) \cdot y} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (23)
\]

251
where,

\[ r = \text{radius of auger-hole, (cm)}, \]
\[ H = \text{depth of hole below the ground water table,} \]
\[ y = \text{distance between groundwater and the average} \]
\[ \text{level of the water in the hole for time interval } dt, \]
\[ (s), \]
\[ s = \text{depth to impermeable layer, in this case} \]
\[ \text{caliche}, \]
\[ dy = \text{the rise of water level in the hole during} \]
\[ \text{measurement, (cm)}, \]
\[ dt = \text{time interval, (s)}. \]

(iii) For areas with layered soils, a graphical method can be used (Van Beers, 1963).

In the diagram,

\[ D = \text{depth of the augerhole, (cm)} \]
\[ W = \text{depth of groundwater level, (cm)} \]
\[ W_1 = \text{tape reading at groundwater level, (cm)} \]
\[ y_0' = \text{tape reading of water surface elev - at } t = 0 \]
\[ y_t = \text{tape reading at different water surface elevation} \]
\[ \text{at times } t = 0 \]
\[ y_0 = \text{distance between groundwater level and the} \]
\[ \text{elevation of the water surface in the hole after} \]
\[ \text{removal of water at the time of the first} \]
\[ \text{reading, (cm)}. \]

\( H, dy, r \ldots \text{remain as before} \)
Fig. D-1: Diagram showing the various parameters in the Auger-hole method of determining hydraulic conductivity.

(iii) Layered Soil: The diagram in Fig. D-2, shows the arrangement for hydraulic conductivity measurement in a layered soil.

If the hydraulic conductivity of the upper layer is \( k_1 \), and the lower layer \( k_2 \), then the rate of rise in the deep hole is given by the equation overleaf;
The $C_2$-value corresponding with $n_2$ and $y_2$, is also read from the graph in Fig.D-3 (a) for which $S > 1/2H$. The C-value is obtained from the graph in Fig.D-3 (b) where $S = dy/\Delta t$, $K_1$, $K_2$ and $K_2$. The graph $S = Co dy/\Delta t - K_1$, $Co$ $\Delta t$, $K_2$ or $K_2 = Co dy/\Delta t - K_1$ or $Co$ and $K_2$ is considered to be the deep flow. If the upper layer is considered as pervious in this case (Van Reenen, 1963).

The value of $K_1$ is computed from $dy/\Delta t$ in the shallow hole (1), and the C-Value for $H_1$ and $y_1$, are obtained from graph in Fig. D-3 (a).

![Diagram of hydraulic conductivity and layer arrangement](image)

**Fig.D-2: Auger hole arrangement for determination of hydraulic conductivity in a layered soil.**
The $C_2$ value corresponding with $H_2$ and $y_2$, is also read from the graph in Fig. D-3 (a) for which $S > 1/2H$. The Co-value is obtained from the graph in Fig. D-3 (b) where $S = 0$, using $D$ and $y_2$. The graph $S = 0$ is used in this case, because only horizontal flow has to be taken into the deep hole. The lower layer is considered impervious in this case (Van Beer, 1963).

(B). Estimates of hydraulic conductivity.

Estimates of hydraulic conductivity for different soil textures as obtained from Smedema and Rycroft (1983) and FAO (1985), are given in Table D-1 below. In Table D-2, an interpretation is given of the hydraulic conductivity rates.

Table D-1: Hydraulic conductivity estimates in m/day.

<table>
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<th>Soil Texture</th>
<th>Range</th>
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<td>medium sand</td>
<td>2 - 60</td>
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<td>sandy loam</td>
<td>0.1 - 4</td>
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<tr>
<td>(very) - fine sand</td>
<td>0.1 - 12</td>
</tr>
<tr>
<td>fine sandy loam</td>
<td>0.1 - 3.5</td>
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<tr>
<td>clay loam</td>
<td>0.02 - 1.2</td>
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<tr>
<td>loam</td>
<td>0.05 - 3.5</td>
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<tr>
<td>heavy clay</td>
<td>&lt; 0.001 - 0.5</td>
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<tr>
<td>medium clay</td>
<td>0.002 - 0.6</td>
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<td>silt loam</td>
<td>0.01 - 3</td>
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<tr>
<td>gravelly silts to loams</td>
<td>0.005 - 4</td>
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Table D-2: Hydraulic conductivity Classes

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<td>4 - 6</td>
<td>Very rapid</td>
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<tr>
<td>1 - 3</td>
<td>Mod. rapid - rapid</td>
</tr>
<tr>
<td>0.1 - 1</td>
<td>Mod. slow</td>
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<td>0.04 - 0.1</td>
<td>Slow</td>
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<tr>
<td>&lt; 0.04</td>
<td>Very slow</td>
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Soils with K-values above 1 m/day are described as having good to very good drainage. Those with K-values between 0.1 - 1 m/day have fair internal drainage and those with K-values of less than 0.1 m/day are poorly drained.

Sample calculations

i) Non-layered soil, augerhole up to calcareous layer

The location considered is at well B5 in Kamleza South scheme. The data obtained during the field measurements are in Table 6.1 below. The calculation procedure and the various dimensions are in Fig. D-1, App.D.
### Table 6.1: Field data at well B5

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<td>H = 155</td>
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The soil layer above the subsoil is fine black sand. The moisture of the subsoil is fine black sand.

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<tr>
<td>50</td>
<td>98.1</td>
<td>0.4</td>
</tr>
<tr>
<td>60</td>
<td>97.7</td>
<td>0.4</td>
</tr>
</tbody>
</table>

\[ dy/dt = 2.3/60 = 0.038 \]

In order to calculate the K-value, eqn. 22 is used (see App.D). The value of \( y \) is obtained as follows:

\[ y = y_0 - 1/2 dy, \]  
where \( y_0 = y_0' - W' \).

By substituting the values of \( y_0' = 100 \) cm, \( W' = 60.4 \) cm and \( dy = 2.3 \) cm from Table 6.2, and \( y_1 = 36.26 \) (from above), we get \( y = 38.45 \) cm.

Using eqn. 22 and substituting \( r = 4 \) cm, \( dy/dt = 0.038 \), \( H = 155 \) cm, \( y = 38.45 \) and \( y/H = 0.248 \), we get:

\[ K = 0.17 \text{ m/day} \]  
or  \[ 0.2 \text{ m/day} \]
ii) K-calculation in a layered soil

The data used is for site G2 in the Block C area where the underlying subsoil, was found to having a higher K-value. Details of dimensions and parameters are given in Appendix D, Fig. D-2. The topsoil is heavy clay of thickness 155 cm thick. The texture of the subsoil is fine black sand. Table 6.2 contains the field data measurements.

The values of $y_1$ and $y_2$ are calculated as in case (1).

The values are:

$y_1 = 36.25$ cm and $y_2 = 24.8$ cm

The $K$-values are found as follows:

1) The value of $K_1 = C_1 \times (dy/dt)_1$ (*see App.D*).

With $dy/dt = 0.0018$, the value of $C_1$ can be read from Fig. D-3, App.D, and is found as 6.6. By substituting $H_1 = 89$ cm and $r = 4$ cm from Table 6.2, and $y_1 = 36.25$ (from above), we get,

$K_1 = 0.0018 \times 6.6 = 0.012$ m/day
Table 6.2: Field data from site G2 (Block C)

<table>
<thead>
<tr>
<th>Observation No.</th>
<th>G2 Location</th>
<th>Block C Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1 = 141$</td>
<td>$W_1^1 = 83.3$</td>
<td>$D_2 = 185$</td>
</tr>
<tr>
<td>$W_1 = 52$</td>
<td>$r = 4$</td>
<td>$W_2 = 52$</td>
</tr>
<tr>
<td>$H_1 = 89$</td>
<td>$S &gt; 1/2H$</td>
<td>$H_2 = 133$ S</td>
</tr>
</tbody>
</table>

\[
\begin{array}{cccccc}
\hline
 t_1 & y_{t_1}' & dy_{t_1} & t_2 & y_{t_2}' & dy_{t_2}' \\
0   & 120.1 &  & 0   & 112.0 &  \\
60  & 119.95 & 0.15 & 15  & 108.5 & 3.5  \\
120 & 119.8  & 0.15 & 30  & 105.4 & 3.1  \\
180 & 119.7  & 0.1  &       &       &      \\
240 & 119.6  & 0.1  &       &       &      \\
300 & 119.5  & 0.1  &       &       &      \\
360 & 119.4  & 0.1  &       &       &      \\
420 & 119.3  & 0.1  &       &       &      \\
480 & 119.2  & 0.1  &       &       &      \\
540 & 119.1  & 0.1  &       &       &      \\
600 & 119.0  & 0.1  &       &       &      \\
\hline
\end{array}
\]

\[
(dy/dt)_1 = 1.1/600 = 0.0018
\]

2) The value of $K_2$ can be obtained by using eqn.23, App.D.

i) Using $dy_1^1/dt_2^2 = 0.22$ and $H_2 = 133$ cm, the value of $C_2 = 6.4$ from the graph in Fig.D-3.

ii) Using $D = H = 103$ cm and $(dy/dt)_2 = 0.22$, the value of $C_0$ from the graph in Fig.1.3(b) is;

$C_0 = 8.5$ cm, ($S = 0$)
iii) By applying eqn. 23, and substituting $C_0 = 8.5$, $C_1 = 6.6$, $C_2 = 6.4$, $(dy/dt)_2 = 0.22$ and $K_1 = 0.012$ m/day, we get,

$$K_2 = 5.66 \text{ m/day}.$$
### TABLE D-1: HYDRAULIC CONDUCTIVITY VALUES

<table>
<thead>
<tr>
<th>Site</th>
<th>H (cm)</th>
<th>W (cm)</th>
<th>D (cm)</th>
<th>S (cm)</th>
<th>Ka (m/day)</th>
<th>Kb (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A5-A6</td>
<td>97</td>
<td>93</td>
<td>190</td>
<td>&gt;1/2H</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>111</td>
<td>34</td>
<td>145</td>
<td>&gt;1/2H</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>92</td>
<td>49</td>
<td>141</td>
<td>0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Profile Pit B5</td>
<td>155</td>
<td>28</td>
<td>183</td>
<td>0</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>B5-B6(near drain)</td>
<td>113</td>
<td>40</td>
<td>153</td>
<td>0</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>B6</td>
<td>163</td>
<td>47</td>
<td>210</td>
<td>&gt;1/2H</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>B7</td>
<td>111</td>
<td>96</td>
<td>207</td>
<td>&gt;1/2H</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>C0</td>
<td>136</td>
<td>50</td>
<td>186</td>
<td>&gt;1/2H</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>CI-C0</td>
<td>135</td>
<td>48</td>
<td>183</td>
<td>&gt;1/2H</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>94</td>
<td>80</td>
<td>174</td>
<td>0</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>C4-C5</td>
<td>49</td>
<td>141</td>
<td>190</td>
<td>0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>105</td>
<td>62</td>
<td>166</td>
<td>0</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>C5-C6</td>
<td>86</td>
<td>67</td>
<td>153</td>
<td>0</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>94</td>
<td>86</td>
<td>186</td>
<td>0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>80</td>
<td>138</td>
<td>218</td>
<td>&gt;1/2H</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>D0-1000</td>
<td>117</td>
<td>176</td>
<td>293</td>
<td>0</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td>108</td>
<td>15</td>
<td>118</td>
<td>0</td>
<td>0.2</td>
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</tr>
<tr>
<td>D1-DO</td>
<td>168</td>
<td>23</td>
<td>191</td>
<td>0</td>
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<td></td>
</tr>
<tr>
<td>D1</td>
<td>94</td>
<td>86</td>
<td>160</td>
<td>0</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>D2-C2</td>
<td>58</td>
<td>65</td>
<td>123</td>
<td>0</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>113.5</td>
<td>48</td>
<td>161.5</td>
<td>&gt;1/2H</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>118</td>
<td>73</td>
<td>191</td>
<td>&gt;1/2H</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>D7-1000</td>
<td>136</td>
<td>141</td>
<td>277</td>
<td>&gt;1/2H</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>D7-1000</td>
<td>125</td>
<td>20</td>
<td>46</td>
<td>&gt;1/2H</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>217</td>
<td>20</td>
<td>210</td>
<td>&gt;1/2H</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>E0</td>
<td>187</td>
<td>10</td>
<td>207</td>
<td>&gt;1/2H</td>
<td>0.06</td>
<td></td>
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<tr>
<td>E2</td>
<td>86</td>
<td>44</td>
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</tr>
<tr>
<td>E3</td>
<td>124.5</td>
<td>60</td>
<td>184.5</td>
<td>&gt;1/2H</td>
<td>0.4</td>
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</tr>
<tr>
<td>E4</td>
<td>80</td>
<td>56</td>
<td>136</td>
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</tr>
<tr>
<td>F0</td>
<td>175</td>
<td>12</td>
<td>187</td>
<td>&gt;1/2H</td>
<td>2.0</td>
<td></td>
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<tr>
<td>F1</td>
<td>136</td>
<td>141</td>
<td>277</td>
<td>&gt;1/2H</td>
<td>2.7</td>
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</tr>
<tr>
<td>F2</td>
<td>59</td>
<td>96</td>
<td>155</td>
<td>&gt;1/2H</td>
<td>0.06</td>
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<tr>
<td>&quot;</td>
<td>190</td>
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<td>280</td>
<td>&gt;1/2H</td>
<td>0.03</td>
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</tr>
<tr>
<td>F3</td>
<td>187</td>
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<td>207</td>
<td>&gt;1/2H</td>
<td>0.01</td>
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</tr>
<tr>
<td>F4</td>
<td>197</td>
<td>93</td>
<td>190</td>
<td>&gt;1/2H</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>89</td>
<td>52</td>
<td>141</td>
<td>&gt;1/2H</td>
<td>0.01</td>
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<tr>
<td>&quot;</td>
<td>133</td>
<td>52</td>
<td>185</td>
<td>&gt;1/2H</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>110</td>
<td>120</td>
<td>230</td>
<td>&gt;1/2H</td>
<td>1.4</td>
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<tr>
<td>G4</td>
<td>97</td>
<td>73</td>
<td>170</td>
<td>&gt;1/2H</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>G5</td>
<td>121</td>
<td>73</td>
<td>194</td>
<td>&gt;1/2H</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

**NB:**
- \( \text{Ka} \) = Hydraulic conductivity of upper layer, (m/day).
- \( \text{Kb} \) = Hydraulic conductivity of underlying layer, (m/day).
- \( \text{D} \) = Depth of the augerhole, (cm)
- \( \text{W} \) = Depth of ground water level, (cm)
- \( \text{S} \) = Depth to impermeable layer, in this case, caliche (cm).
- \( \text{H} \) = Depth of augerhole below the groundwater table, (cm).