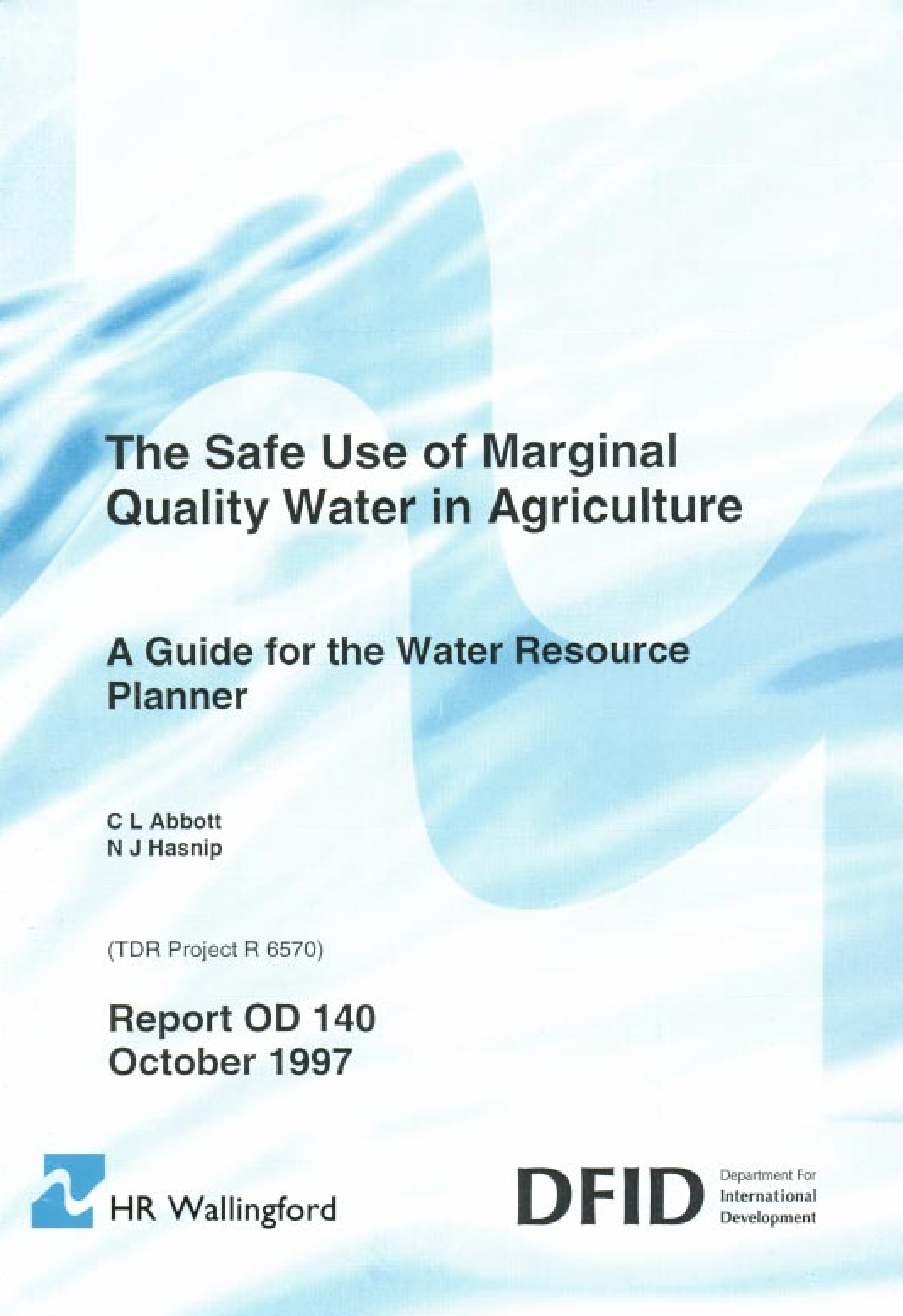

# The Safe Use of Marginal Quality Water in Agriculture

## A Guide for the Water Resource Planner

**C L Abbott**
**N J Hasnip**

(TDR Project R 6570)

**Report OD 140**
**October 1997**

HR Wallingford

DFID Department For International Development

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# *Summary*

The Safe Use of Marginal Quality Water in Agriculture

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Water scarcity is a major issue in many areas of the world. Good quality water supplies are insufficient to meet rising demands from agriculture, municipal use and industry. The agricultural sector is a major user of global water resources. Global estimates are that 73% of water supplied is used for irrigation, and in developing countries, an even larger percentage is used for irrigation. Sufficient and reliable volumes of water are required to maintain agricultural production and, consequently, planners in many regions are being forced to consider alternative sources of water for agricultural use.

Available water resources for agriculture can often be increased by using water of marginal quality. This includes reuse of agricultural drainage water and utilisation of wastewater or contaminated groundwater. The planner may be able to significantly increase available water supplies by including these water resources in regional water-use plans. However, whilst the use of marginal quality water can increase the supply available for agricultural production, there are dangers. Marginal quality water supplies have been polluted by industry, agricultural or human activities and, without proper management, pollutants found in these sources pose a serious threat to soils, crops and human health.

To plan for successful integration of marginal quality water sources into agricultural water use policy, planners must be aware of the associated dangers and available management options. Informed decision making is essential to success. Different strategies must be evaluated and their impacts assessed so that maximum benefit is derived from marginal quality water resources. Intelligent and thorough planning will allow marginal quality water resources to maintain or improve sustainable agriculture in a region whilst minimising or avoiding detrimental effects.

This guide has been prepared to help planners successfully integrate marginal quality water supplies into regional water use strategy. They are guided through the necessary procedures to identify and assess potential marginal quality water supplies, and provided with the tools to evaluate impacts on crops, soils and human health in the region. Different management options are presented to maintain long-term sustainable agriculture, together with the advantages and disadvantages of each.

# Glossary of terms and abbreviations

BOD = biochemical oxygen demand
$dS\,m^{-1}$ = deciSiemens per metre
EC = electrical conductivity
$EC_w$ = electrical conductivity of water
$EC_e$ = electrical conductivity of saturated soil extract
ESP = exchangeable sodium percentage
LF = leaching fraction
RSC = residual sodium carbonate (residual alkalinity)
meq/l = milli-equivalents per litre
mg/l = milligrams per litre
mm/hr = millimetres per hour
[P] = pollutant concentration
SAR = sodium adsorption ratio
$Y_r$ = relative yield
CEC = cation exchange capacity
TDS = total dissolved salts
$EC_{sat\ extract}$ = electrical conductivity of saturated soil extract
MAC = maximum acceptable concentration
LR = leaching requirement
SAT = soil aquifer treatment
Cations:
- $Na^{1+}$ = sodium ion
- $Ca^{2+}$ = calcium ion
- $Mg^{2+}$ = magnesium ion
- $K^{1+}$ = potassium ion

Anions:
- $CL^{1-}$ = chloride ion
- $SO_4^{2-}$ = sulphate ion
- $CO_3^{2-}$ = carbonate ion
- $HCO_3^{1-}$ = bicarbonate ion

ppm = parts per million

## Useful Conversion Factors and Formulae

TDS (ppm) ≈ EC ($dSm^{-1}$) x 640 for $0.1 < EC < 5.0$ $dSm^{-1}$
TDS (ppm) ≈ EC ($dSm^{-1}$) x 800 for $EC > 5.0$ $dSm^{-1}$

SAR is sodium adsorption ratio, given by

$$\mathrm{SAR} = \frac{\left[\mathrm{Na}^{+}\right]}{\sqrt{\dfrac{[\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}]}{2}}}$$

Where $[Na^+]$ = sodium concentration (meq/l)
$[Ca^{2+}]$ = calcium concentration (meq/l)
$[Mg^{2+}]$ = magnesium concentration (meq/l)

ESP is exchangeable sodium percentage, given by

$$\mathrm{ESP} = \frac{\text{exchangeable sodium ions}}{\text{soil cation exchange capacity}} \ \mathrm{x}\,100$$

or it can be estimated from the SAR by the formula:

$$\mathrm{ESP} = \frac{(1.47\ \mathrm{x}\ \mathrm{SAR}) - 1.26}{(0.0147\ \mathrm{x}\ \mathrm{SAR}) + 0.99}$$

RSC is residual sodium carbonate, given by

$$\mathrm{RSC} = \left( [\mathrm{CO_3}^{2-}] + [\mathrm{HCO_3}^{1-}] \right) - \left( [\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}] \right)$$

where $[CO_3^{2-}]$ = carbonate concentration (meq/l)
$[HCO_3^{1-}]$ = bicarbonate concentration (meq/l)
$[Ca^{2+}]$ = calcium concentration (meq/l)
$[Mg^{2+}]$ = magnesium concentration (meq/l)

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**Appendix**

Appendix 1 Laboratory analysis techniques

# 1 Introduction

**Marginal quality water is defined as that which poses a threat to sustainable agriculture and/or human health by virtue of its quality, but which can be used safely for irrigation provided certain precautions are taken.**

The **aim** of this guide is to integrate marginal quality water use into agriculture. The management, allocation and distribution of marginal quality water sources requires a new approach to conventional water resource planning, in which water quality becomes an important constraint.

## 1.1 Readership and scope of the guide

The institutions and processes by which water is allocated, regulated and controlled in developing countries are often complex. The need to integrate water quantity and quality issues is recognised, but governments still assign responsibilities for water quality planning, management and operations to units separate from those responsible for the water quantity. To be effective water management requires a joint approach to water quality and quantity and the use of marginal quality water raises new issues in water resource planning which must be addressed. This guide attempts to highlight those issues and provide strategies for the planner to assist in allocation, distribution and management of marginal quality water resources. The procedures and tools presented are suitable for use by non-specialists.

**This guide is aimed at water resource planners and managers in areas that incorporate, or will incorporate, water of marginal quality for agricultural production.** It may also be of use to agricultural planning departments, land development agencies, environmental impact assessors and as an educational tool. Guidelines and procedures are set out which will assist planners and managers to realise the following objectives:

- To increase water resources available for agricultural production in a region.
- To plan for long-term, sustainable agricultural production in a region.
- To avoid or minimise threats posed to human health through contact with water supplies used for agricultural purposes.

Specifically, the guide gives information on:

- Identifying primary sources of marginal quality water, likely pollutants and their associated dangers.
- Assessing the potential of a marginal quality water source for sustainable agricultural production.
- Determining the hazards to humans through use of marginal quality water for irrigation.
- Assessing the risk of soil degradation.
- Prediction of long-term soil pollutant accumulation.
- Determining the long-term effects on crop yield.
- Different management options for marginal quality water:
    - Water treatment
    - Blending with other available water sources
    - Cyclic use of marginal quality supplies
    - Leaching of salts

## 1.2 Content

Chapter 2, *Hazards of marginal quality water,* provides:

- Background information on processes of water resource pollution.
- Summary of the primary sources of marginal quality water and the likely dangers.
- Description of the pollutants of most concern and the associated risks to soils, crops and human health.

Chapter 3, *Assessment of marginal quality water,* defines the measured parameters, water sampling procedures and 'safe' pollutant levels which permit the user to:

- Evaluate marginal quality water sources for sustainable agricultural production.
- Evaluate the associated human health risks.

Chapter 4, *Suitability of agricultural soils for irrigation with marginal quality water.* Productive soils are essential to sustainable agriculture. The application of marginal quality water can result in serious soil degradation and it is vital that planners assess the risk. The chapter sets out:

- Recommended sampling procedures.
- Predictive tools for soil hazard risk assessment.

Chapter 5 *Assessment of risk to long-term crop production*:
Pollutants can accumulate in soils through use of marginal quality water, ultimately leading to depressed crop development and yield. The chapter provides guidance on:

- Prediction of long-term soil pollutant accumulation.
- Assessment of long-term risk to crops currently grown or proposed.

Chapter 6 *Water resource planning options*
The final chapter sets out the range of management options that can be used to ameliorate the effects of marginal quality water on crops, soils and human health. The chapter describes:

- Water treatment.
- Blending of marginal quality water supplies with other sources.
- Cyclic use of marginal quality supplies.
- Control of soil pollutant accumulation by leaching.

## 1.3 How to use the guide

**The guide is intended for use at the project planning stage of the project cycle.** It is an impact assessment tool for irrigated agriculture with marginal quality water allowing evaluation of the likely effects on sustainable agriculture and human health, and consideration of the benefits of alternate management options. Figure 1.1 demonstrates how to use the guide, depending on the pollutants present in the marginal quality water source in question.

It is recommended that each marginal quality water source is tested for all pollutants included in this guide. Further analysis and action should then be undertaken depending on the range of pollutants present.

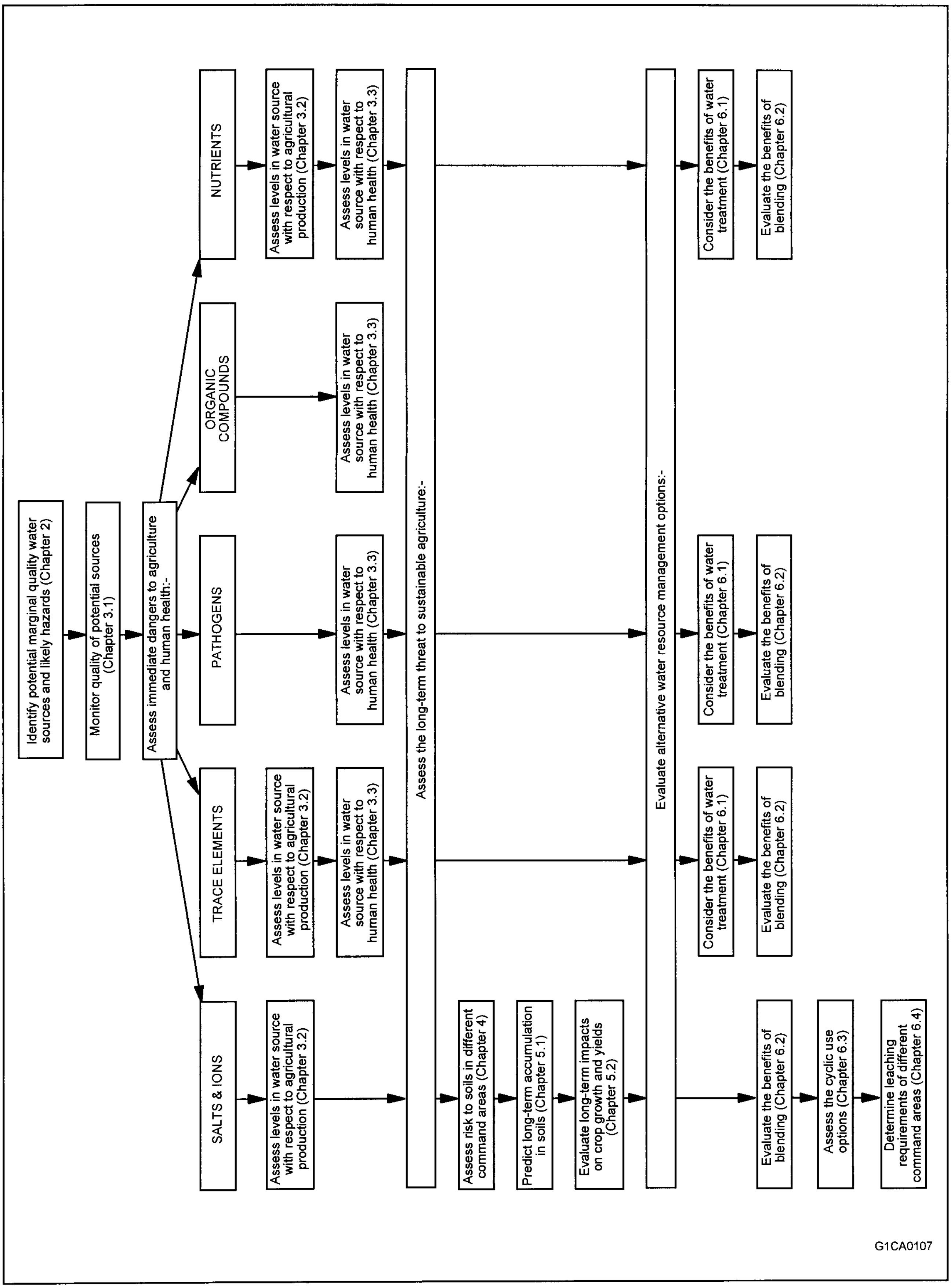


**Figure 1.1** How to use the guide

# 2 Hazards of marginal quality water

## 2.1 Pollution pathways and main pollutants

Pollution of water sources is a growing problem in both the developing and developed world. In the developing world rapid growth in population and industry, coupled with inadequate regulation and control of polluters has led to severe contamination in many areas. Many pollutants enter water supplies either directly or indirectly leading to serious environmental problems.

**Examples of water resource pollution:**

- The river Ganges receives untreated sewage from 114 cities with populations of more than 50,000. Industries including DDT factories discharge untreated waste directly into the river.
- Untreated industrial and domestic effluents are discharged directly into Lake Maryut in Egypt. Fish production has declined by 80% in the last decade.
- An epidemic of shell-fish borne hepatitis A in China in 1988 affected 292,000 people and was related to the consumption of clams contaminated by polluted water.

(Birley, 1995)

Pollutants enter waterways by natural processes and from industrial, domestic and agricultural activities. The main pollution pathways are indicated in Figure 2.1.

POLLUTANT

| ACTIVITY | Pathogens | Nutrients | Organic compounds | Trace elements | Salts and toxic ions |
|---|---|---|---|---|---|
| Urbanisation | ● |  | ● |  |  |
| Industrial development |  |  | ● | ● | ● |
| Agriculture - agrochemicals |  | ● | ● |  |  |
| Agriculture - irrigation & drainage |  | ● | ● |  | ● |
| Livestock rearing | ● | ● | ● |  | ● |
| Mining development |  |  |  | ● | ● |

Adapted from Chapman (1992)

**Figure 2.1 Primary water pollution pathways**

Marginal quality water contains pollutants that pose a threat to crops, soils and human health (see Figure 2.2). The main dangers come from salts and toxic ions, faecal pathogens, nutrients, trace elements and organic compounds. Salts and toxic ions accumulate in agricultural soils leading to soil degradation and crop yield depressions whilst pathogens and heavy metals can cause serious diseases in humans and livestock. Planning for sustainable use of marginal quality water is paramount. Risks should be assessed and appropriate management strategies implemented.

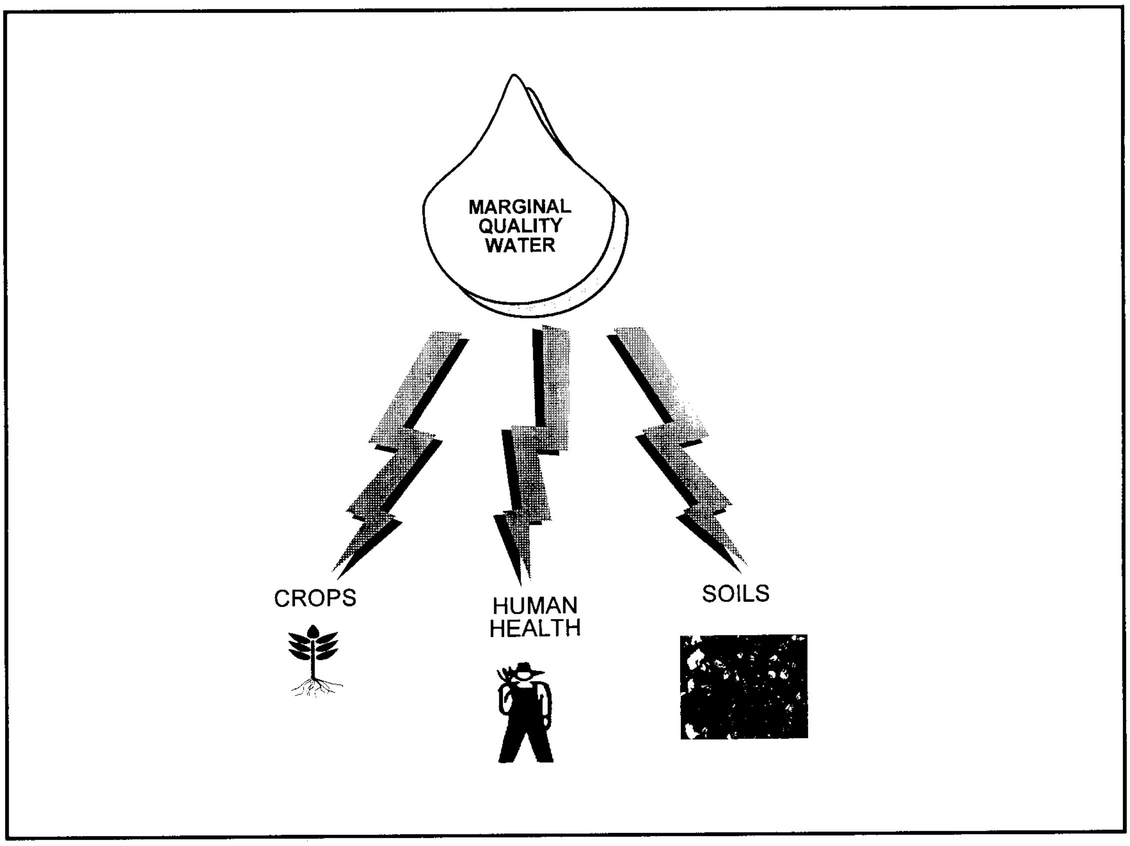


Figure 2.2 The dangers of marginal quality water

## 2.2 Marginal quality water sources

Within an agricultural region there are likely to be several sources of water that may be suitable for agricultural use. The planner must identify which sources are likely to be acceptable for agricultural purposes and what the management options are.

The most common sources of marginal quality water available within agricultural catchments, which may be suitable for agricultural use, are:

- Agricultural drainage water
- Municipal and industrial wastewater
- Shallow groundwater

With careful planning and management, these sources can be entirely suitable for agricultural purposes. It is possible for any of these sources to be contaminated with any of the pollutants highlighted earlier, but some general trends can be identified. These are summarised in Figure 2.3 and discussed below.

|  | Salts and toxic ions | Trace elements | Organics | Nutrients | Pathogens |
|---|---|---|---|---|---|
| Agricultural drainage water | ● | ○ | ○ | ● | ○ |
| Wastewater | ○ | ● | ● | ● | ● |
| Groundwater | ● | ○ | ○ |  |  |

● Major pollutant
○ Minor pollutant

**Figure 2.3** **Pollutants often found in common sources of marginal quality water**

### *2.2.1 Agricultural drainage water*

This is water that has passed through the soil profile and entered the drainage system via artificial subsurface drains or through natural drainage. Salts and toxic ions are the main pollutants likely to be picked up as water passes through the soil profile. Organic compounds and nutrients may be applied to the soil surface as agro-chemicals. These compounds enter drains primarily via surface runoff following irrigation or rainfall events. Pathogens can enter surface drains in human and animal waste products either directly or in surface runoff. Trace elements from industrial pollution may also find their way into drainage channels.

Some areas routinely produce significant volumes of drainage water (typically 10-20% of water applied leaves the field as drainage water) and exploitation of this valuable resource can contribute considerably to water use efficiency and agricultural production.

**Reuse of agricultural drainage water – Egypt**

Drainwater reuse is a major component of water use strategy in the prime agricultural area of the Nile Delta. It was started in the 1930s and is now the largest source of irrigation water after the river Nile. In 1990 the total amount of drainwater generated in the Nile Delta was 16.19 billion m$^3$. It is estimated that at least 3.2 billion m$^3$ of this is reused for irrigation. Current policies are based on increasing this to a value of 7 billion m$^3$ by the year 2000 (Abdel-Dayem and Abu-Zeid, 1991).

### *2.2.2 Wastewater*

Wastewater is principally domestic sewage but it may contain a proportion of industrial effluents discharged into public sewers. Pathogens, nutrients and some organic compounds will come from domestic sewage. Other organic compounds and trace elements (frequently heavy metals) may come from industrial effluents. Salts may enter wastewater from agricultural areas.

These pollutants, in particular pathogens, present a serious risk to human health if not handled properly. Reuse of wastewater for irrigation is widely practised in both the developed and developing world, in many cases without treatment, which constitutes a major health risk.

**Use of wastewater for irrigated agriculture**

**Near East**
Due to increasing pressures on available water, wastewater reuse is a common practice in several countries of the Near East including Kuwait, Saudi Arabia, Libya, Tunisia and Israel. In Israel wastewater is considered a vital water resource with an annual flow of 420 million $m^3$ planned for the year 2010 (Shelef, 1991). This constitutes 19% of the total water supply and about one third of the total water allocated to the agricultural sector.

**Mexico**
The use of wastewater for agricultural irrigation is widespread in the semi-arid regions of Mexico. Very rapid urban growth has put enormous strain on scarce water resources and one strategy has been to make extensive use of wastewater. The city of Leon has a rapidly expanding population (currently 1.2 million) with increasing water demands and unreliable rainfall. Wastewater irrigation began in the region about 40 years ago and the agricultural area currently licensed is 3286 hectares (BGS *et al*, 1996).

### *2.2.3 Groundwater*

Although groundwater is potentially a source of good quality water, it is open to pollution from several areas. Coastal areas may suffer from intrusion of seawater, and salts, toxic ions, nutrients and organic compounds can percolate to groundwater from agricultural areas. Nitrate is the most mobile of the nutrients in soils and is a common pollutant of groundwater. Effluent from badly managed landfill sites may contribute numerous organic compounds and trace elements.

Salts and toxic ions pose most risk to sustainable agriculture, whilst organic compounds and heavy metals constitute greatest risk to humans. Nutrients contained in applied water may have some positive benefits for agricultural production by reducing fertiliser requirements.

**Groundwater irrigation – Jordan**

There are a number of groundwater irrigation projects in Eastern Jordan. The Wadi Dhuleil scheme is the largest, supplying an estimated 1560 hectares of agricultural land (Ayers and Westcot, 1985). The irrigation supply comes entirely from groundwater. Although the water was initially of good quality, this has deteriorated gradually leading to problems of crop development and yield.

## 2.3 Pollutants and dangers

The main threat posed by each group of pollutants is summarised in Figure 2.4 and discussed in the following sections.

| POLLUTANT | THREATENED GROUP | | |
|---|---|---|---|
| | Soils | Crops | Human health |
| Salts | ● | ● | |
| Trace elements | | | ● |
| Pathogens | | ● | ● |
| Organic compounds | | ○ | ● |
| Nutrients | | ○ | ● |

● Major threat
○ Minor threat

**Figure 2.4** **The main pollutants and threatened groups**

### *2.3.1 Salts and toxic ions*

The major solutes comprising dissolved mineral salts are the cations sodium, calcium, magnesium and potassium and the anions chloride, sulphate, carbonate, bicarbonate and nitrate. These are derived from naturally occurring salts in soils and rocks that pass into solution in the surrounding soil water. This soil water drains into surface rivers or passes to the groundwater table. In coastal areas, intrusion of seawater into aquifers and surface flooding by seawater can greatly increase concentration of salts in surface and groundwater resources.

It is estimated that worldwide, 20-30 million hectares of agricultural land are severely affected by salinity and an additional 60-80 million hectares are affected to some extent (FAO, 1990). Salt accumulation in soils results in plant damage, yield reduction and crop failure, as well as posing a serious threat to soil fertility and physical structure. Crops can suffer large yield reductions in salinised soils, to the point where land is abandoned.
The detrimental effects of salts can be divided into three types:

1. Physico-chemical effects on soils
2. Stress effects on crops
3. Toxicity effects on crops

**Physico-chemical effects of salts on soils**
Salts contained in marginal quality water sources pose a danger to agricultural soils due to their strong influence on the processes of soil swelling and dispersion, which account primarily for degradation in soil hydraulic properties and structure (Oster, 1994). These processes are directly influenced by the total salinity and ionic composition of the soil water surrounding the soil colloids, and the cations bound onto the surface of the soil colloids (which are strongly influenced by the salt content and composition of the applied water).

*Swelling* is caused predominantly by the cations held on the surface of the clay crystals attracting water. When a soil swells, the pore radii are decreased, reducing both saturated and unsaturated hydraulic conductivity. The extent of swelling is determined both by the type of clay crystal and the dominant cations held on the reactive surfaces of the clay. Smectites show greatest swell/shrink properties, vermiculite clays are intermediate and kaolinite, chlorite and illite clays show little swelling.

Aggregate structure is maintained when divalent and trivalent cations such as calcium, magnesium and aluminium predominate within the soil. Swelling and shrinking occur but the clay particles retain their internal structure. If these divalent and trivalent ions are replaced by the larger monovalent sodium ion, the swelling and shrinking of the soil becomes more pronounced on wetting and drying with consequent effects on hydraulic conductivity, porosity and root growth.

*Dispersion* occurs if the process of replacing the smaller divalent and trivalent cations with sodium continues beyond a given point. The clay particles break down into individual platelets resulting in serious loss of soil structure. The number and volume of pores is decreased as this happens, and hydraulic conductivity can be reduced to the point where impermeable layers are formed. This process is not easily reversed and the impermeable layers can usually only be ameliorated by mechanical means.

The effects of soil swelling are normally only significant in soils with high clay content. However, the effects of dispersion can be seen even in soils with a relatively low clay content (Shainberg and Letey, 1984). Even sandy loam soils may suffer large reductions in hydraulic conductivity due to dispersion.

### Stress effects of salts on crops

When soluble salts, from a marginal quality water source, accumulate in the soil water of the crop root zone, plant growth is retarded. As the concentration of salts in the soil water increases the osmotic gradient between the soil water and the plant root cells increases. To abstract water from the soil, plants must expend more energy, which is diverted from other growth processes. Plants exhibit symptoms of drought including stunted growth and reduced yields.

Sensitivity to salinity varies between crops and with stage of growth. Salt-sensitive crops include beans and most fruit crops and salt-tolerant crops include cotton and wheat. Plants are usually more salt-sensitive during emergence and early seedling stages of growth than during germination (Shalhevet, 1994).

Climate can have a large effect on crop response to salinity. In cool, humid climates most crops will tolerate higher salinity than in hot, dry climates.

### Toxicity effects of salts on crops

Some ions are taken up with water through the plant roots and accumulate in the leaves as water is lost to transpiration. Many of them are beneficial to crop growth - potassium and calcium are important nutrients. At low levels, ion build-up in the plant is not a problem, but if the concentration of some ions increases beyond threshold levels, crop damage and yield reduction can occur.

The build-up of ions in plants is likely to be greater in hot areas where larger volumes of water are transpired.

#### Chloride

Most damage occurs when the chloride of calcium, potassium or magnesium is present. The chloride ion moves readily with the soil water, is taken up by the crop, moves in the transpiration stream, and accumulates in the leaves. Crop tolerance to chloride is variable. Vegetable crops like onion and carrot are most susceptible, along with maize, flax, broad beans and berseem. Tolerant crops include wheat, sugarbeet, cotton and barley. (See Table 5.6)

Sodium

Sodium is not required for crop growth. High concentrations of sodium in applied water may result in a toxicity problem for the crop. Symptoms of sodium toxicity include leaf burn, scorch and dead tissue along the outside edges of leaves. Sensitive crops include maize. Semi-tolerant crops include rice and wheat. Barley and sugarbeet are tolerant to sodium. (See Table 5.7)

Calcium, magnesium, potassium

An excess of these ions is unlikely to inhibit crop growth, but since each of these ions is required by the plant, uptake of one ion is hindered if there is too much of another ion present. For example, an excess of magnesium, compared to calcium can cause calcium deficiencies in plants. (See Table 5.8)

Boron

Boron, in small quantities, is essential for plant growth. If too much is taken up it becomes toxic. Toxicity symptoms normally show first on older leaves as a yellowing, spotting or drying of leaf tissue at the tips and edges.

### *2.3.2 Trace elements*

Trace elements are those that occur in samples at concentrations of less than a few milligrams per litre. Although some trace elements are essential to plant growth, all can become toxic at higher concentrations. A number of trace elements (particularly the heavy metals) are also dangerous to human health. The most dangerous being:

Aluminium
Cadmium
Chromium
Copper
Iron
Mercury
Manganese
Nickel
Lead
Zinc
Arsenic
Selenium (WHO, 1991).

Humans are at most risk from these elements when they use water for bathing, recreation or domestic supply.

**Selenium Poisoning in Kesterson, California**

In 1982, scientists discovered that irrigation drainage water had contaminated the ponds at Kesterson National Wildlife Refuge in California with toxic levels of selenium, a naturally occurring trace element (Presser and Ohlendorf, 1987). As a result, waterfowl died and suffered reproductive failures, fish populations suffered and algal blooms and cattails all indicated a problem of serious proportions.

Arsenic

Arsenic may come from fertilisers and sewage. It is toxic and carcinogenic. The recommended drinking water limit, set by the World Health Organisation, is 10 micrograms per litre. Chronic arsenic poisoning commonly causes skin diseases, but other renal, gastrointestinal, neurological, haematological, cardiovascular and respiratory symptoms can result. Pyrite-rich sedimentary aquifers can pollute groundwater with arsenic. Smelting or fossil fuel combustion can produce arsenic and it is commonly used in pesticides, wood preservatives and pharmaceuticals.

Cadmium

Long-term exposure to cadmium in air, food or water leads to a build-up in the kidneys and possible kidney disease. Other possible long-term effects are lung disease and fragile bones. Some cadmium dissolves in water and it binds strongly to soil particles.

Lead

Lead is one of the most toxic metals found in aquatic systems. Hazards include kidney damage, metabolic interference and damage to the central nervous system.

Mercury
In its inorganic form, mercury may cause kidney damage and ulceration. In its organic form, methyl mercury can affect the central nervous system and cause death even at low doses.

Trace elements are readily fixed and accumulate in soils. Repeated applications of water containing trace elements at levels above crop uptake will lead to build-up in the soil profile, and possible subsequent damage to crops. (See Table 3.5)

### 2.3.3 Pathogens

Pathogens in marginal quality water used for agriculture pose the greatest risk to human health. They are introduced into waterways as human and animal waste products and can cause diseases ranging from mild gastro-enteritis to fatal dysentery, cholera and typhoid. Pathogenic viruses, bacteria, protozoa and helminths will survive in the environment for long periods of time as shown in Table 2.1, presenting a risk to people using the water for domestic use, irrigation, recreation or other purposes.

A measure of the number of faecal coliforms is the standard indicator of bacteriological quality of water. These bacteria are only found in water contaminated by human sewage and their presence indicates that other pathogenic organisms may also be present.

***Table 2.1 Survival times, in days, of excreted pathogens (at 20-30$^{o}$C)***

| Type of pathogen | Environment | | | |
|---|---|---|---|---|
| | **In faeces, nightsoil and sludge** | **In freshwater and sewage** | **In the soil** | **On crops** |
| VIRUSES | | | | |
| Enteroviruses | <100 (<20) | <120 (<50) | <100 (<20) | <60 (<15)[*] |
| BACTERIA | | | | |
| Faecal coliforms | <90 (<50) | <60 (<30) | <70 (<20) | <30 (<15) |
| Salmonella | <60 (<30) | <60 (<30) | <70 (<20) | <30 (<15) |
| Shigella | <30 (<10) | <30 (<10) | - | <10 (<5) |
| Vibrio cholerae | <30 (<5) | <30 (<10) | <20 (<10) | <5 (<2) |
| PROTOZOA | | | | |
| Entamoeba histolytica cysts | <30 (<15) | <30 (<15) | <20 (<10) | <10 (<2) |
| HELMINTHS | | | | |
| Ascaris lunbricoides eggs | Many months | Many months | Many months | <60 (<30) |

After: Pescod, (1992)

[*] Figures in brackets show usual survival time.

### 2.3.4 Organic compounds

Organic compounds are introduced into surface and subsurface waterways by industrial, urban and agricultural activities. Main groups include:

- Mineral oils
- Petroleum products
- Phenols
- Biocides
- Polychlorinated biphenyls (PCBs)
- Surfactants

Mineral oil and petroleum products are considered major pollutants as they cause considerable ecological damage in inland surface waters.

Phenols can be formed under natural conditions, but are also included in waste products of many industries that enter waterways. As they are easily oxidised, they have a detrimental effect on the quality and ecological condition of water bodies due to the depletion of free oxygen.

There are an estimated 10,000 different biocides products in the world today, covering insecticides, herbicides and fungicides. Many of these break down into toxic products that pose a risk to living organisms including humans.

Surfactants enter water bodies with industrial and household wastewaters. They are not highly toxic, but can affect aquatic biota. They are responsible for foam formation in surface waters. Other pollutants, including pathogens, can become concentrated in this foam.

### *2.3.5 Nutrients*

Nitrates, phosphates and potassium will enter watercourses in surface runoff from agricultural land and are also contained in human and animal waste products. Nutrients are essential to crop development, but in large quantities, they can become toxic. They are also toxic to humans who may be exposed.

**Nitrate health hazard**

The main danger from nitrate is perceived to be methaemoglobinaemia, 'Blue Baby Disease' where haemoglobin in the blood of infants is converted to a form that cannot carry oxygen (methaemoglobin). Clinical diagnosis of this condition is generally possible when around 15% of the blood haemoglobin is affected, causing a blue discoloration of the skin to become apparent. When haemoglobin inactivation approaches 50% shortness of breath and a fast heart rate are apparent, and death may result from asphyxiation. Infants up to 4-6 months of age are particularly susceptible to methaemoglobinaemia because of the lack of acidity in their stomachs and possible gastrointestinal infection, allowing nitrogen-converting bacteria to flourish (Klassen et al, 1986; Wetzlich, 1991). Such dangerously high impairment of oxygen transportation capacity is reported to develop only when nitrate concentrations in drinking water approach around 15,000mg/l.

# *3 Assessment of marginal quality water sources*

The first step in planning for sustainable use of marginal quality water is to measure and evaluate pollutant levels in the water source at the proposed abstraction point. This chapter identifies the main pollutants to be monitored and provides guidance on acceptable levels to protect agriculture and human health. Wherever there are uncertainties about the type of pollutant present in a marginal quality water, samples should be tested for all the pollutants discussed in this chapter.

## 3.1 Sampling procedures

### *3.1.1 Parameters measured*

The following parameters should be determined for any marginal quality water considered for use in irrigation:

| Parameter | Unit of measure |
|---|---|
| Total salinity | $dS\ m^{-1}$ |
| Sodium content | meq/l |
| Calcium content | meq/l |
| Magnesium content | meq/l |
| Chloride content | meq/l |
| Boron content | meq/l |
| pH | |
| Trace element concentrations | mg/l |
| Nutrient levels | mg/l |
| Faecal coliforms | no. per 100ml |
| Intestinal nematodes | eggs per litre |
| Organic pollutants | µg/l |

Methods of analysis are given in Appendix 1.

### *3.1.2 Spatial distribution*

Water samples from canals should be taken at the point of entry to the project area. At the first stage of the monitoring programme, 3 or 4 samples should be taken depending on the width of the canal (2 near each bank, 2 in the middle) to check the heterogeneity throughout the cross-section of the canal. If the pollutant cross-section is uniform, future samples can be taken from the most convenient location (usually the bank). If the cross-section is not uniform, future samples should be taken from the mid-point of the canal, by means of a bridge or boat if necessary, at thirty centimetres depth below the surface (Hutton, 1983). Care should be taken to ensure no accidental contamination of the sample during sampling and transport. Glass bottles can be used for storage and a sample size of 500ml is adequate.

**For further guidance on surface water sampling techniques and equipment the reader is referred to the following texts:**

A.E. Greenberg et al. 1992. Standard methods for the examination of water and wastewater.

J.B. Bartram and R. Balance. 1996. Water Quality Monitoring. Chapman and Hall.

L.R. Shelton. 1994. Field guide for collecting and processing stream-water samples for the national water quality assessment program. U.S. Geological Survey, Open-File Report 94-455.

WHO 1991. GEMS/WATER 1990-2000. The Challenge Ahead. WHO/PEP/91.2.

Initial sampling of shallow groundwater may be possible by hand-digging or augering to a depth below the watertable, and collecting samples in glass bottles. For abstraction of groundwater from shallow depths, not more than 5-8m below the soil surface, horizontal methods (galleries) are recommended. They are especially appropriate in coastal areas where the ‘fresh’ water to be withdrawn floats on top of underlying salt water.

**For more information on groundwater sampling and abstraction techniques the reader is referred to the following texts:**

Driscoll, F.G. 1986. Groundwater and Wells.

International Reference Centre for Community Water Supply and Sanitation. 1981. Small Community Water Supplies. Technical paper 18. The Hague, Netherlands.

### *3.1.3 Sampling frequency*

Seasonal variations in water quality may be significant so it is necessary to measure pollutant concentrations several times per year. This should be done at least on a monthly basis.

## 3.2 Acceptable levels for crop growth

The main pollutants in marginal quality waters that pose a threat to irrigated agriculture are salts and toxic ions. Tables setting out permitted safe levels of these pollutants are provided in this section together with information on safe levels of trace elements and nutrients. Pathogens and organic compounds have their primary effects on human health and are considered in Section 3.3.

### *3.2.1 Salts and toxic ions*

Table 3.1 summaries the recommendations published by the FAO in 1985. However, it is now widely acknowledged that these and other early guidelines on acceptable salinity levels for agricultural use were very conservative. Based on more recent work carried out in India, Rao *et al,* (1994) have developed the recommendations set out in Tables 3.2 and 3.5. Although these were developed for monsoonal agriculture in India, they can also be applied to other areas with seasonal rainfall.

## Table 3.1 FAO guidelines for interpretation of water quality for irrigation

| **Potential irrigation problem** | | | **None** | **Slight to moderate** | **Severe** |
|---|---|---|---|---|---|
| | | | **CROP EFFECTS** | | |
| Salinity | $EC_w$ | (dS $m^{-1}$) | < 0.7 | 0.7 - 3.0 | > 3.0 |
| | | | **SOIL EFFECTS** | | |
| Infiltration | SAR = 0-3 | and $EC_w$ = | > 0.7 | 0.7 - 0.2 | < 0.2 |
| | 3-6 | | > 1.2 | 1.2 - 0.3 | < 0.3 |
| | 6-12 | | > 1.9 | 1.9 - 0.5 | < 0.5 |
| | 12-20 | | > 2.9 | 2.9 - 1.3 | < 1.3 |
| | 20-40 | | > 5.0 | 5.0 - 2.9 | < 2.9 |
| | | | **CROP EFFECTS** | | |
| Specific ion toxicity | Sodium | SAR | < 3.0 | 3.0 - 9.0 | > 9.0 |
| | Chloride | meq/l | < 4.0 | 4.0 - 10.0 | > 10.0 |
| | Boron | mg/l | < 0.7 | 0.7 - 3.0 | > 3.0 |
| pH | Normal range = | | 6.5 - 8.4 | | |

Ayers and Westcot, (1985)

SAR is the sodium adsorption ratio and $EC_w$ is the electrical conductivity (see glossary and useful conversion factors for definitions).

Rao *et al* (1994) classify water as saline or alkali (sodic) depending on the ratio of sodium to other dissolved ions. The classification is based on measures of Residual Sodium Carbonate (RSC, see definition in the glossary of terms and definitions) and electrical conductivity ($EC_w$) of the water.

| | |
|---|---|
| SALINE WATER | RSC < 2.5 meq/l<br>Water poses a threat to crops due to the concentration of dissolved salts and their effect on soil water matric potential |
| ALKALI WATER | RSC > 2.5 meq/l and $EC_w$ < 4.0 dS $m^{-1}$<br>Water poses a threat to soil structure due to the high concentration of sodium in the water |

Saline waters:

Safe limits are given in Table 3.2. These limits vary according to soil type, crop salt tolerance and total annual rainfall in the area.

## Table 3.2 Acceptable salinity levels in irrigation water supply

| **Soil Texture (% clay)** | **Crop Tolerance** | **Upper limit of $EC_w$ (dS $m^{-1}$) in regions with different annual rainfall total** | | |
|---|---|---|---|---|
| | | <350 mm | 350-550 mm | 550-750 mm |
| Fine<br>(>30%) | Sensitive | 1.0 | 1.0 | 1.5 |
| | Semi-tolerant | 1.5 | 2.0 | 3.0 |
| | Tolerant | 2.0 | 3.0 | 4.5 |
| Moderately fine<br>(20-30%) | Sensitive | 1.5 | 2.0 | 2.5 |
| | Semi-tolerant | 2.0 | 3.0 | 4.5 |
| | Tolerant | 4.0 | 6.0 | 8.0 |
| Moderately coarse<br>(10-20%) | Sensitive | 2.0 | 2.5 | 3.0 |
| | Semi-tolerant | 4.0 | 6.0 | 8.0 |
| | Tolerant | 6.0 | 8.0 | 10.0 |
| Coarse<br>(<10%) | Sensitive | - | 3.0 | 3.0 |
| | Semi-tolerant | 6.0 | 7.5 | 9.0 |
| | Tolerant | 8.0 | 10.0 | 12.5 |

Rao *et al*, (1994)

Notes:

1. Textural criteria should be applicable for all soil layers down to at least 1.5m depth.
2. In areas where groundwater lies within 1.5m of the surface at any time of the year, or a hard subsoil layer is present in the root zone, the limits of the next finer textural class should be used.

These limits are based on field experiences in different agro-climatic zones. It is expected that with waters of salinity equal to or lower than those shown, there should be no yield reduction on a long-term basis and no adverse effect on the soil structure. The relationships are illustrated in Figure 3.1.

Examples of sensitive, semi-tolerant and tolerant crops are given in Table 3.3 and also in Chapter 5.

## *Table 3.3 Examples of salt tolerant, semi-tolerant and sensitive crops*

| **Tolerant** | **Semi-tolerant** | **Sensitive** |
|---|---|---|
| Barley | Wheat | Maize |
| Cotton | Barley | Flax |
| Asparagus | Squash | Bean |
| Date Palm | Sorghum | Potato |
| Sugarbeet | Berseem | Paddy Rice |

Adapted from Ayers and Westcot, (1985)

<u>Alkali waters:</u>
Safe limits for water classified as alkali are dependent on soil type, and the SAR and RSC of the water source, as shown in Table 3.4.

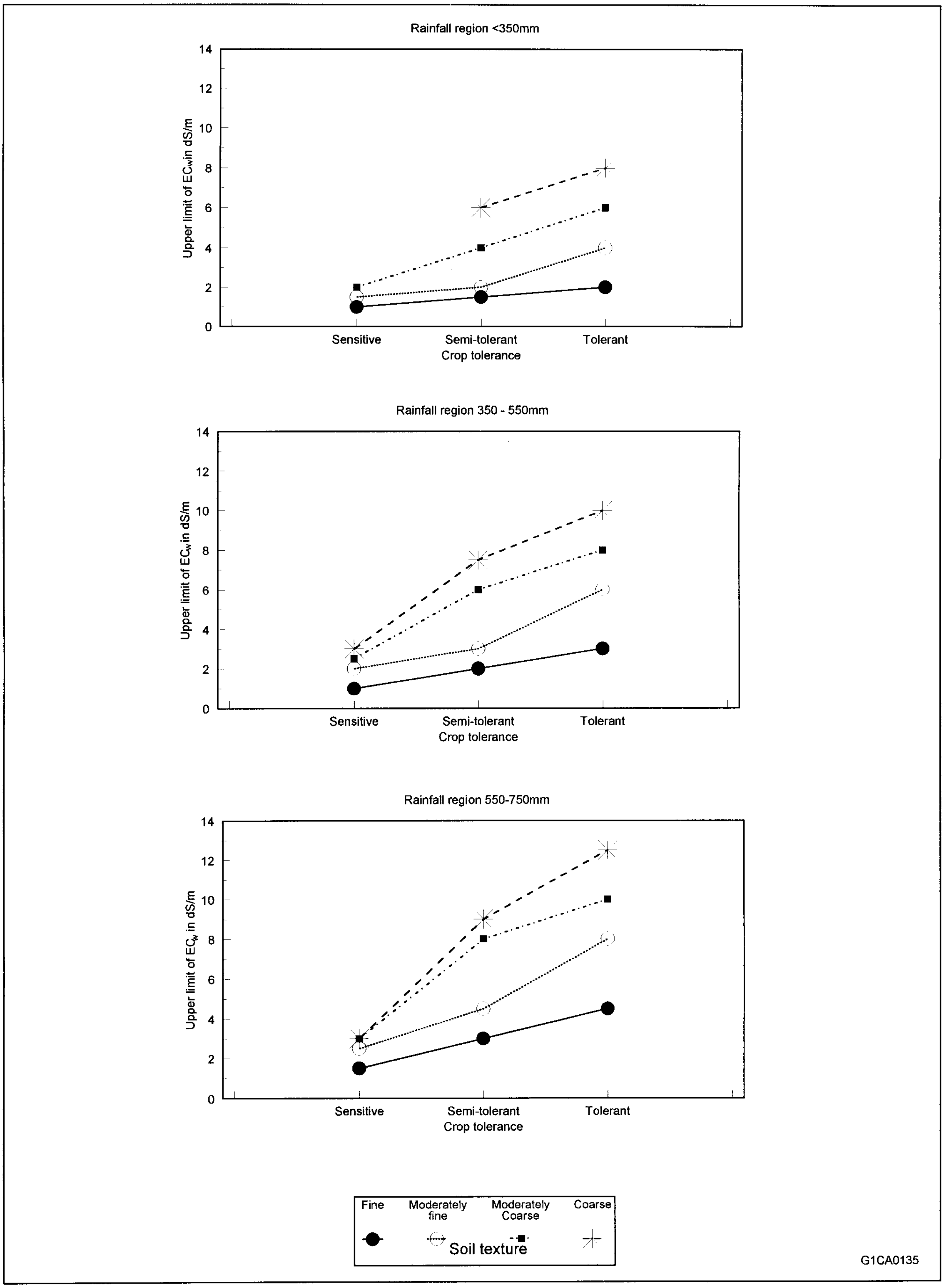
## *Table 3.4 Acceptable limits of SAR and RSC in water for agricultural use*

| **Soil texture (% clay)** | **Upper limits of SAR (mmole/l$^{0.5}$)** | **Upper limit of RSC (meq/l)** |
|---|---|---|
| Fine (>30%) | 10 | 2.5 - 3.5 |
| Moderately fine (20-30%) | 10 | 3.5 - 5.0 |
| Moderately coarse (10-20%) | 15 | 5.0 - 7.5 |
| Coarse (<10%) | 20 | 7.5 – 10 |

Singh *et al,* (1996)

Notes:

1. Textural criteria should be applicable for all soil layers down to at least 1.5m depth.
2. In areas where groundwater lies within 1.5m at any time of the year, or a hard subsoil layer is present in the root zone, the limits of the next finer textural class should be used.



Rainfall region <350mm

Rainfall region 350 - 550mm

Rainfall region 550-750mm

**Figure 3.1 Acceptable levels of salinity ($EC_w$) in irrigation water supply**
(adapted from Rao et al, 1994)

It is expected that where SAR and RSC are equal to or lower than these limits, there would be no yield reduction on a long-term basis.

The relationships are shown in Figure 3.2.

Guiding principals that can be deduced from the data in Figures 3.1 and 3.2 are:

- More saline water can be used on coarse soils.
- More saline water can be used in high rainfall regions.
- Soils with high clay content are more susceptible to salinity damage.
- More saline water can be used if salt-tolerant crops are grown.

### *3.2.2 Trace elements*

Trace elements present in irrigation water are taken up by crops and can accumulate to toxic levels. Recommended acceptable levels are given in the table below.

***Table 3.5 Recommended maximum concentrations of selected trace elements in irrigation waters for agricultural production and drinking water supply***

| **Element** | **Recommended maximum concentration (mg/l)** | |
|---|---|---|
| | **For Crop Production** | **For Drinking Water Supply** |
| Aluminium | 5.0 | - |
| Antimony | - | 0.003 |
| Arsenic | 0.1 | 0.01 |
| Barium | - | 0.7 |
| Boron | 0.7 | 0.3 |
| Beryllium | 0.1 | - |
| Cadmium | 0.01 | 0.003 |
| Chromium | 0.1 | 0.05 |
| Cobalt | 0.05 | - |
| Copper | 0.2 | 2 |
| Fluoride | 1.0 | 1.5 |
| Iron | 5.0 | - |
| Lead | 5.0 | 0.01 |
| Lithium | 2.5 | - |
| Manganese | 0.2 | 0.5 |
| Mercury | - | 0.001 |
| Molybdenum | 0.01 | - |
| Nickel | 0.2 | - |
| Selenium | 0.02 | 0.01 |
| Vanadium | 0.1 | - |
| Zinc | 2.0 | - |

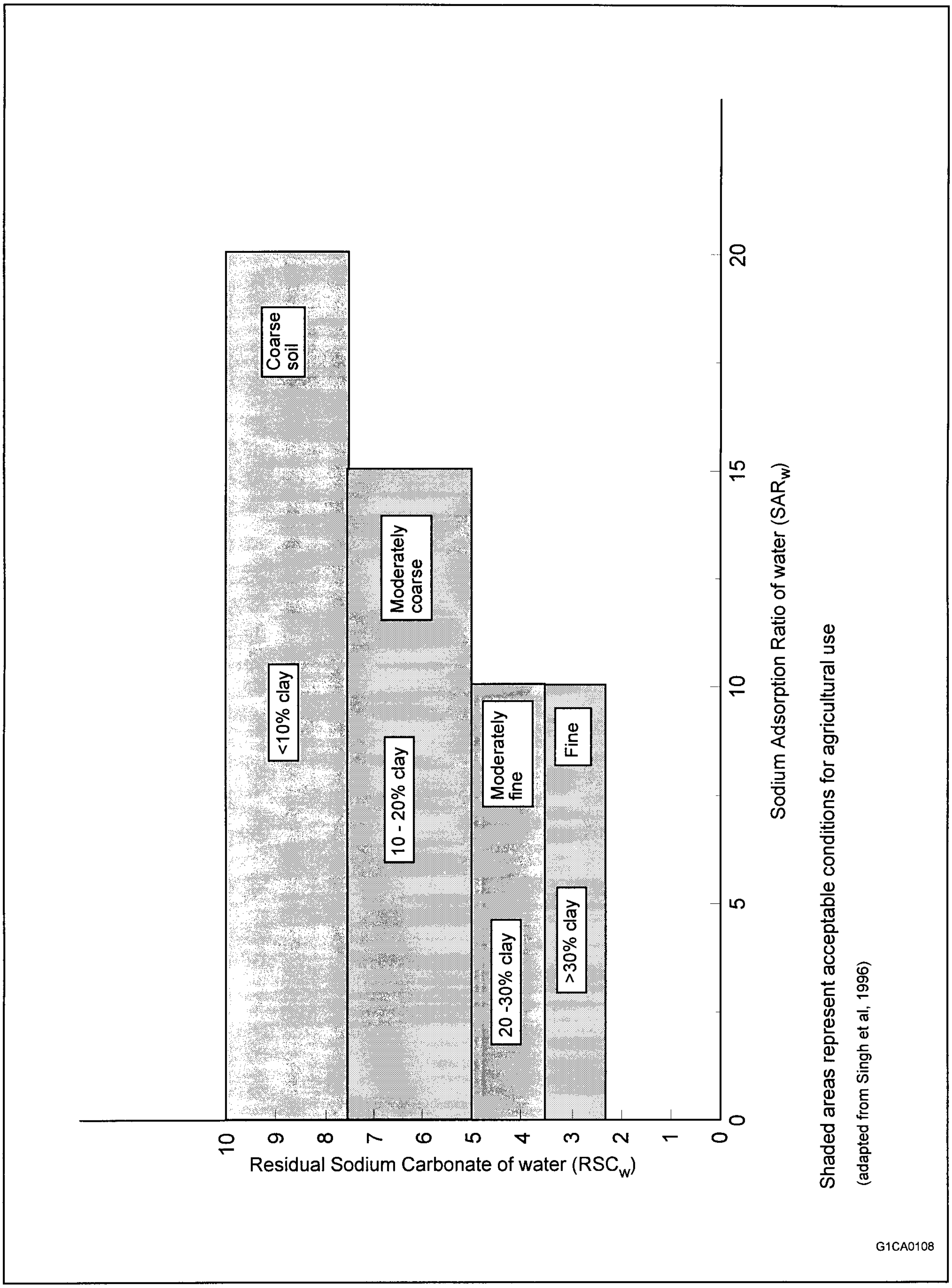
Adapted from Ayers and Westcot, (1985) and WHO (1993)

### *3.2.3 Nutrients*

Sensitive crops may be affected by nitrogen concentrations above 5 mg/l. Most other crops are relatively unaffected until nitrogen exceeds 30mg/l. Crop sensitivity varies with growth stage. High nitrogen levels may be beneficial during early growth stages but may cause yield decline during later flowering and fruiting stages.

## 3.3 Acceptable levels for other uses

When water of marginal quality is used for agricultural purposes in the developing world there will be direct human contact with the pollutants in the water supply. As well as contact associated with irrigation practice, water may be used for livestock, domestic and recreational purposes. Where such contact is likely to occur the more stringent guidelines laid down for drinking water quality standards should be applied.



Shaded areas represent acceptable conditions for agricultural use

(adapted from Singh et al, 1996)

**Figure 3.2** **Acceptable limits of SAR and RSC in water for agricultural use**

The main threat to human health comes from pathogens, but the presence of trace elements and organic pollutants can also pose a health risk. Recommended maximum concentrations of these pollutants are therefore included in this section.

### 3.3.1 Pathogens

Pathogens are disease causing organisms. They are usually introduced into waterways through untreated human and animal waste products. They can cause diseases ranging from mild gastro-enteritis to fatal dysentery, cholera and typhoid. The survival times of common pathogenic organisms in water and the soil are given in Table 2.1.

The WHO guideline (Table 3.6) allows unrestricted irrigation of all crops including vegetables eaten raw, with an effluent standard of 1 or less helminths/litre and a mean of 1000 faecal coliform/100 ml (Shuval, 1991).

**Table 3.6 Guidelines for use of wastewater in agriculture and aquaculture (WHO, 1989)**

| Category | | Reuse Conditions | Exposed group | Intestinal nematodes[2] (arithmetic mean number of eggs per litre[3]) | Faecal coliforms (geometric mean number per 100 ml[2]) |
|---|---|---|---|---|---|
| Unrestricted | A | Irrigation of crops likely to be eaten uncooked, sports fields, public parks[4] | Workers, consumers, public | ≤ 1 | ≤ 1000[4] |
| Restricted | B | Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees[5] | Workers | ≤ 1 | No standard recommended |
| Localized | C | Localized irrigation of crops in category B if exposure of workers and the public does not occur | None | Not applicable | Not applicable |

1 In specific cases, local epidemiological, sociocultural and environmental factors should be taken into account, and the guidelines modified accordingly.
2 *Ascaris* and *Trichuris* species and hookworms
3 During the irrigation period

4 A more stringent guideline (≤ 200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.
5 In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

The most important bacterial pathogens found in waters in hot climates are salmonellae and shingellae, which cause typhoid and paratyphoid and vibrrios which is a causative agent of cholera.

### 3.3.2 Trace elements

Guidelines for safe levels of trace elements in water used for domestic supply are shown in Table 3.5.

### 3.3.3 Organic pollutants

Mineral oil and petroleum products
Recommended maximum concentrations for drinking water and fisheries:- between 0.01 and 0.1 mg/l.

Concentrations of 0.3mg/l or more can cause toxic effects in freshwater fish.

Phenols
The WHO guideline level for drinking waters is 0.001mg/l

Concentrations of 0.01mg/l and above have toxic effects on freshwater fish.

Biocides
Biocides can cause both acute and chronic health problems. With agricultural biocides, human intake occurs mainly through ingestion of contaminated crops. WHO reports that 500,000 people are poisoned by biocides each year, of whom at least 5,000 die. Biocide poisoning is 13 times higher in developing countries than in the United States (Wier & Schapiro, 1981).

*Herbicides*
Human exposure to herbicides can result in a wide range of symptoms such as skin irritation, hyperthermia, rapid breathing, dehydration, liver and kidney degeneration, and neutropenia (Morgan, 1989).

*Insecticides*
Recent studies suggest that prolonged exposure to organo-phosphate insecticides may be associated with long-term nervous system disorders.

*Fungicides*
A number of fungicides are associated with respiratory and dermal irritation and/or sensitisation (Morgan, 1989).

### *Table 3.7 Recommended maximum levels of biocides in drinking water*

| Biocide | Guideline level (μg/l) |
|---|---|
| Alachlor | 0.3 |
| Aldrin/dieldrin | 0.03 |
| Atrazine | 2 |
| Bentazone | 25 |
| Chlordane | 0.03 |
| HCB | 0.01 |
| Heptachlor/epoxide | 0.1 |
| MCPA | 0.5 |
| Methoxychlor | 30 |
| Metolachlor | 5 |
| Molinate | 7 |
| Pendimethalin | 17 |
| Propanil | 175 |
| Pyridate | 60 |
| Simazine | 17 |
| Trifluralin | 170 |
| 2,4-D | 100 |

WHO, 1987 (in Richardson, 1991)

Surfactants
They are not highly toxic, but can affect aquatic biota. They are responsible for foam formation in surface waters. Other pollutants, including pathogens, can become concentrated in this foam. Detergents can impart taste or odour to water at concentrations of 0.4 to 3mg/l.

### *3.3.4 Nutrients*

The principal health hazard from agricultural nutrients is presented by nitrate and the associated risk of methaemoglobinaemia or 'Blue Baby Disease', (See Section 2.3.5).

There is wide disparity in water quality standards that claim to provide 'safe exposure levels' to nitrates in drinking water.

*The European Community*

- Safe upper limit 50 mg/l of nitrate.

- Guideline level 25 mg/l of nitrate.
  This will eventually be adopted as the Maximum Acceptable Concentration (MAC) for nitrate throughout the EC.

*The World Health Organisation (WHO)*

- Safe upper limit 45 mg/l

- Guideline level 10 mg/l

*Austria*

- Safe upper limit until 1994 100 mg/l
  Current safe upper limit 50 mg/

- From July 1999 safe upper limit 30 mg/l.

*United States*

- US EPA ‘Maximal Contaminant Level’ (MCL) is 10mg/l of nitrate nitrogen, which is equivalent to 45mg/l of nitrate.
- The US Department of Agriculture regards levels as low as 20mg/l as ‘elevated’ concentrations, and it is only levels as low as 4.5mg/l that are regarded as unremarkable.

*Canada*

- Nitrate levels above 1 mg/l are considered to be worthy of note.

*FAO*

- Nitrate levels greater than 10mg/litre (expressed as nitrogen) pose risk of methemo-globinemia in bottle fed infants.

Phosphates form an important constituent of most municipal, and some industrial, effluents. However, no drinking water standards have been established for phosphates (EPA, 1989).

### *3.3.5 Salts and toxic ions*

Salts and constituent ions in water sources do not pose a significant threat to human health. Salt concentrations will make drinking water supplies unpalatable long before they pose a threat to health. Excessive salinity, especially if magnesium sulphate is present, can have a laxative effect.

# *4 Assessment of hazards to agricultural soils*

The continuing productivity of soil depends on its physical ability to conduct water and make it available for root uptake and crop development. Pollutants contained in marginal quality water can adversely affect soil structure and hydraulic properties. Impacts depend on pollutant type and concentration, as well as on soil type and antecedent hydraulic properties. An assessment of the likely impact of marginal quality water utilisation on soil structure and permeability is thus essential when planning for sustainable agriculture.

## 4.1 Soil sampling procedures

### *4.1.1 Parameters measured*

To assess the risk to agricultural soils of using water of marginal quality, information is required on soil properties as well as knowledge of the salinity and alkalinity (sodium content) of the water source.

The following soil parameters should be determined:

| | |
|---|---|
| • Textural classification | (% clay, % silt, % sand) |
| • Steady-state infiltration rate | (mm/hr) |
| • Sodium content | (meq/l for saturated soil extract) |
| • Calcium content | (meq/l for saturated soil extract) |
| • Magnesium content | (meq/l for saturated soil extract) |
| • Applied water salinity content | (dS $m^{-1}$) |

Measurement and analysis techniques are described in Appendix 1

### *4.1.2 Spatial distribution*

A soil sampling programme should be carried out at the pre-feasibility stage, generating soil maps at a scale of 1:50,000 or 1:25,000. The density of soil sampling at this stage may be as low as one sample per 12 ha. For detailed design and layout, particularly where early studies show marked variation in soil properties, more detailed sampling may be required to define soil boundaries with greater accuracy. For detailed studies sampling density may be as high as one per ½ ha Site specific factors and the scale of the overall project will determine the exact density and distribution of survey sites (FAO 1979).

Soil samples should be taken by auger (a 70mm Dutch combination auger is suitable in most cases) and cover the whole root zone depth. A suggested strategy is to take samples (500 - 1000g size) from 15cm, 50cm, 75cm, 1.0m and 1.5m depth.

### *4.1.3 Sampling frequency*

Seasonal variation in soil salinity and toxin levels may be considerable (Abbott and El Quosy, 1995). Seasonal variation depends largely on water applications and abstractions, so it is advisable to sample in both dry and wet periods. For example, in irrigated agricultural areas with two cropping seasons per year, samples should be taken four times per year, after irrigation at start of each crop season and around harvest time when soil has dried out. In un-cropped areas (e.g. pre-project) samples should be taken twice per year, once in mid-summer and once in mid-winter.

## 4.2 Soil hazard assessment

The likelihood of soil damage occurring when irrigation water is applied depends on a number of factors. The most important ones are:

- Soil texture
- Soil hydraulic conductivity
- Sodium content of the soil relative to other cations
- Sodium content of the applied water
- Total salt content of the applied water

### *4.2.1 Soil texture and hydraulic properties*

The hydraulic conductivity of a soil depends on a number of factors of which soil texture and therefore pore volume, is the most important. Figure 4.1 shows the USDA textural classification triangle for soil fractions of less than 2.0 mm.

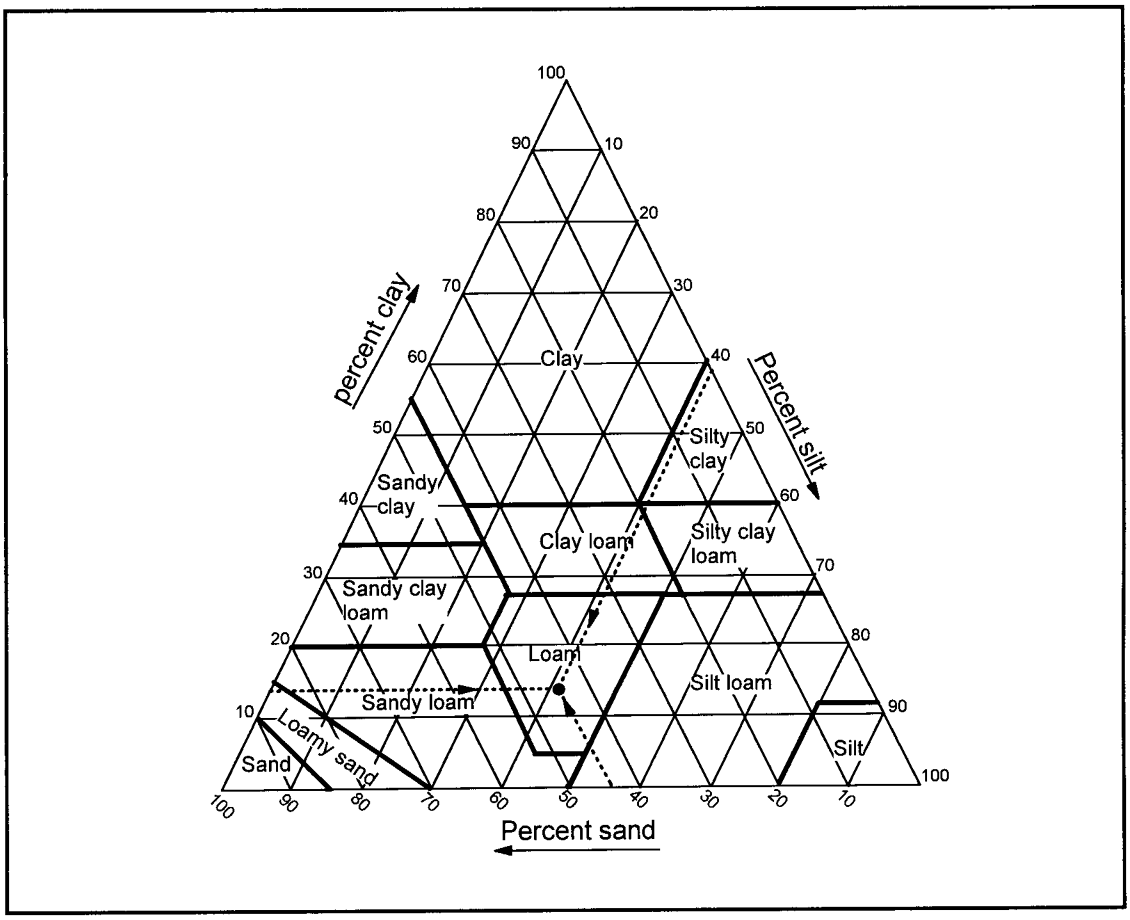


**Figure 4.1** **The USDA soil textural triangle** (from Rowell, 1994)

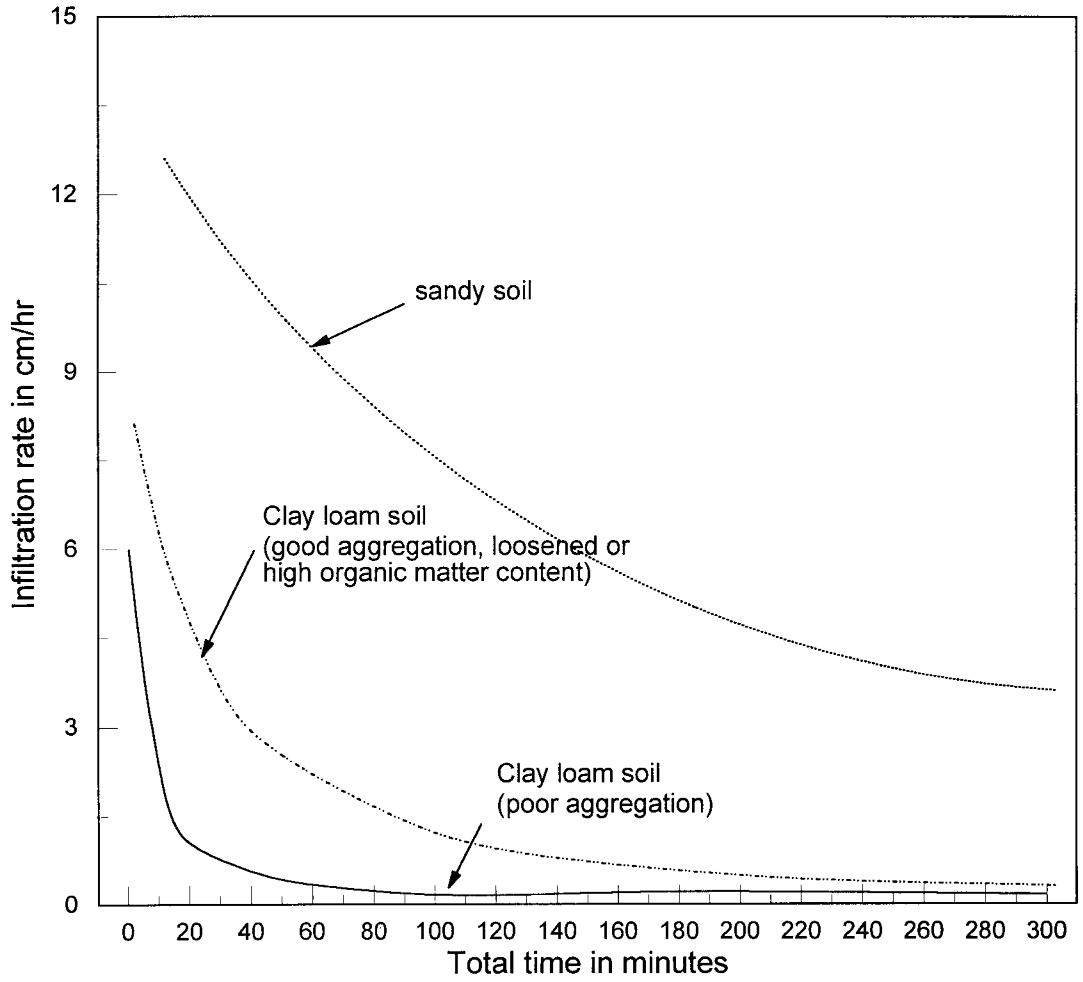
The impact of a reduction in hydraulic properties is greater in soils with high clay content, as infiltration rate and permeability are often very low to start with, as illustrated in Figure 4.2 and Table 4.1.

The clay fraction in soils is susceptible to long-term damage as it is subject to physico-chemical interactions with salt ions, which alter the soil's structure and its hydraulic properties, sometimes irreversibly. Clay dominated soils are therefore most vulnerable to damage from waters rich in sodium and the reduction in conductivity and surface infiltration rate caused by clay dispersion (See Section 2.3.1) can render them unsuitable for irrigated crop production.

***Table 4.1 Classification of soil infiltration rate according to the United States national cooperative soil survey***

| **Infiltration Rate** | **Classification** | **Soil Type** |
|---|---|---|
| < 2.5 mm/hr | Very low | Clays |
| 2.5 - 12.5 mm/hr | Low | Clay loams |
| 12.5 - 25 mm/hr | Medium | Loams/silts |
| > 25 mm/hr | High | Sands/silt loams |

Donahue *et al,* (1987)



G1CA0136

**Figure 4.2 Rates of infiltration achieved with different soil textures**
(Donahue et al, 1987)

### 4.2.2 Soil sodicity hazard

Sodium has a detrimental influence on soil structure and hydraulic properties. Soils containing high levels of sodium (as opposed to calcium or other divalent cations) are most at risk of damage when water is applied.

The risk of adverse soil reaction due to sodium ions can be assessed as follows:

1) The simplest assessment looks at the ratio of sodium to calcium ions in soils at the project site. Structural damage is only likely if sodium exceeds calcium by a ratio of about 3:1 (Boyer, 1978).

2) Another method to assess sodium risk is to look at the sodium adsorption ratio (SAR) of the soil at the project site.

Sodic soils are defined as those with an SAR (of the saturated soil extract) greater than 13 (Donahue *et al* 1987). In most irrigated agricultural areas, this is the SAR at which irrigation water is likely to affect the soil structure and permeability.

3) The sodium risk can also be assessed at the project site by measuring the exchangeable sodium percentage ESP (see glossary and useful conversion factors).

Dispersion (release of individual clay platelets from aggregates) and slaking (breakdown of aggregates into subaggregate assemblages) can occur at relatively low ESP values (< 15), provided the electrolyte concentration ($EC_w$)is sufficiently low (Rhoades et al, 1992). In clay soils the ESP at which this may happen is lower, and in sands it is higher.

Soil (clay) swelling and dispersion increase with increasing SAR and decreasing salinity. Significant reductions (10-25%) in saturated hydraulic conductivity for soils with ESP values of 15 can be expected if salt concentrations are less than 0.5 to 5dS $m^{-1}$. Similar reductions will occur in soils with ESP as low as 3 if soil salinity is less than 0.2 to 1dS $m^{-1}$ (Oster, 1994).

### 4.2.3 Applied water quality

The total salinity of the applied water is a major factor in determining soil damage and hydraulic effects. Many people are surprised to learn that water with low total salinity content poses a greater threat when applied to soils with high sodium content, than water with high total salinity content. The salt content of rainfall ($EC_w$) is very low and consequently soil damage is very often brought about by it. It is thus also advisable to consider rainfall patterns in the project area.

The planner can assess likely structural damage and permeability reduction in soils from use of marginal quality water, using the relation shown in Figure 4.3 (Rhoades et al, 1992). This combines knowledge of the salinity of applied water ($EC_w$) and the ionic composition of the topsoil, given in terms of sodium adsorption ratio (SAR). It provides representative threshold values of SAR and the electrical conductivity ($EC_w$) of infiltrating water for maintenance of soil permeability. The figure provides a useful means of predicting a soil problem. As soils vary considerably in their response, this relation should be considered a rough guide.

Guiding principles for soil hazard assessment are:

- Water of marginal quality can damage agricultural soils
- Clay soils are most at risk
- Sodic soils are vulnerable
- Water sources high in mono-valent cations such as sodium pose the greatest threat
- Water sources with low total salinity ($EC_w$) such as rainfall will do most damage if the conditions are right
- Assess the risk using guidelines given

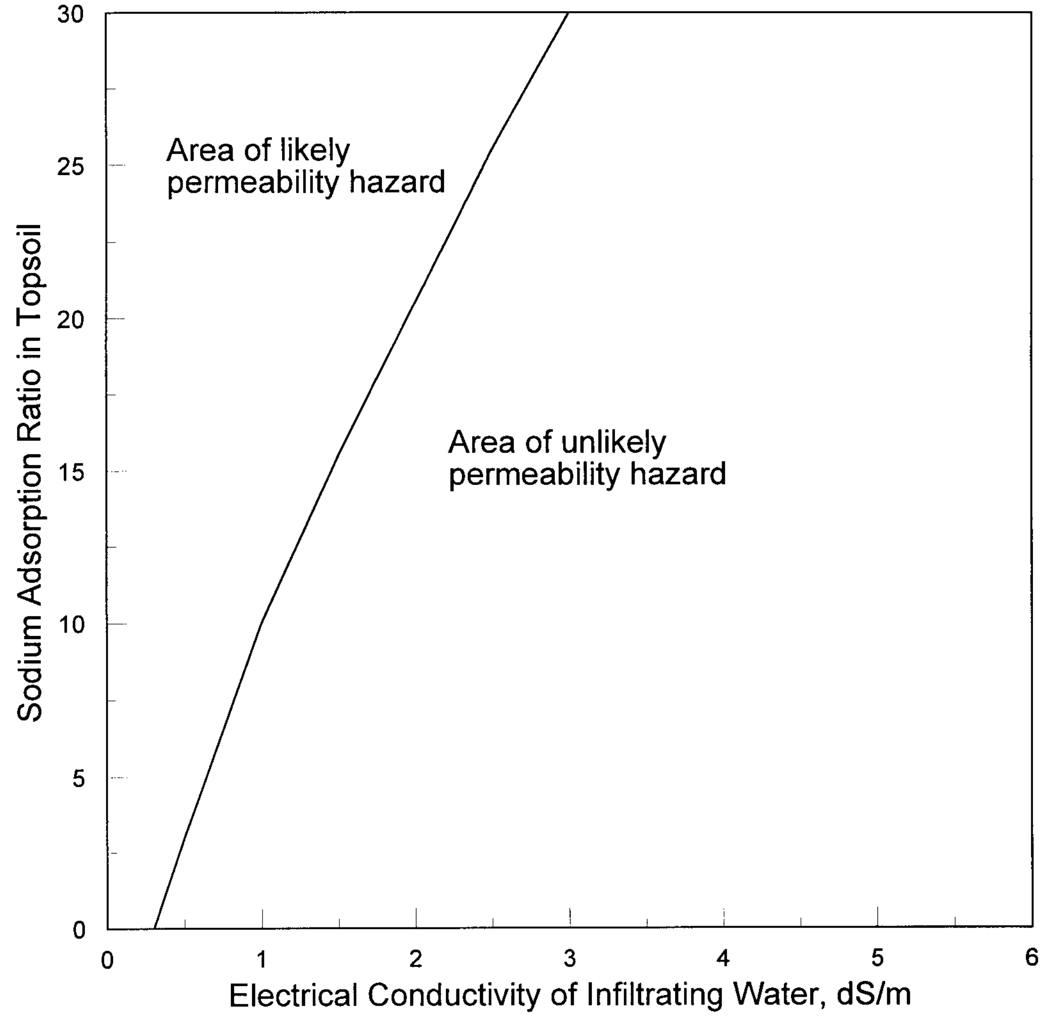


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**Figure 4.3 Threshold values of SAR of topsoil and EC of infiltration water for maintenance of soil permeability** (Rhoades et al, 1992)

# *5 Assessment of risk to long-term crop production*

Crop growth and yield may be detrimentally affected by the use of irrigation water of marginal quality. Salts and toxic ions pose the greatest threat although other elements and compounds may also influence crop development. Crop choice within a region may already be governed by factors other than water quality, but when marginal quality water is used, it may pose a serious constraint to crop selection and management.

When considering the allocation of marginal quality water to existing agricultural areas, the water resource planner should evaluate the effects on current cropping patterns. Alteration in quality of water supplied to command areas will affect crop development and yield. Farmers should be kept aware of likely impacts so that they can adjust cropping and management practice if required. If the use of marginal quality water is proposed to develop new areas for agricultural production, an appropriate cropping regime can be defined at the planning stage, based on the quality constraints imposed by the water source.

Sensitivity to salinity varies between crops and with stage of growth. Salt sensitive crops include beans and most fruit crops, and salt tolerant crops include cotton and wheat. Some crops, such as sugarbeet, are most sensitive during germination, whereas others including barley, rice and wheat are most sensitive during early seedling growth. There is also difference in response between varieties of the same crop. The planner should examine what tolerant strains are available and assess their relative costs, yields etc.

Plants respond to salinity and toxin levels in soil-water. Carrying out an assessment of a marginal quality water source for agricultural use provides a basic evaluation of crop effects. However, if the planner can predict future salinity and toxin levels in soils as a result of using marginal quality water, then specific crop response can be evaluated far more accurately.

## 5.1 Prediction of long term salt accumulation in the soil

To plan for sustainable agriculture using marginal quality water, it is necessary to make long-term predictions of soil salinity and toxin accumulation, so that future crop and soil hazards can be assessed. Several predictive methods have been developed which make use of different base data. These methods and their data requirements are summarised in Table 5.1. The methods have been reviewed and tested with field data in Abbott and El-Quosy, (1996).

*Table 5.1 Methods for prediction of long-term soil salinity and ion accumulation*

| Available Data | Recommended Methods | Outputs | Range of Assessment |
|---|---|---|---|
| Applied water salinity<br>$SAR_w$ | Empirical relations | Soil salinity<br>$SAR_e$ | Crop yield reductions due to soil salinity and sodicity |
| Applied water salinity<br>Leaching Fraction | Hoffman and van Genuchten method or Rhoades equation | Soil salinity | Crop yield reductions due to soil salinity |
| Concentrations of major ions in applied water<br>Leaching Fraction | WATSUIT model | Salinity and major ion concentrations in soil water<br>SAR<br>PH | Crop yield reductions due to soil salinity and toxic ions |
| Applied water salinity<br>Initial soil salinity<br>Land use<br>Existing hydrology and water balance<br>Soil and aquifer properties | SALTMOD model | Salinity concentrations in root zone and below<br>Predicted water balance and hydrology | Crop yield reductions due to soil salinity |

From: Abbott and El-Quosy, (1996)

### 5.1.1 Empirical relations

The steady-state salinity level within the root zone of an irrigated soil depends primarily on:

- Salinity of applied water
- The fraction of applied water passing through the root zone (the leaching fraction)
- Soil texture

In areas where applied water salinity is high, this is likely to be a prime factor controlling soil salinity levels. It is also possible that this could be the only data available on which to make a prediction of future soil salinity levels. The following method is recommended:

Ayers and Westcot, 1985, present a theoretical empirical relationship between applied water salinity ($EC_w$) and soil salinity ($EC_e$) as below:

$$EC_e = 1.5 \times EC_w$$

It is a rule of thumb that assumes a 15-20 percent leaching fraction and is intended to reflect changes due to long-term water use.

Another rule of thumb can be used to estimate the longterm sodicity of the soil ($SAR_e$) from the sodicity of the applied water ($SAR_w$). Smedema and Rycroft, 1983, assert that at a low leaching fraction of 5-10%, the soil solution in the saturated paste (saturation extract) would be about 2-2.5 times as concentrated as the irrigation water, and it follows that:

$$SAR_e = \sqrt{2.0 \text{ to } 2.5} \times SAR_w \text{ or } SAR_e \simeq 1.5 \times SAR_w$$

### 5.1.2 Soil salinity calculations

The fraction of applied water that passes through the entire rooting zone and percolates below is the leaching fraction.

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

After several years of irrigation with a marginal quality water source, the salt accumulation within the root zone approaches an equilibrium concentration ($EC_e$) determined by the salinity of the applied water ($EC_w$) and the leaching fraction (LF). The calculation of the required leaching fraction to maintain a soil at a given salinity is set out in Chapter 6 (Section 6.4).

When the leaching fraction is known the equilibrium salt concentration can be predicted using one of the following methods:

<u>Hoffman and van Genuchten Equation</u>

This equation determines the linearly averaged, mean root zone salinity and has the form:

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

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

(Hoffman and van Genuchten, 1983)

The relation is shown graphically in Figure 5.1.

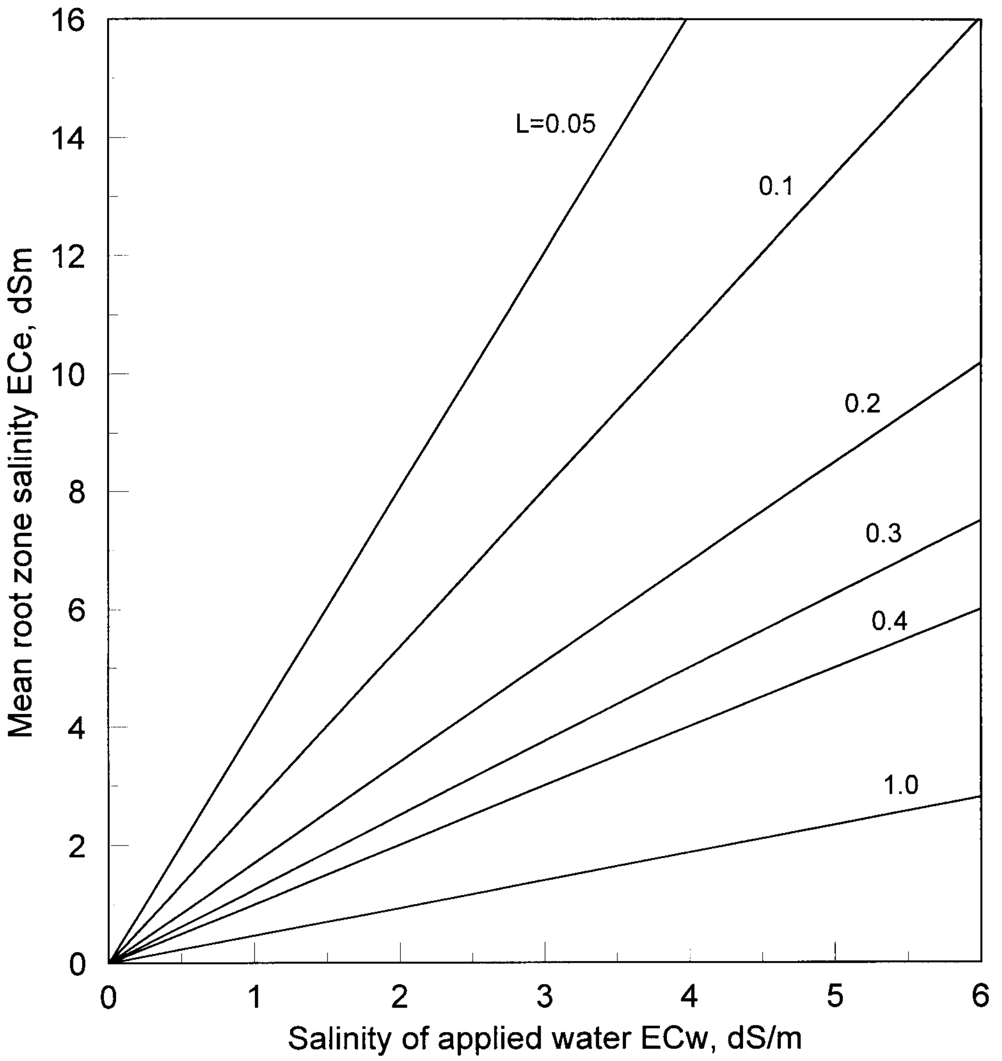

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**Figure 5.1 Mean root zone soil salinity as a function of applied water salinity and leaching fraction, L** (Hoffman and van Genuchten 1983)

Rhoades Equation

This procedure estimates the steady-state soil water salinity ($EC_e$) by multiplying the electrical conductivity of the irrigation water ($EC_w$) by a relative concentration factor, $F_c$, appropriate to the leaching fraction and depth in the root zone (Rhoades, 1982).

$$EC_e = EC_w * F_c$$

Values of $F_c$ are given in Table 5.2 below:

### *Table 5.2 Relative concentration factor ($F_c$)*

| $F_c$ | Leaching Fraction | | | | | |
|---|---|---|---|---|---|---|
| | **0.05** | **0.1** | **0.2** | **0.3** | **0.4** | **0.5** |
| Conventional irrigation management[1] | 2.79 | 1.88 | 1.29 | 1.03 | 0.87 | 0.77 |
| High frequency irrigation management[2] | 1.79 | 1.35 | 1.03 | 0.87 | 0.77 | 0.7 |

Rhoades (1982)

Notes

1. Linear average (mean) of $EC_e$ for whole rootzone.
2. Whole water-uptake weighted average of $EC_e$ for rootzone. Use for high frequency irrigation management or where matric potential development between irrigations is insignificant.

### *5.1.3 Computer models*

A number of computer models are available which can predict soil salinity and ion concentrations when marginal quality water is used for irrigation. These models are more complex than the equations given in 5.1.2 and require more input data.

WATSUIT

WATSUIT (Rhoades *et al* ) predicts the salinity, sodicity and toxic-solute concentration of the soil-water within a simulated crop root zone resulting from the use of irrigation water of given composition with a specified leaching fraction. The concentrations of the major cations and anions in the soil water within the root zone are predicted.

SALTMOD

The SALTMOD program (Oosterbaan *et al*) was developed to predict the long-term effects of varying water management options on desalinisation or salt accumulation in the irrigated soils. The water management options include irrigation, drainage, and the reuse of surface or subsurface drainage water from pipe drains, ditches or wells. The model predicts depth to watertable, the salt concentration of the groundwater and of the drain or well water.

## 5.2 Prediction of long-term crop effects

### *5.2.1 Total salinity*

Once the long term, steady-state soil salinity has been predicted, using one of the methods described, the effect of that salinity on crop production can be assessed

When crops are irrigated with saline water, salinity levels within the root zone do not increase uniformly but rather a salinity gradient develops. The direction and slope of the gradient are influenced by the antecedent soil conditions, the conductivity of the irrigation water and the degree of leaching taking place. Although quite marked variation in measured salinity can exist over the root zone depth, research suggests that the mean salinity with depth, integrated over time, is an acceptable measure of soil salinity on which to base predictions of relative crop yield potential (Shalhevet, 1994). This is the value given by the application of the predictive models set out in Section 5.1.

Since crop sensitivity to salinity can vary with growth stage, separate guidelines have been developed which predict crop response during germination, emergence and later growth stages for a number of crops. Table 5.3 shows relative salt tolerance of some crops at emergence and during growth to maturity.

## *Table 5.3 Relative salt tolerance of crops at emergence and during growth to maturity*

| **Crop** | **Critical salinity for 50% yield ($EC_e$ dS $m^{-1}$)** | **Critical salinity for 50% emergence ($EC_e$ dS $m^{-1}$)** |
|---|---|---|
| Barley | 18 | 16 - 24 |
| Cotton | 17 | 15 |
| Sugarbeet | 15 | 6 - 12 |
| Wheat | 13 | 14 - 16 |
| Maize | 5.9 | 21 - 24 |
| Onion | 4.3 | 5.6 - 7.5 |
| Rice | 3.6 | 18 |
| Bean | 3.6 | 8 |

Maas, (1986)

The critical limits for emergence are based on a 50% survival rate, whereas the figures for later growth are given in terms of a 50% reduction in crop yield.

Experimental work has shown that reduction in growth rate (post emergence) usually starts at some threshold salinity level, (depending on crop, climate, soil type and other factors) and increases as salinity increases until the plant dies. The majority of crop salt tolerance guidelines therefore have the following form:

$$Y_r = 100 - b(EC_e - a)$$

Where:

$Y_r$ = Percentage of the yield of the crop grown under saline conditions relative to that obtained under non-saline conditions.
$a$ = Threshold salinity in dS $m^{-1}$
$b$ = Slope expressed in % per dS $m^{-1}$
$EC_e$ = Mean electrical conductivity of a saturated soil extract taken from the crop root zone.

Tolerance data in this form, which represents the effects of salinity averaged over the full growing cycle of the crop after emergence, exists for a large number of agricultural crops. Examples are shown in Table 5.4.

## *Table 5.4 Relative salt tolerance of various crops*

| **Crop** | **a, threshold $EC_e$ (dS $m^{-1}$)** | **B, slope (% per /dS $m^{-1}$)** |
|---|---|---|
| Barley | 8.0 | 5.0 |
| Maize | 1.7 | 12 |
| Rice | 3.0 | 12 |
| Onion | 1.2 | 16 |
| Carrot | 1.0 | 14 |
| Tomato | 0.9 | 9 |
| Berseem | 1.5 | 5.7 |
| Cotton | 7.7 | 5.2 |
| Flax | 1.7 | 12 |
| Sugarbeet | 7.0 | 5.9 |
| Wheat | 4.5 | 2.6 |
| Broad Beans | 1.6 | 9.6 |

Tanji, (1990)

These tolerance relations, based on extensive experimental work, are shown graphically in Figure 5.2.

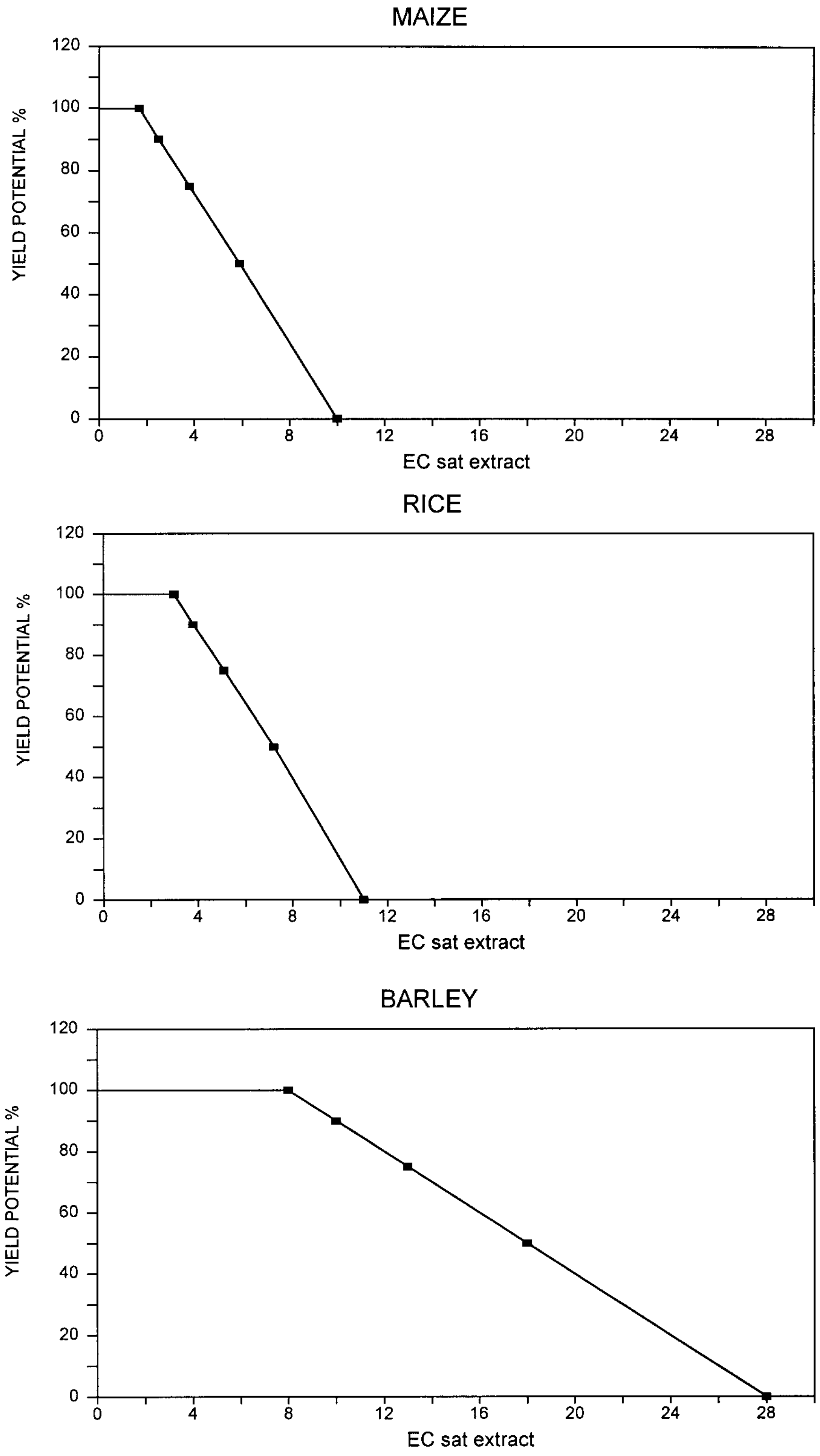

Figure 5.2 **Relative salt tolerance of various crops** (Tanji, 1990)

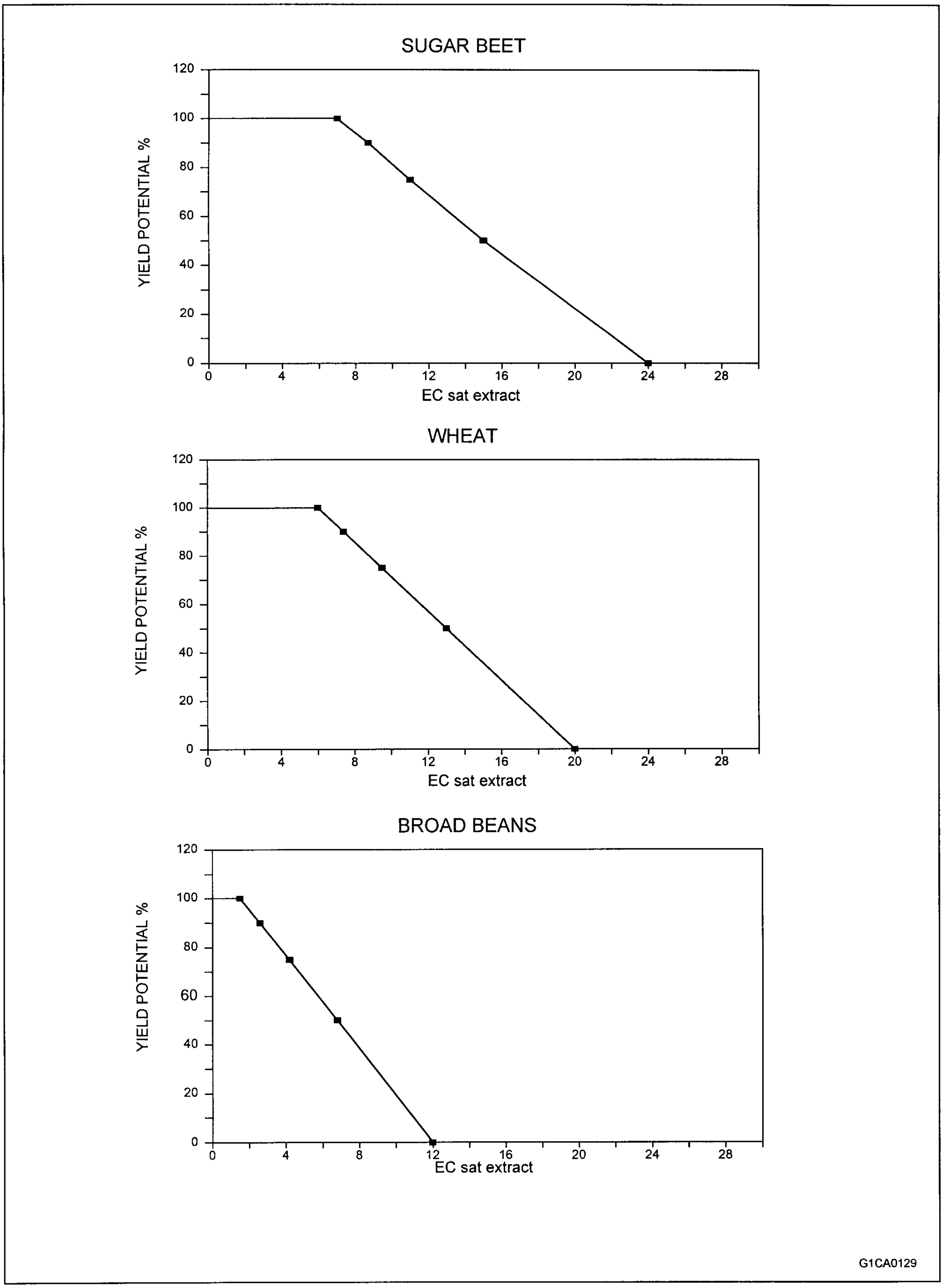

**Figure 5.2 Relative salt tolerance of various crops** (Tanji, 1990) *(continued)*

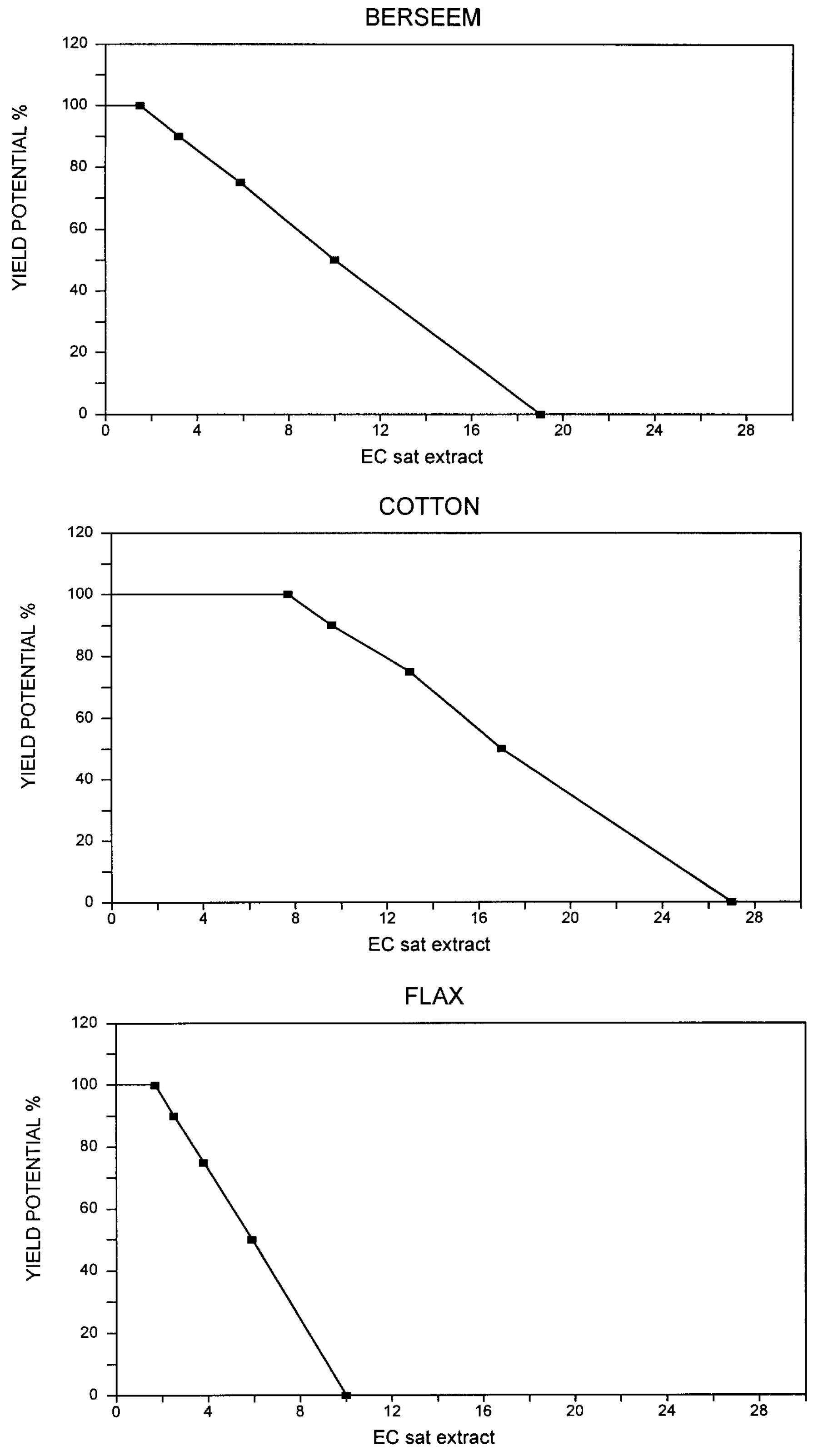

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**Figure 5.2 Relative salt tolerance of various crops** (Tanji, 1990) *(continued)*

There is a large variation in crop tolerance to soil salinity. Whilst barley is quoted (Maas, 1986) as being unaffected at an $EC_e$ value of 8.0 dS $m^{-1}$, beans and carrots will suffer yield reductions with soil salinity $EC_e$ values as low as 1.0 dS $m^{-1}$. Some plants are more able to make the osmotic adjustments necessary to extract water from saline soils.

A summary of the effects of soil salinity, resulting from the use of marginal quality water, on crops is presented in Table 5.5.

### *Table 5.5 Summary table indicating the effect of soil salinity on crop yields*

| **Soil Salinity** | **Predicted Crop Effects** |
|---|---|
| $EC_e < 5$ dS $m^{-1}$ | LITTLE EFFECT - most crops should suffer no yield reductions. Only salt sensitive crops (e.g. Maize and broad beans) affected (less than 50% yield reduction). |
| $5 < EC_e < 15$ dS $m^{-1}$ | SIGNIFICANT EFFECT - sensitive crops suffer large yield reductions (greater than 50%). Salt tolerant crops (e.g. cotton, wheat and barley) are now affected (up to 40% yield reduction). |
| $EC_e > 15$ dS $m^{-1}$ | SEVERE EFFECT – sensitive crops should not grow. Tolerant crops now suffer large yield reductions (greater than 50% yield reduction). |

Abbott and El-Quosy, (1996).

### *5.2.2 Specific ion toxicity*

Where no other model is available, the build-up of specific ions in the soil of the crop root zone can be assumed to follow the same pattern as that for total salinity. Where available, the WATSUIT computer model can provide more accurate prediction of specific ion accumulation as a consequence of using marginal quality water.

Chloride

Chloride toxicity to crops is assessed on the basis of chloride ion concentration in the saturated soil extracts. Crop response to chloride is given in Table 5.6.

### *Table 5.6 Chloride tolerance of some agricultural crops*

| **Crop** | **Threshold chloride ion concentration in saturated soil extract where yield loss commences (meq/l)** | **Percent decrease in yield at $Cl^-$ concentrations above the threshold** |
|---|---|---|
| Carrot | 10 | 1.4 |
| Onion | 10 | 1.6 |
| Maize | 15 | 1.2 |
| Flax | 15 | 1.2 |
| Broad Beans | 15 | 1.0 |
| Berseem | 15 | 0.6 |
| Wheat | 60 | 0.7 |
| Sugar Beet | 70 | 0.6 |
| Cotton | 75 | 0.5 |
| Barley | 80 | 0.5 |

Maas, (1990)

These relations are shown in Figure 5.3.

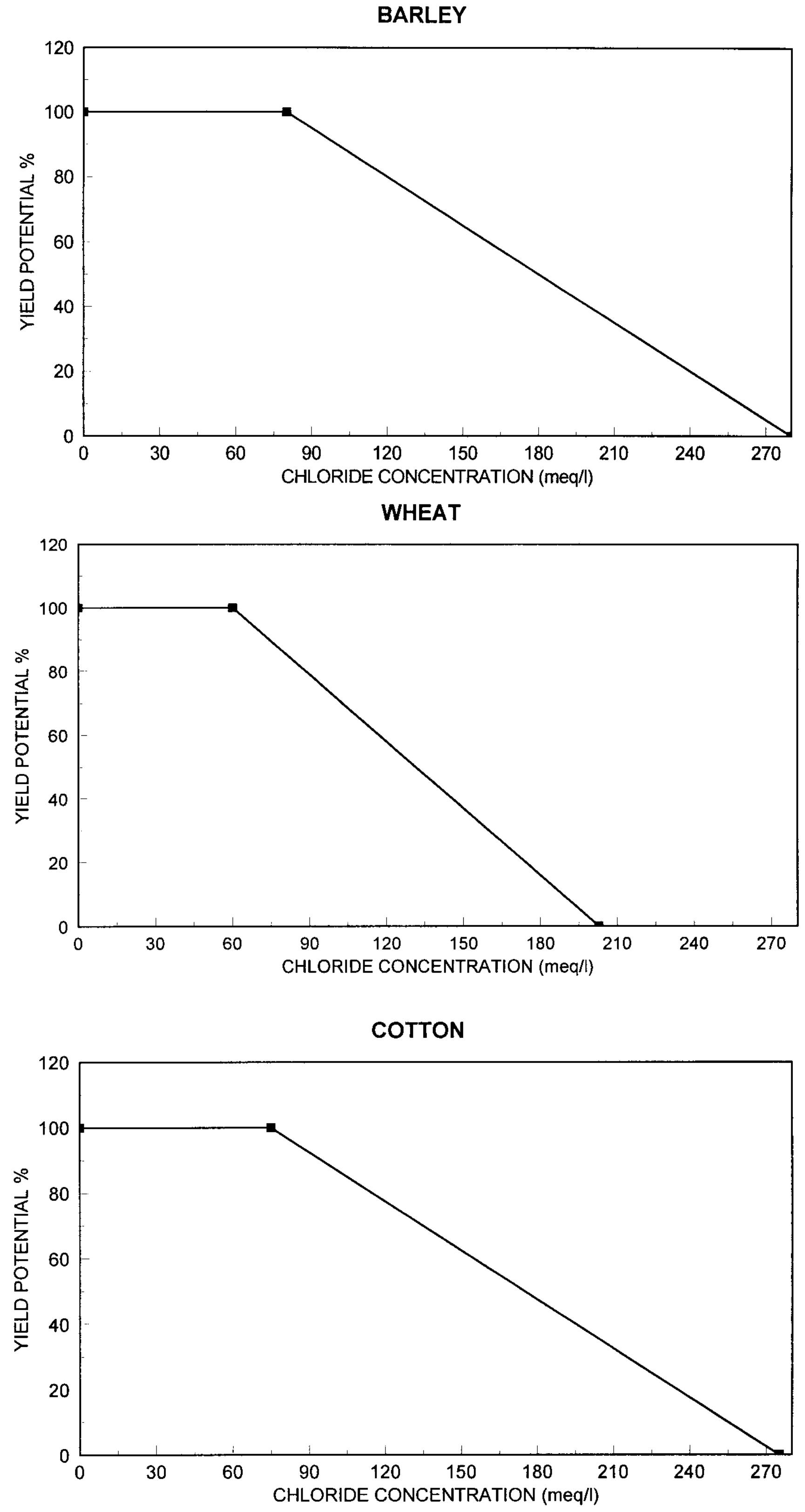

**Figure 5.3 Chloride tolerance of some agricultural crops** (Maas, 1990)

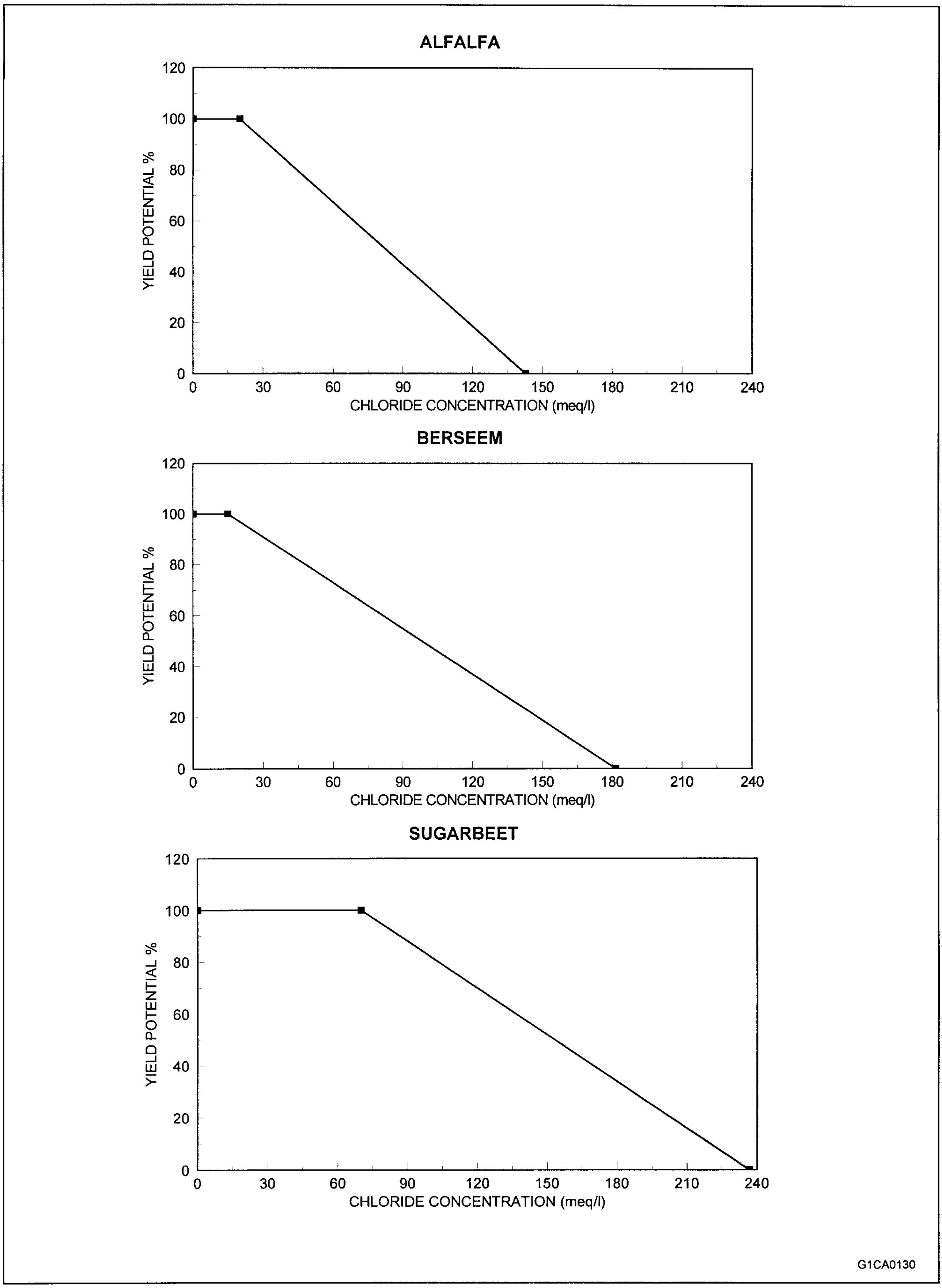

**Figure 5.3 Chloride tolerance of some agricultural crops** (Maas, 1990) *(continued)*

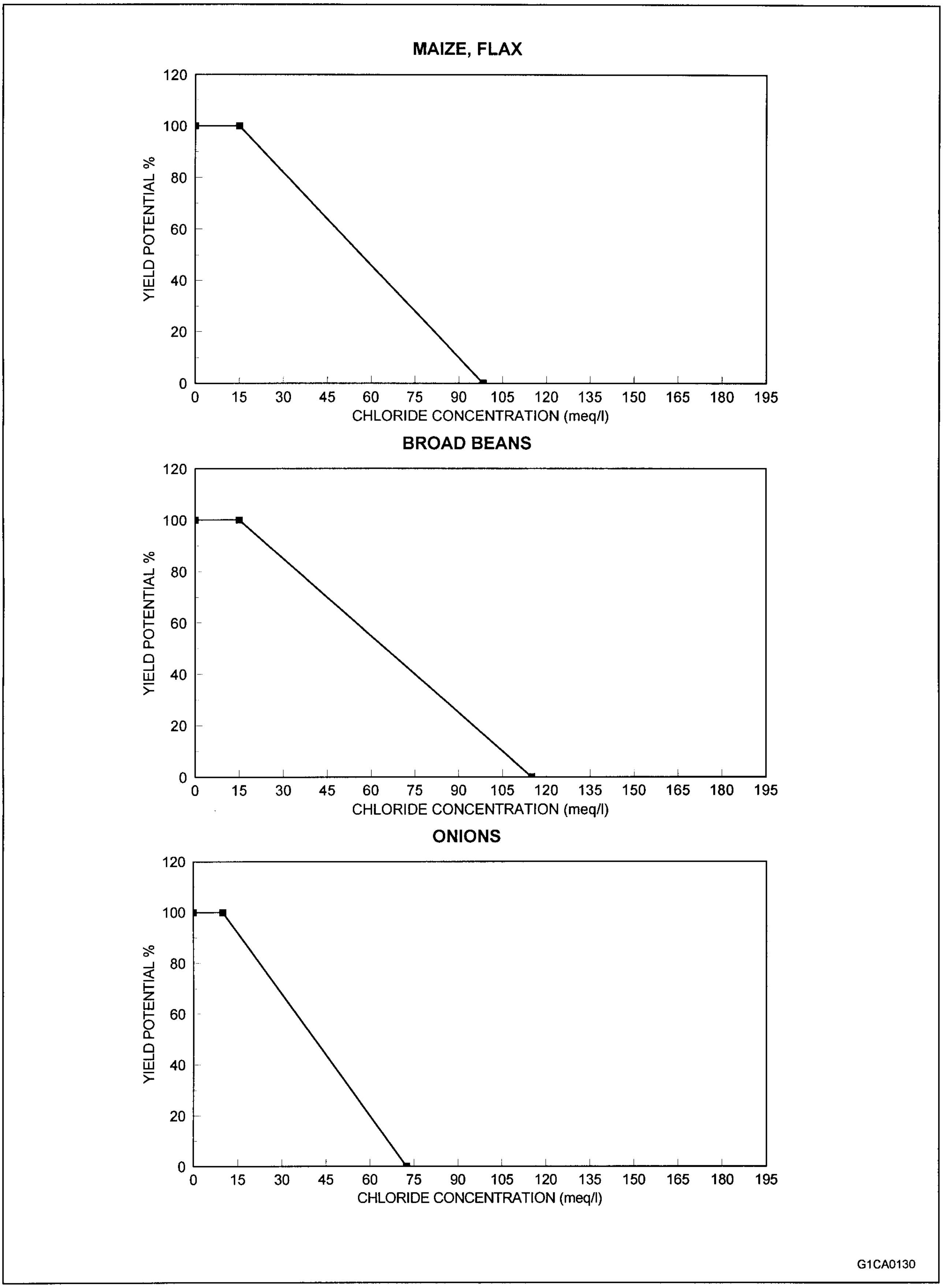

Figure 5.3 **Chloride tolerance of some agricultural crops** (Maas, 1990) *(continued)*

Sodium

An assessment of sodium toxicity can be made using the critical limits given in the Table 5.7:

### Table 5.7 Tolerance of various crops to percentage of exchangeable sodium in soils (ESP)

| **Tolerance to ESP and range at which affected** | **CROP** | **Growth response under field conditions** |
|---|---|---|
| Extremely sensitive<br>ESP = 2-10% | Citrus | Sodium toxicity symptoms even at low ESP |
| Sensitive<br>ESP = 10-20% | Beans | Stunted growth at low ESP values even though the physical condition of the soil may be good |
| Moderately tolerant<br>ESP = 20-40% | Rice, oats | Stunted growth due to both nutritional factors and adverse soil conditions |
| Tolerant<br>ESP = 40-60% | Wheat, cotton, alfalfa, barley, beets | Stunted growth usually due to adverse physical conditions of soil |
| Most tolerant<br>ESP > 60% | Wheat, grass | Stunted growth usually due to adverse physical conditions of soil |

Pearson, (1960).

Calcium, magnesium and potassium

An assessment of the effects of these ions can be obtained by measuring the following ratios in applied water or in the soil, and using Table 5.8.

### Table 5.8 Critical ratios for ions in applied water or soil water

| **Ratio** | **Critical Level** | **Optimum Level** |
|---|---|---|
| Calcium/Potassium | 0.1 < Ca/K < 14 | 6 - 12 |
| Magnesium/Potassium | citrus: 2 < Mg/K < 12<br>cotton: 3 < Mg/K < 25 | around 4 - 6 |
| Calcium/Magnesium | Must be above 1 | |

Boyer (1978)

Soils containing high levels of exchangeable magnesium often experience infiltration problems. Magnesium is not as effective as calcium in maintaining infiltration rates because hydrated magnesium is larger than hydrated calcium, so it enhances swelling and dispersion. There is also evidence (Oster, 1994) that in magnesium soils the damaging effects of sodium may be increased.

Boron

Boron *deficiencies* occur in the microgram/l concentration range in soil solutions. Toxicity arises at concentrations above a few mg/l for most plants. Detailed information on critical levels is limited, but the following data are reported.

### Table 5.9. Relative boron tolerance of agricultural crops

| **Maximum boron concentration tolerated in soil saturation extract without yield reduction** | **Crop** |
|---|---|
| Very sensitive ( < 0.5mg/l ) | Lemon, Blackberry |
| Sensitive ( 0.5 - 0.75 mg/l ) | Avocado, Grape, Onion |
| Sensitive ( 0.75 - 1 mg/l ) | Wheat, Barley, Sunflower, Groundnut |
| Moderately sensitive ( 1 - 2 mg/l ) | Pea, Potato |
| Moderately tolerant ( 2 – 4 mg/l ) | Cabbage, Maize |
| Tolerant ( 4 – 6 mg/l ) | Sugarbeet |
| Very tolerant ( 6 - 15 mg/l ) | Cotton |

Maas, (1990)

# 6 Water resource planning options

In the preceding chapters guidelines have been provided to allow assessment of the hazards of using water of marginal quality in different situations. The planner can assess the impacts of the water on crops, soils and human health. This will help with allocation and distribution of marginal quality water within the region. In this chapter the main management techniques are presented that allow the planner to make best use of marginal quality resources.

If the quality of a water source is judged as hazardous to soils, crops or humans there are a number of management options the water resource planner can consider. These are:

- **Water treatment** Used to bring water containing pathogens, trace elements and nutrients to acceptable quality for agricultural use.
- **Blending** Blending of marginal quality water sources with other 'fresher' water sources can dilute pollutant concentrations to safe levels.
- **Cyclic use** It may be possible for the planner to allocate different quality waters to different areas at different times in the growing season, depending on quality tolerance of the crops grown at different times.
- **Leaching** Long-term, sustainable use of marginal quality supplies depends on prevention of soil pollutant (in particular salts) accumulation to dangerous levels. Additional water must be supplied to affected areas to allow for soil leaching. A strategy is presented to enable planners to determine the additional quantities required for each command area.

The potential application of each of these management options is summarised in Table 6.1.

## Table 6.1 Water resource management options

| Pollutant Group | Main Water Management Options |
|---|---|
| Salts and Ions | Blending, cyclic use, leaching |
| Pathogens | Treatment, blending |
| Trace Elements | Blending, treatment |
| Organic Compounds | ------- |
| Nutrients | Blending, treatment |

## 6.1 Water treatment options

It is not yet economically viable to remove most water pollutants through water treatment, but low-cost, robust systems are available which will remove large amounts of pathogens as well as some trace elements and nutrients.

Some degree of treatment of raw municipal wastewater should occur before agricultural use, to minimise adverse health impacts. The extent and nature of treatment should depend on the proposed cropping system and the likely degree of exposure to human habitation.

In developing countries it is desirable to adopt wastewater treatment processes that result in effluent quality that meets the required international guidelines (recommended levels of microbiological and chemical quality) at low cost and with minimal operational and maintenance requirements. Complex water treatment systems are often inappropriate, as they require specialist maintenance and complicated operational procedures.

Less than 2% of the cities of the world have treatment plants, and without treatment or dilution, untreated sewage water represents a serious health hazard, especially if the water is then used for agricultural purposes.

In Latin America, less than 7% of the sewage is treated before it is discharged into the aquatic environment (FAO, 93). Many rivers being used for irrigation thus contain untreated sewage.

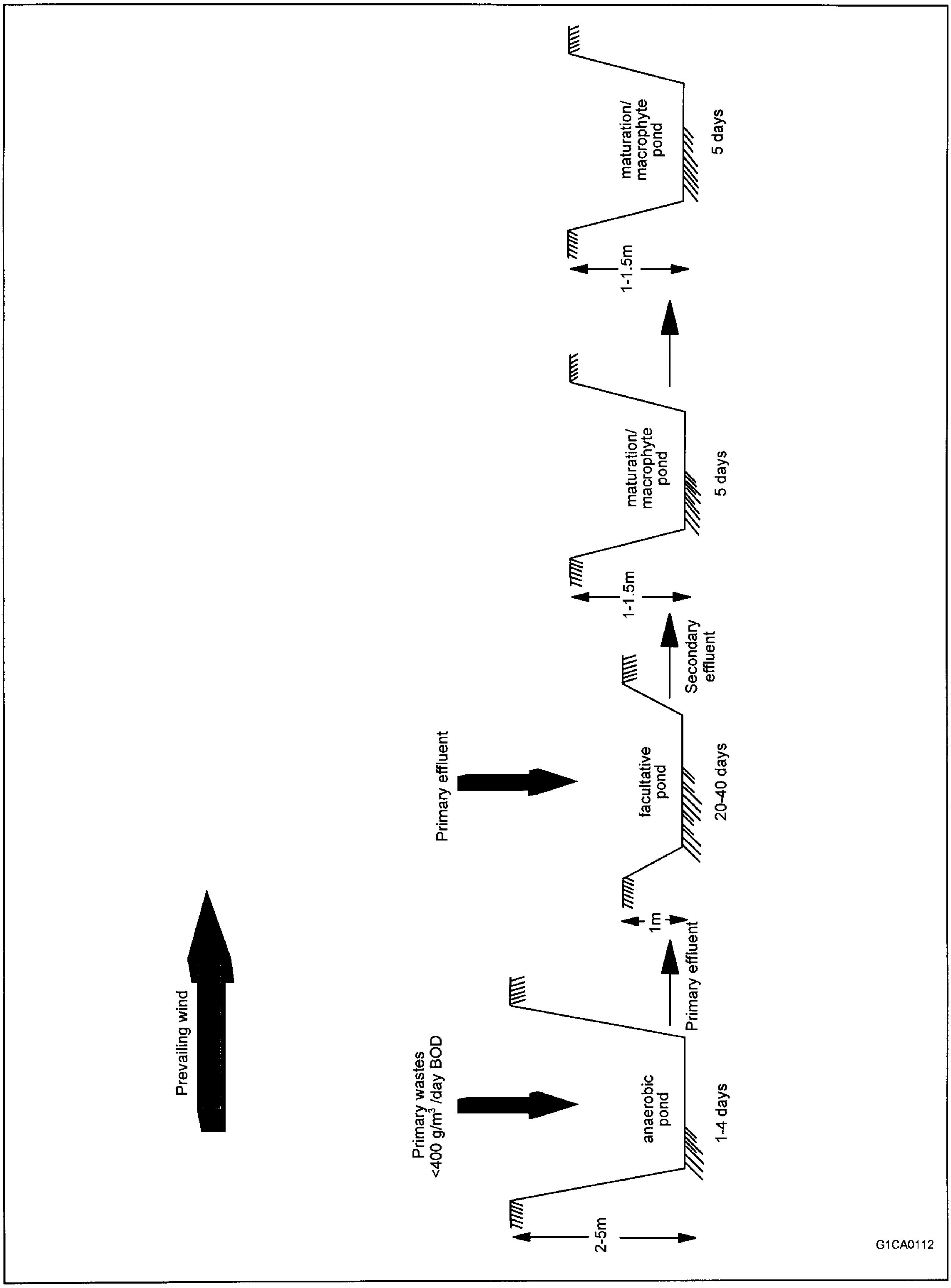

Figure 6.1 Waste stabilisation ponds

Two effective, low-cost systems are described in this chapter:

| | |
|---|---|
| • Stabilisation ponds | - for pathogen and trace element removal |
| • Soil Aquifer Treatment (SAT) Systems | - for pathogen and nutrient removal |

### *6.1.1 Stabilisation ponds*

Stabilisation ponds are the simplest of all treatment technologies, and with respect to pathogens, are capable of providing a very high quality effluent. They can reduce levels of pathogenic micro-organisms well below those obtained by other types of treatment and treated water is of good enough quality to use for unrestricted irrigation based on WHO, (1973) guidelines.

Stabilisation ponds are shallow basins with earth embankments or retaining walls, designed for treating raw wastewater or pre-treated effluents. They are the most suitable technology for wastewater treatment in developing countries, particularly in tropical and subtropical regions where there is an abundance of sunlight, ambient temperature is normally high, land is often available at reasonable opportunity cost and skilled labour is in short supply.

Stabilisation pond systems compromise a series of shallow lakes through which the sewage flows, (See figure 6.1). No machinery or energy input apart from the sun is required; treatment occurs through natural physical, chemical and biological processes. The stabilisation ponds are designed to achieve different forms of treatment in up to three stages in series, depending on the organic strength of the input waste and the effluent quality objectives.

**Advantages of waste stabilisation ponds:**

1. They can remove a high percentage of organic matter (figure 6.2), and excreted pathogens (bacteria, viruses, protozoa and helminths) which enable their effluents to be reused for agricultural purposes without risk to human health.
2. They can absorb concentrations of heavy metals at rates as high as 30 mg/l.
3. They are simple to construct, operate and maintain.
4. The energy they require comes from the sun and chemical reactions instead of electrical energy.
5. They are the cheapest method of wastewater treatment.

**Disadvantages of waste stabilisation ponds:**

1. They require large areas of land.

Silva *et al*, (1996).

A waste stabilisation pond system contains the following elements:

i) *Anaerobic pond*

Anaerobic ponds are essentially open septic ponds, about 2m to 5m in depth, used to provide pre-treatment of large volumes of strong wastes such as raw material. They are very efficient at removing Biological Oxygen Demand (BOD) when it is present in high concentration, although to avoid odour release the volumetric loading (see below) should not exceed 400g/m$^3$/day of BOD. The ambient temperature in hot climates aids anaerobic decomposition, releasing gas to the atmosphere. Retention times are typically in the range of 1 to 4 days. These ponds require de-sludging every 3-5 years.

At temperatures above 20$^o$C, BOD removal may be estimated as follows:

| | |
|---|---|
| 1 day retention: | at least 50% BOD removed |
| 2.5 day retention: | at least 60% BOD removed |
| 5 day retention: | at least 70% BOD removed |

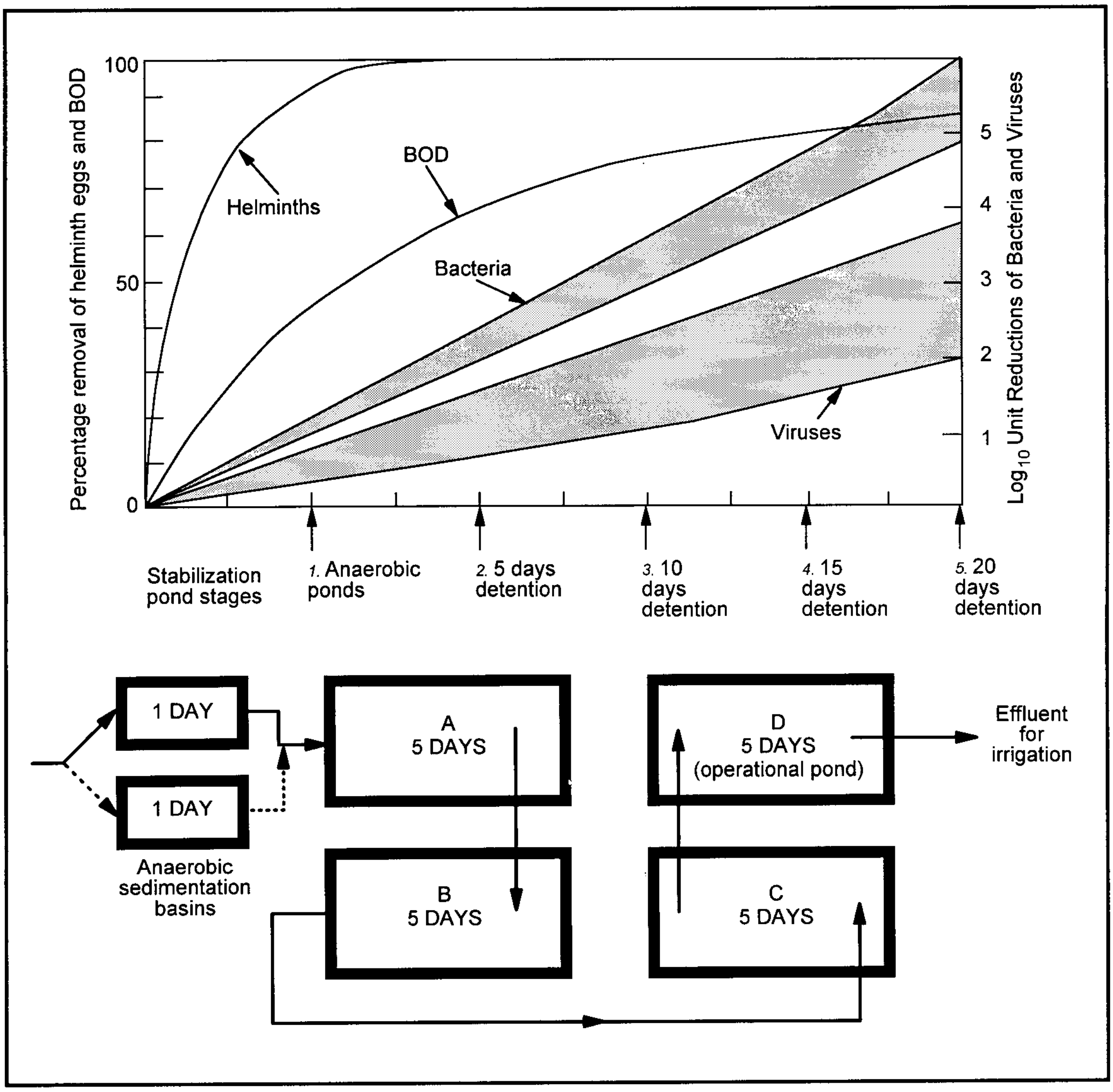

**Figure 6.2** Generalised removal curves for BOD, helminth eggs, excreted bacteria, and viruses in waste stabilisation ponds at temperatures above 20°C (source – World Bank, 1986)

For temperatures in the range 15-20°C these values should be reduced by about one quarter (Mara, 1977b).

Anaerobic ponds can save land when large pond systems are being designed, as they can reduce the BOD of a strong sewage from, for example 600mg/l to 240 mg/l and thus greatly reduce the area of the facultative (second stage) pond required.

Anaerobic conditions in these ponds are created by maintaining a high volumetric loading. It is recommended that volumetric loading is greater than 100g BOD/m$^3$ to maintain anaerobic conditions, but less than 400g BOD/m$^3$ to prevent odour.

Volumetric loading is given by:

$$\lambda_v = \frac{L_i Q}{V}$$

Where:

$\lambda_v$ = Volumetric loading (g/m$^3$/day)
$L_i$ = Influent BOD (mg/l)

$Q$ = Influent flow rate ($m^3/d$)
$V$ = Pond volume ($m^3$)

Pescod, (1992)

If the rate of inflow ($m^3$/day) and strength (BOD) of influent sewage are known, the pond volume required can be calculated and, selecting a convenient depth of 2 to 5m, the appropriate area can be derived.

Retention time is given by:

$$t = \frac{V}{Q}$$

Where:

$t$ = Retention time (days)
$V$ = Pond volume ($m^3$)
$Q$ = Influent flow rate ($m^3/d$)

Pescod, (1992)

If a retention time of less than one day is indicated, i.e. if influent has a BOD of less than 250 mg/l, an aerobic pond should not be used and wastes should pass directly to a facultative pond.

ii) *Facultative pond*

Facultative ponds are usually the largest pond in the stabilisation pond system and can receive either raw or pre-treated effluents. In the upper layers of the pond, oxidation of organic matter takes place with oxygen provided by photosynthesising algae. Retention time is normally 20 to 40 days. Sludge accumulates and digests anaerobically at the base of the pond so that de-sludging is required only every 10 to 20 years.

The surface area is more important than the volumetric rate when designing a facultative pond as the capacity of the pond is determined by the amount of sunlight it receives, which in turn determines the algal productivity. Depth is usually only about 1m, deeper ponds would encourage excessive anaerobicity and shallower ponds would encourage excessive growth of vegetation.

The design equation for the pond area is:

$$A = \frac{Q\,L_i}{(2T - 12)}$$

where:

$A$ = Pond area ($m^2$)
$Q$ = Flow of sewage ($m^3$/day)
$Li$ = BOD of influent (mg/l)
$T$ = Mean monthly ambient air temperature of the coldest month in $^oC$

Cairncross and Feachem, (1983)

Wind is also important for operation of facultative ponds as it mixes the organic matter and the degrading organisms. Facultative ponds should therefore be orientated with the longest dimension in the direction of the prevailing wind.

iii) *Maturation pond*

Maturation ponds receive the effluents from facultative ponds or alternatively from a conventional wastewater treatment station. They are primarily used for the reduction of pathogenic organisms. Maturation ponds are wholly aerobic and are responsible for the final improvement in chemical quality (BOD removal) and for most of the reduction in the numbers of faecal bacteria and viruses.

A good rule of thumb is to provide three maturation ponds, each with a retention time of five days and a depth of 1-1.5m. However, four maturation ponds, each with a four day retention time and the same depth (thus having a similar total area) will provide a greater degree of microbiological purification (Cairncross and Feachem, 1983). In a warm climate each maturation pond with a five-day retention time will remove at least 95% of faecal coliforms (Cairncross and Feachem, 1983).

Stabilisation ponds are very easy to maintain and require no routine operation. Maintenance is restricted to controlling vegetation growth. The type of pond to be used, as well as its location, depends on the characteristics of the wastewater to be treated and various environmental parameters, such as air temperature, altitude, velocity and direction of wind, solar radiation, cloud cover and the temperature of the water (Lumbers, 1979).

iv) *Design of pond systems*

The normal design is an aerobic pond followed by a facultative pond, followed by about three maturation ponds. The inlet pipe to the facultative pond should discharge below the water level, and should be carried on pillars to at least 10m from the pond edge, to prevent it from becoming blocked by the sludge which will accumulate below it. Embankments are usually made with slopes of 1 in 2-3. See Figure 6.3 for example of inter-pond connection.

### *6.1.2 Soil aquifer treatment*

Soil Aquifer Treatment (SAT) uses the soil and aquifer as a natural treatment system for wastewater. The wastewater infiltrates through the soil into a shallow aquifer where it is stored. Passage through the soil removes pathogens, nutrients and trace elements from the wastewater. This type of treatment however, does require suitable hydro-geological conditions and, because high rates of evaporation accelerate the process, it is especially useful in arid zones. As the performance of SAT systems is site dependent and controlled by wastewater quality, soils, hydro-geology, and climate, pilot or experimental systems should always precede full scale and operational systems. In this way the feasibility of SAT can be evaluated and a full-scale system can be designed and managed for optimum performance.

**Advantages of soil aquifer treatment systems**

Relatively inexpensive – the cost is mainly that for pumping the water from the aquifer (if wells are used for water recovery).

Robust and fail-safe - do not require highly skilled technical personnel for operation.

Underground storage absorbs seasonal or other differences between the supply of wastewater and the demand for treated water.

Water recovered from systems is clear, odour free and comes from a well, drain, or via natural drainage to a stream or low area, rather than from a sewer or sewage plant. This improves public acceptability of treated water.

When Soil Aquifer Treatment is used, the quality of the water improves significantly as it moves downward through the unsaturated zone to the groundwater and then laterally through the aquifer to the collection system such as a pumped well, gravity subsurface drains, or surface drains. See figure 6.4.

In order for SAT to be successful there are certain soil requirements:

- Infiltration basins for SAT systems should be located in soils that are permeable enough to give high infiltration rates.
- The soils should be fine enough to provide good filtration and quality improvement of the effluent as it passes through.
- Materials deeper in the unsaturated layer should be granular and preferably coarser than the surface soil.

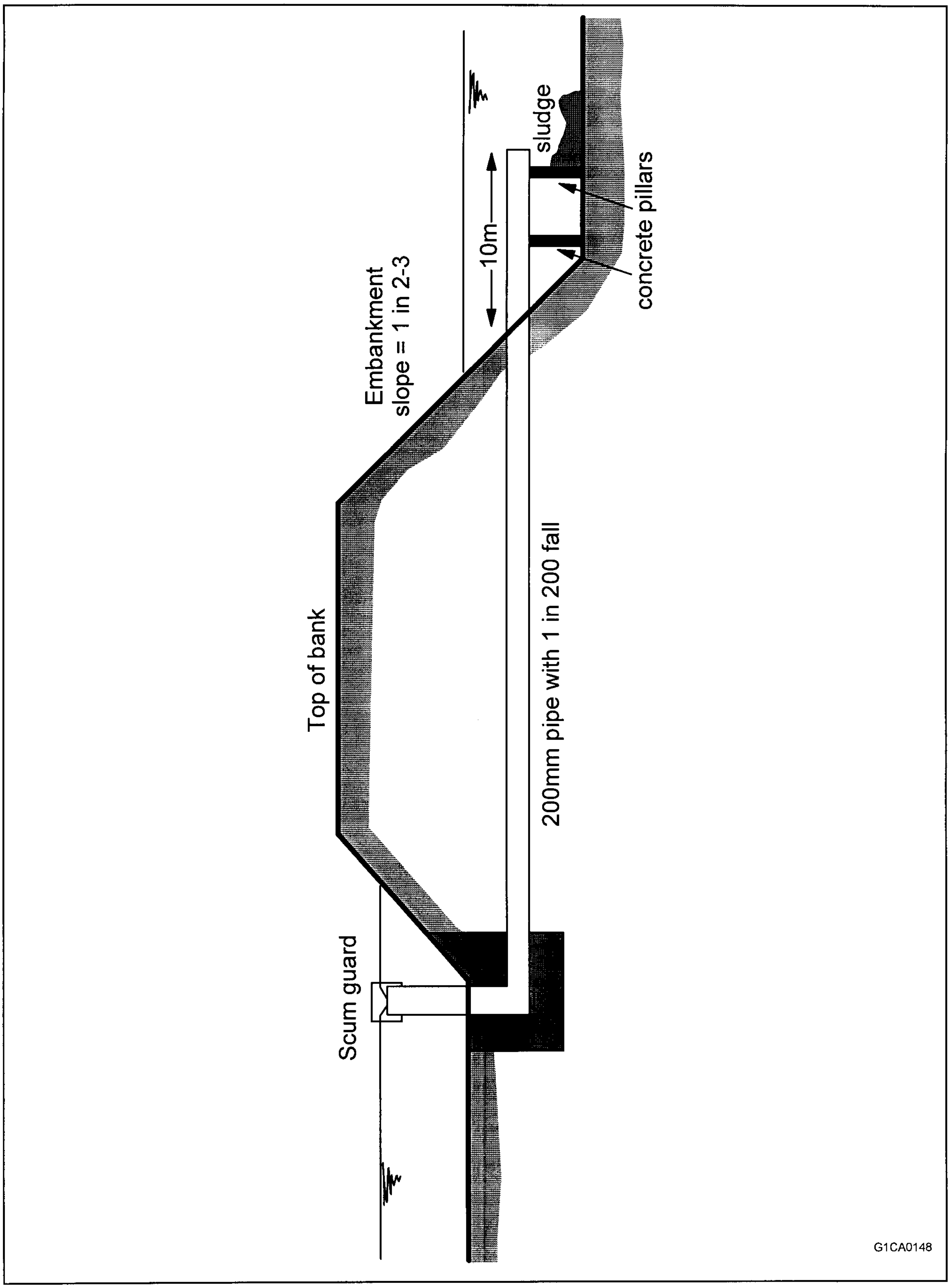

**Figure 6.3 Example of interpond connections (Adapted from Cairncross and Feacham, 1983)**

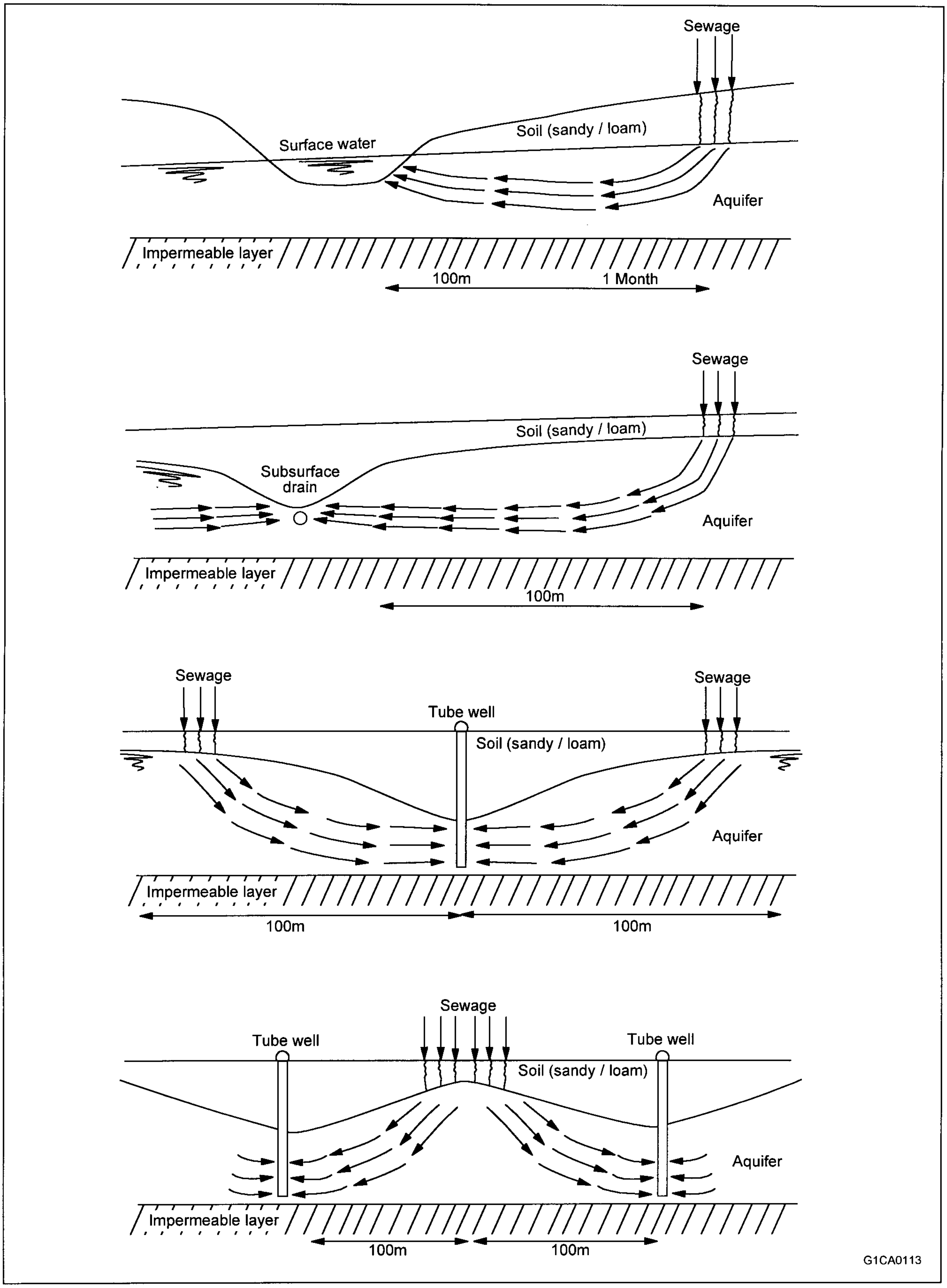

**Figure 6.4 Schematic of Soil aquifer treatment systems** (From Bouwer, 1987)

- Profiles that are coarse textured on top and finer textured deeper down, should be avoided to prevent fine suspended material in the sewage from moving through the coarse upper material clogging the soil profile deeper down.
- The unsaturated zone should not contain clay layers or other soils that could restrict the downward movement of water and lead to the formation of a perched watertable.

- SAT systems should be granular - soils underlain by fractured rock are not suitable.

The most suitable soils for SAT systems are:

- fine sand
- loamy sand
- sandy loam

Prior to SAT, conventional primary pre-treatment (removal of coarse solids, large materials and settable organic and inorganic solids by sedimentation and floating materials by skimming) is necessary, whereas secondary pre-treatment (removal of residual organics and suspended solids) is not, as SAT systems can remove more BOD than is in secondary effluent. Elimination of the secondary treatment step is also more economical, although it does mean that more frequent cleaning of the system is necessary.

Annual infiltration amounts or hydraulic loading rates vary from 15 m/year to 100 m/year, (Pescod, 1992) depending on:

- Soil
- Climate
- Quality of effluent
- Frequency of basin cleaning

After the treated sewage reaches the groundwater it usually flows some distance through the aquifer before it is collected. This additional movement through the aquifer can produce further purification of the sewage. Residence times in the SAT system should be long enough to produce renovated water of the desired quality. Although most of the quality improvements of effluent takes place in the top 1m of the soil, longer travel is desirable as it gives more complete removal of micro-organisms.

A general rule of thumb is: 100m underground travel and one month retention underground.

Whist SAT systems do considerably improve the quality of the sewage effluent, the quality is not often as good as that of the native groundwater. SAT systems should therefore be designed and managed to prevent encroachment of sewage water into the aquifer outside the portion of the aquifer used for SAT.

Infiltration basins are intermittently flooded and periodically cleaned (Bouwer, 1991). As the basins are frequently flooded and then dried out, to restore infiltration rates and aeration of the soil, there should be a number of basins so that some can be flooded whilst some are drying out. (The watertable should be at least 1m below the bottom of the infiltration basins during flooding). Primary waste requires about 2 days flooding and 8 days drying out, with cleaning at the end of every drying period, whilst secondary waste requires flooding and drying for two weeks each and cleaning once a year.

**For further guidance and information on water treatment systems the reader is referred to the following texts:**

| | |
|---|---|
| Bouwer H. 1991. | Groundwater Recharge with sewage effluent. Water Science and Technology. Vol. 23. No. 10-12. pp 2099-2108 |
| Bouwer H. 1992. | Agricultural and Municipal Use of Wastewater. Water Science and Technology. Vol. 26. No. 7-8. pp 1583-1591 |
| Cairncross S. & Feachem R. G. 1983. | Environmental Health Engineering in the Tropics. An Introductory Text. John Wiley & Sons Ltd, |

| | |
|---|---|
| Lumbers J. P. 1979. | Waste Stabilisation Ponds: Design Considerations and Methods. The Public Health Engineer. 7(2), 70. |
| Mara D. D. 1977a. | Waste water treatment in hot climates, In: Water, Wastes and Health in Hot Climates, Feachem R., McGarry M. and Mara D. (eds) London: John Wiley, pp 364-283 |
| Mara D. D. 1977b. | Sewage Treatment in Hot Countries, Overseas Building Note No. 174 (London: Building Research Establishment) |
| Silva, S. A., de Oliveira, R. & Mara, D. D. 1996. | Performance of Waste Stabilisation Ponds in Northeast Brazil. Research Monograph in Tropical Health Engineering. No. 9. University of Leeds. Department of Civil Engineering. |

## 6.2 Blending strategies

The blending of marginal quality water supplies with 'fresh' water supplies is a strategy that reduces the concentration of any soluble pollutant in the resulting blend. It is therefore a strategy that has wide application in the management of marginal quality water for agriculture. A common practice in some countries is for pumping stations to lift marginal quality water supplies into irrigation canals. This blended water then supplies agricultural areas downstream.

**Advantages of blending:**

1. Dilution of pollutants to acceptable levels in canals.
2. Reduction in need for new waterways.

**Disadvantages of blending:**

1. Total biomass production may be less than if water sources were kept separate .
2. Possible increase in disposal and off-site pollution problems.

**(see Rhoades *et al*, 1992)**

Blending of water sources is usually carried out in the water distribution system, but can also be adopted by farmers at field level if they have more than one source of water available. However, the control of blending and mixing ratios adopted will generally occur at the pumping station .

The mixing ratio is determined by the desired quality of the resultant water. Acceptable quality of the mix should be determined to minimise adverse impacts on agriculture and human health, using the guidelines given in Chapter 3.

The following equation can be used to calculate pollutant concentrations in the mixed water:

$$[P]_m = (a \times [P]_a) + (b \times [P]_b)$$

Where:

$[P]_m$ = Pollutant concentration of mixed water
$[P]$ = Concentration of pollutant in meq/l
a and b = relative fractions of supplies a and b

Pollutants may be ions, salts, pathogens, heavy metals etc.

**Blending example**

In the San Joaquin Valley in California some regions have access to four sources of water of differing quality. These are non-saline surface water ($EC_w = 0.4\ dSm^{-1}$), shallow watertables with salinities ranging from 8 to as 12 $dSm^{-1}$, and groundwater with salinity ranging from 1 to 4$dSm^{-1}$.

It is proposed to blend non-saline surface water of $EC_w = 0.4\ dSm^{-1}$ with shallow groundwater of salinity 10 $dSm^{-1}$ to produce a blend with a salinity of less than 4 $dSm^{-1}$. What are the required blending fractions for the mixture?

The blending equation becomes:

$$EC_m = (a \times EC_a) + (b \times EC_b)$$

Where $EC_m$ = acceptable salinity of mixed water = 4 $dSm^{-1}$
$EC_a$ = salinity of first water source = 0.4 $dSm^{-1}$
$EC_b$ = salinity of second water source = 10 $dSm^{-1}$
a = fraction of first water source in mixed water
b = fraction of second water source in mixed water and is equal to (1-a)

So $EC_m = (a \times EC_a) + [(1 - a) \times EC_b]$
$4 = (a \times 0.4) + [(1 - a) \times 10]$
$4 = 0.4a + 10 - 10a$
$9.6a = 6$
$a = 0.625$
$\therefore \quad b = 1 - a = 0.375$

So the necessary blend uses at least 62.5% of the non-saline surface water with up to 37.5% of the saline shallow groundwater.

In the case of mixing sodic water with good quality water, it is desirable to keep $SAR_m$ and $RSC_m$ below critical limits (See Table 3.4) to avoid soil and crop degradation. It is necessary to use a trial and error approach to determine the values of $SAR_m$ and $RSC_m$ using the following equations:

Sodium adsorption ratio SAR of the mixed water:

$$SAR_m = \frac{[Na]_m}{\sqrt{\frac{([Ca] + [Mg])_m}{2}}}$$

Residual sodium carbonate RSC of the mixed water:

$$RSC_m = ([CO_3] + [HCO_3])_m - ([Ca] + [Mg])_m$$

where [Na], [Ca], [Mg], $[CO_3]$, $[HCO_3]$ are concentrations of sodium, calcium, magnesium, carbonate and bicarbonate respectively, and salt concentrations in the mixed water are given by:

$$[Na]_m = ([Na]_a \times a) + ([Na]_b \times b)$$

$$([Ca] + [Mg])_m = ([Ca]_a + [Mg]_a) \times a + ([Ca]_b + [Mg]_b) \times b$$

$$([CO_3] + [HCO_3])_m = ([CO_3]_a + [HCO_3]_a) \times a + ([CO_3]_b + [HCO_3]_b) \times b$$

Singh *et al*, (1996).

## 6.3 Cyclic use

This involves alternate application of good and poor quality water sources to agricultural areas.

A cyclic strategy can be implemented in the main distribution system or at farm level if the farmer has alternate water supplies available. Availability of supplies both in the distribution network and at farm level may demand cyclic use of good and poor quality supplies. In India and Pakistan it is common for high quality water to be available in the early growing season, but be either too costly or too limited in supply to meet the entire season’s requirements. Where high quality water costs are prohibitive, crops of moderate to high salt tolerance can be irrigated with saline drainage or groundwater, especially late in the growing season when tolerance is higher.

**Advantages of cyclic use**

It can maximise biomass production for a given water volume.
It may allow greater flexibility in cropping patterns.
Intermittent leaching which occurs can be more efficient than continuous leaching.

**Disadvantages of cyclic use**

Additional waterways may be required.
Without careful management, crop growth can be impaired.

A recommended strategy is to utilise good quality water sources early in the crop seasons of moderately tolerant crops and for the entire growing seasons of moderately sensitive crops. Poor quality water sources can be used later in the growing season of moderately tolerant and tolerant crops without significant reduction in crop yields (Shalhevet, 1991, Rhoades, 1987, Oster, 1994)

**Examples of cyclic strategies:**

In the San Jaoquin Valley of California, cotton was irrigated during germination and seedling development with low salinity ($EC_w$ = 0.5dS $m^{-1}$) water. Thereafter high salinity ($EC_w$ = 7.9 dS $m^{-1}$) water was used. (Rhoades, 1987), also applied the same strategy to wheat.

Drip irrigation was used to employ saline (8 dS $m^{-1}$) water to cotton after it was established with 0.5 dS $m^{-1}$ water (Ayars, 1986). A wheat crop was then grown with 0.5 dS $m^{-1}$ water before growing sugar beet with 8 dS $m^{-1}$ water after stand establishment.

Yields under these conditions were as good as with continuous irrigation from good quality water.

## 6.4 Leaching strategies

The provision of additional water to the soil profile to facilitate movement of soluble pollutants down and out of the crop root zone is called ’leaching’. The amount of water required to do this is the Leaching Requirement.

It may be necessary to provide up to 10-20% extra water, above normal water requirements to meet the leeching requirement in areas irrigated with marginal quality water. It is important not to overlook this additional requirement at the planning stage when water allocation plans are being formulated.

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

In order to estimate the leaching requirement for salinity control it is necessary to know:

1. The irrigation water salinity ($EC_w$)
   This can be for a marginal quality water source used directly or after mixing with a ’fresh’ water source, and is obtained from laboratory analysis.

2. The crop tolerance to soil salinity ($EC_e$)
   This can be estimated from appropriate crop tolerance data (see Section 5.2.1).

**General crop rotations**
$EC_w$ is obtained as above and the acceptable $EC_e$ for general crop rotations can be estimated from Table 5.5.

These values for $EC_w$ and $EC_e$ are then put into Figure 5.1 and where the lines cross gives an estimate of the leaching requirement for total salinity control.

**Specific crops**
Where planners have specific information on existing or proposed crop rotations, the leaching requirement can be derived from:

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

Where:

LR = Minimum leaching requirement needed in order to control salts within the tolerance ($EC_e$) of the crop using surface irrigation.

$EC_w$ = Salinity of the applied irrigation water (dS $m^{-1}$)

$EC_e$ = Average soil salinity tolerated by the crop - measured on a soil saturation extract. Acceptable $EC_e$ values are given for specific crops, appropriate to the tolerance degree of yield loss, in Table 5.4 and Figure 5.2.

Note:
Use the $EC_e$ value that can be expected to result in at least a 90% or greater yield. Maximum yield potential (100%) should be used for water in the moderate to high salinity range (>1.5 dS $m^{-1}$) where salinity control is critical for obtaining high yields.

**Command Area Calculations**
It is recommended that the water resource manager calculate an estimate of the leaching requirement for each command area under consideration. An area is defined as a distinct agricultural unit under the command of one irrigation supply canal.

A command area LF is defined as:

$$\frac{\text{Amount of water required for leaching in command area}}{\text{Total water supplied to command area}}$$

This may be done on a seasonal or annual basis.

**To calculate quantities of additional water required for leaching:**

Divide the agricultural area into distinct units. It is usually best to use command areas defined by supply canals.

Calculate size of command areas under irrigated cropping.

Using information on the cropping patterns in each area, calculate the normal crop water requirements for each area, using conventional methods, on either a seasonal or annual basis.

Calculate the effective rainfall using locally accepted methods and subtract this from the crop water requirements.

For each command area, calculate the additional water depth required for leaching.

Additional quantity of water required for leaching in the command area (seasonal or annual basis) is then given by:

LF ($m^3$) = water depth (m) x command area ($m^2$)

Each command area is then supplied with the normal crop water requirement plus the calculated additional quantity required for leaching.

### *6.4.1 Drainage requirements for leaching*

Successful leaching requires an effective drainage system. Planners should assess current drainage status of each command area when planning allocation and distribution of marginal quality water sources. The watertable should be kept deep enough to prevent capillary rise of salts and other solutes into the root zone. Subsurface drainage should maintain watertables below this critical depth.

**Critical watertable depths to avoid capillary rise:**

Artificial drainage should maintain watertables below $D_c$ the critical watertable depth. Guidance on acceptable values of $D_c$ depending on the soil texture and type of crop are given below:

| | Fine textured (permeable) soil | Light textured soil |
|---|---|---|
| Field crops | 1.2m | 1.0m |
| Vegetables | 1.1m | 1.0m |
| Tree crops | 1.6m | 1.2m |

From FAO 28

The percentage silt content is the dominant factor controlling the critical depth due to its influence on capillary rise.

Root zone depths will vary between crops and according to stage of growth. Some examples are given in Table 6.2. For general crop rotations a rooting depth of 1.5m is suggested. Drainage should be installed to maintain watertables below these depths.

## *Table 6.2 Some typical rooting depths for agricultural crops*

| Crop | Max. root depth (m) | Soil depth from where water used | Characteristics of root development |
|---|---|---|---|
| Alfalfa | 3 | 100% from first 1-2m soil depth | Maximum root depth reached after one year |
| Bean | 1.5 | Mainly from first 0.5-0.7m | Lateral root system mainly concentrated in first 0.3m |
| Cabbage | 0.5 | 100% between 0.4 & 0.5m | Extensive shallow root system. Majority of roots in layer 0.4-0.5m |
| Cotton | 1.8 | 70-80% from first 0.9m<br>100% from first 1-1.7m | 90% of root weight is in the first 0.9m |
| Maize | 2 | 80% from first 0.8-1m<br>100% from first 1-1.7m | Highly branched root system in first 0.8 -1m |
| Potato | 0.6 | 70% from first 0.3m<br>100% from first 0.4-0.6m | Shallow root system |
| Rice | 1 | | Root system gradually increases from transplanting. Max root at time of heading. Decreases after flowering. At maturity roots are dead |
| Sorghum | 2 | 60-90% from first 1m | Max. roots at time of heading |
| Sugarbeet | 1.2 | 100% from first 0.7-1.2m | |
| Sugarcane | 2 | 100% from first 1.2-2m | |
| Tomato | 1.5 | 80% from first 0.5-0.7m<br>100% from first 0.7-1.5m | Max rooting depth about 60 days after planting |
| Spring wheat<br>Winter wheat | 1.5<br>2 | 50-60% from first 0.3m<br>20-25% from second 0.3m<br>10-15% from third 0.3m<br>< 10% from fourth 0.3m<br>(100% from first 1-1.5m) | Spring wheat - roots most active at 0.9m<br>Winter wheat - roots most active at 1.2m |

Adapted from Ayers and Westcot, 1985

**For more information on drainage systems, design and requirements the reader is referred to the following texts:**

Ochs, W.J. and Bishay, B.G. 1992. Drainage Guidelines, World Bank Technical Paper no.195.

Smart, P and Herbertson, J.G. 1992. Drainage Design.

Smedema, L.K. and Rycroft, D.W. 1983. Land Drainage: Planning and Design of Agricultural Drainage Systems

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# 8 Full reference list

Abbott, C.L. & El-Quosy, D.E.D. 1996. A Procedure to Assess the Impacts of Drainwater Reuse. HR Wallingford Report OD 134.

Abbott, C.L. & El-Quosy, D.E.D. 1995. Soil Salinity Levels due to Reuse of Drainage Water in the Nile Delta, Egypt. HR Wallingford Report OD/TN 71.

Abdel-Dayem, S. and Abu-Zeid, M. 1991. Salt load in irrigation and drainage water in the Nile Delta. Proc. African Regional Symposium on Techniques for Environmentally Sound Water Resources Development, Alexandria. HR Wallingford, UK.

Arar, A. 1988. Background to treatment and use of sewage effluent. Ch.2, Treatment and Use of Sewage Effluent for Irrigation, M.B. Pescod and A. Arar (eds). Butterworths, Sevenoaks, Kent.

Ayers, R.S. and Westcot, D.W. 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper 29.

Bartram, J.B. and Ballance, R. 1996. Water Quality Monitoring. Chapman and Hall.

BGS, CNA, SAPAL and UACH. 1996. Effects of Wastewater Reuse on Urban Groundwater Resources of Leon, Mexico. Final Report.

Birley, M.H. 1995. The Health Impact Assessment of Development Projects. London, HMSO.

Bockman, O. C. & Granli, T. 1991. Human Health Aspects of Nitrate Intake from Food. In Chemistry, Agriculture and the Environment, Edited by Mervyn L. Richardson. ISBN 0-85186-228-4

Bolton, P. 1992. Water Resources Planning and Management in Developing Countries. HR Wallingford Report EX 2437.

Bouwer, H. 1991. Groundwater recharge with sewage effluent. Water Science and Technology. Vol.23 no. 10-12. 2099-2108.

Bouwer, H. 1992. Agricultural and municipal use of wastewater. Water Science and Technology. Vol.26 no. 7-8. 1582-1591.

Bouwer, H. & Idelovitch, E. 1987. Quality requirements for Irrigation with sewage water. ASCE Irrigation and Drainage, 113, 4.

Bower, C. A. & Wilcox, L. V. in Methods of Soil Analysis, Chemical & Microbiological Properties (1979), Monograph No. 9, part 2 (Black, C. A. (ed)) pg 947-948, American Society Agronomy.

Boyer, J. 1978. Le calcium et le magnesium dans les sols des regions tropiclaes humides et sub-humides. Orstom, Paris (IDT no. 35).

Cairncross, S. & Feachem, R.G. 1983. Environmental Health Engineering in the Tropics. An Introductory Text. John Wiley and Sons Ltd.

Chapman, D. (ed) 1992. Water Quality Assessments - a guide to the use of biota, sediments and water in environmental monitoring. Chapman and Hall.

Conway, G. R. & Pretty J. N. 1991. Unwelcome Harvest. Agriculture & Pollution. Earthscan Publications Ltd. ISBN 1-85383-036-4

Donahue et al 1987. Soils - An introduction to soils and plant growth, 5th Ed. Prentice Hall Inc.

Doneen, L. D. and Westcot, D. W. 1984. Irrigation Practice and Water Management. FAO Irrigation and Drainage Paper No. 1.

Driscoll, F.G. 1986. Groundwater and Wells. ISBN 0-9616456-0-1

FAO 1993. Prevention of water pollution by agriculture and related activities. Proceedings of the FAO Expert Consultation, Santiago, Chile. Water Report no.1. ISSN 1020/1203.

FAO 1990. Mar del Plata Action Plan. FAO, Rome.

FAO 1986. Drainage design factors. FAO Irrigation and Drainage Paper 28, FAO, Rome.

FAO 1979. Soil Survey Investigations for Irrigation. FAO Soils Bulletin No. 42. FAO, Rome.

Frederiksen, H. D. 1992. Water Resources Institutions – Some Principles and Practices. World Bank Technical Paper 191.

Greenberg, A. E., Clesceri, L. S. and Eaton, A. D. (Eds) 1992. Standard methods for the examination of water and wastewater.

Hamdy, A. 1988. Research work at Bari Institute for reuse of low quality water and its impact on soils and crops. Reuse Conference, International seminar on the reuse of low quality water for irrigation, Egypt.

Hinnawi, E.El and Hashmi, M.H. 1987. The State of the Environment, United Nations Environment Programme, Butterworth Scientific, Guildford, UK.

Hoffman, G.J. & van Genuchten, M.T. 1983. Soil properties and efficient water use: water management for salinity control. In: H.M. Taylor, W.R. Jordan & T.R. Sinclair (Editors), Limitations to Efficient Water Use in Crop Production. American Soc. of Agronomy, Madison, Wisconsin.

Holden, P. W. 1991. Pesticides and Groundwater Quality (Washington DC: National Academy Press, 1986). In Conway, G. R. & Pretty., J. N. Unwelcome Harvest. Agriculture & Pollution. Earthscan Publications Ltd. ISBN 1-85383-036-4

Hutton, L.G. 1983. Field Testing of water in developing countries. Water Research Centre, Medmenham, UK, 125p.

International Reference Centre for Community Water Supply and Sanitation. 1981. Small Community Water Supplies. Technical paper no.18. The Hague, Netherlands.

Kay, M. 1986. Surface Irrigation Systems and Practice. Cranfield Press.

Klassen, C. D., Amdur, M. O. and Doull, J. (Eds) 1986. Casarett and Doulls Toxicology. 3rd ed. MacMillan Publishing Co., New York

Lawrence, A. R. & Foster, S.S.D. 1991. The pollution threat from agricultural pesticides and industrialised solvents: a comparative review in relation to British aquifer (Wallingford, Oxon: British Geological Survey, 1987) In Conway, G. R. & Pretty., J. N. Unwelcome Harvest. Agriculture & Pollution. Earthscan Publications Ltd. ISBN 1-85383-036-4

Lumbers, J.P. 1979. Waste Stabilisation Ponds: Design Considerations and Methods. The Public Health Engineer. 7(2), 70.

Maagee, P. N. & Barnes, J. M. 1967. "Carcinogenic nitroso compounds", Adv. Cancer Research. 10. 163-246;

Maas, E.V. 1986. Salt Tolerance of Plants. Applied Agricultural Research Vol.1, no.1, 12-26.

Maas, E.V. 1990. Crop salt tolerance. In: K.K. Tanji (ed), Agricultural salinity assessment and management. ASCE Manuals and Reports on Engineering Practice No.71. Am. Soc. Civil Engineers, New York, pp 262-304.

Mara, D.D. 1977a. Wastewater treatment in hot climates. In: Water, Wastes and Health in Hot Climates. Feachem, R., McGarry, M. & Mara, D.D. (eds), pp283-364.

Mara, D.D. 1977b. Sewage Treatment in Hot Countries. Overseas Building Note No. 174 London: Building Research Establishment.

Menzer, R. E. 1991. Water and soil pollutants. In: M. O. Amdur, J. Doull, and C. D. Klassen (Eds.) Casarett and Doulls Toxicology. 4th ed. MacMillan Publishing Co., New York

Morgan, D. P. 1989. Recognition and management of pesticide poisoning. Health Effects Division, Office of Pesticide Programs. U. S. Environmental Protection Agency, U.S. Government Printing Office, Washington, D. C.

Ochs, W.J. and Bishay, B.G. 1992. Drainage Guidelines. World Bank Technical Paper no.195.

Ongley, E.D. 1996. Control of water pollution from agriculture. FAO Irrigation and Drainage Paper No.55.

Oster, J.D. 1994. Irrigation with poor quality water - a review. Agricultural Water Management 25:271-297.

Pearson, G.A. 1960. Tolerance of crops to exchangeable sodium. US Dept. Agric. Info. Bull. 216.

Pescod, M.B. 1992. Wastewater treatment and use in agriculture. FAO Irrigation and Drainage Paper 47.

Pressor, I. and Ohlendorf, H.M. 1987. Biogeochemical cycling of selenium in the San Joaquin Valley, California, USA. Environmental Management 11, 805-821.

Rao, D.L.N., Singh, N.T., Gupta, R.K. and Tyagi, N.K. (eds) 1994. Salinity Management for Sustainable Agriculture. Central Soil Salinity Research Institute, Karnal, India.

Rhoades, J.D. 1982. Reclamation and management of salt-affected soils after drainage. Proc. First Annual Western Provincial Conf. Rationalisation of Water and Soil Resources and Management, Lethbridge, Alberta, Canada. 29 Nov-2 Dec. pp.123-197.

Rhoades, J.D. et al 1992. The use of saline waters for crop production. FAO Irrigation and Drainage Paper 48.

Richardson, M. L. (ed). Chemistry and the Environment 1991 (ISBN 0-85186-228-4). WHO “Drinking Water Quality: Guidelines for selected herbicides”, Copenhagen, 1987.

Roberts, Pesticides in Water - Human Health, Agricultural and Environmental Aspects. In Chemistry, Agriculture and the Environment, Edited by Mervyn L. Richardson, 1991. ISBN 0-85186-228-4

Rowell, D. L. 1994. Soil Science – Methods and Applications, Longmann, London.

Shalhevet, J. 1994. Using water of marginal quality for crop production: major issues - a review. Agricultural Water Management 25:233-269.

Shainberg, I. & Letey, J. 1984. Response of soils to sodic and saline conditions. Hilgardia, vol.52, no.2.

Shelef, G. 1991. The Role of Wastewater Reuse in Water Resources Management in Israel. Wat. Sci. Tech. Vol.23, pp2081-2089.

Shelton, L.R. 1994. Field guide for collecting and processing stream-water samples for the national water quality assessment program. U.S. Geological Survey, Open-File Report 94-455.

Shuval, H. I. 1991. Health Guidelines and standards for wastewater reuse. In: Agriculture: Historical perspectives. Water Science and Technology. Volume 23, pp. 2073-2080

Silva, S.A., Oliveira, R. & Mara, D.D. 1996. Performance of Waste Stabilisation Ponds in Northeast Brazil. Research monograph in Tropical Health Engineering, No.9, University of Leeds.

Singh, C.S., Gupta, S.K. and Ram, Sewa. 1996. Assessment and management of poor quality waters for crop production: A simulation model (SWAM). Agricultural Water Management, 30, 25-40.

Smart, P and Herbertson, J.G. (eds) 1992. Drainage Design. Blackie and Son Ltd. ISBN 0-442-31334-9.

Smedema, L.K. and Rycroft, D.W. 1983. Land Drainage: Planning and Design of Agricultural Drainage Systems. ISBN 07134 35003

Tanji, K.K. (ed). 1990. Agricultural salinity assessment and management. American Society of Civil Engineers, New York.

United Sates Department of Agriculture (USDA) 1954. Diagnosis and improvement of saline and alkali soils, Agriculture handbook no. 60.

U.S Environmental Protection Agency. 1989. Nonpoint sources Agenda for the future. WH-556. EPA Office of Water, U.S. Environmental Protection Agency, Washington, D.C. January.

U.S Environmental Protection Agency. 1990. Drinking water regulations and health advisories. Office of Drinking Water, U.S. Environmental Protection Agency, Washington, D.C

Ward, R.C. 1967. Principles of Hydrology, McGraw-Hill.

Wauchope, R. D., Baker, D.B., Balu, K. & Nelson, H. 1994. Pesticides in Surface and Ground Water. Council for Agricultural Science and Technology, Issue Paper Number 2, April 1994. Ames, IA.

Wetzlich, S. 1991. Nitrates. Environ. Toxicol. Newlett. 11:6-10. Co-operative Extension, University of California

WHO, 1989. Guidelines for use of wastewater in agriculture and aquaculture. WHO technical report series 778.

WHO 1991. GEMS/WATER 1990-2000. The Challenge Ahead. WHO/PEP/91.2.

WHO 1987. ’Drinking-Water Quality: Guidelines for selected herbicides’, World Health Organisation, Copenhagen,1987. In: Chemistry, Agriculture and the Environment. Edited by Mervyn L. Richardson, 1991. ISBN 0-85186-228-4

Wier, D. & Schapiro, M. 1981. Circle of poison: pesticides and people in a hungry world. San Francisco, Inst. for food and Development Policy, 101p

World Bank 1986. Integrated Resource Delivery. Wastewater Irrigation in Developing Countries. Health Effects and Technical Solutions. Technical patr 51.

SALTMOD - R.J. Oosterbaan, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

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# Appendix

# Appendix 1

Laboratory analysis techniques

# Appendix 1 Laboratory analysis techniques

## Irrigation water

### Salinity – Electrical Conductivity ($EC_w$)

Electrical conductivity is measured using a conductivity meter that measures the current passing through a solution between two electrodes in a conductivity cell.

| | |
|---|---|
| Equipment: | Electrical conductivity meter<br>Conductivity cell<br>Conductivity standards |

To prepare the conductivity standards: First dry NaCl at 105$^o$C for one hour and then cool it in a desiccator. Then dissolve 2.922 g in water and make it up to 1 litre, thus making 50 mM NaCl. Next dilute this by 10 and also by 100 to give 5 and 0.5 mM solutions. The respective resulting EC values are 5.550, 0.604 and 0.625 dS m$^{-1}$ at 25$^o$C or 4.995, 0.543 and 0.0562 dS m$^{-1}$ at 20$^o$C (It is important that temperature is recorded as conductance is proportional to temperature).

To test the electrical conductivity of the irrigation water, the meter has first to be calibrated with the standard NaCl solutions. Use the 5 mM solution to calibrate the meter and then check that it works by testing if it reads correctly on the other two standards. Once the meter is calibrated, the electrical conductivity of the sample can be measured. It is best to work at 25$^o$C. To convert values measured at 20$^o$C to values at 25$^o$C, multiply by 1.112.

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 285, Longmann, London.

### Sodium

| | |
|---|---|
| Equipment: | Flame photometer<br>Sodium filter<br>Sodium Chloride Standards |

To prepare the sodium chloride standards: First dry NaCl at 105$^o$c for one hour and then cool it in a desiccator. Then dissolve 0.254 g in water and make it up to 100 ml, thus creating a solution that contains 1 g $Na^+$ per litre. Next, pipette 10 ml into a 100 ml volumetric flask and make it up to the mark. Then pipette 0, 2, 4, 7 and 10 ml of this diluted standard into 100 ml volumetric flasks and make up to the mark. These will then contain 0, 2, 4, 7 and 10 mg $Na^+$ per litre respectively.

Place the sodium filter in the flame photometer, and then set the milliammeter to zero on the zero standard and to full scale deflection with the 10 mg $Na^+$ per litre standard. Read all of the standards as a check to see if the machine is functioning properly. The irrigation water should be diluted x50 to bring it into the range for measurement. This is done by pipetting 1 ml of the water into a 50 ml volumetric flask and then making it up to the mark. Then measure the concentration of this diluted irrigation water. The resulting figure is then multiplied by 50 to get the correct reading.

Reference: Rowell, D. L., Soil Science, Methods and Applications, pg 286, 141, Longmann, London.

### Calcium

Calcium can be measured using a flame photometer, but it is less sensitive and subject to interference. Due to this, calcium is often determined by titration.

Reagents: Ethylenediaminetetra-acetic acid (EDTA), disodium salt, 0.005 M. Dry the salt at 105$^o$C for one hour and cool in a desiccator. Weigh 1.86 g, and then dissolve in water in a 250 ml beaker. Then transfer with washings into a 1 litre volumetric flask and make up to the mark.

Buffer solution. Dissolve 17.5 g of ammonium chloride in water in a 250 ml beaker, and then transfer with washings into a 250 ml volumetric flask, and add 143 ml of ammonia solution (approx. 35% $NH_3$) and make up to the mark. (This should be handled in a fume cupboard).

Murexide indicator. Shake 0.5 g of murexide in 100 ml of water for 30 min. Then filter through a Whatman No. 1 paper. (This should be prepared fresh for use).

Calcium solution 250µg $Ca^{++}$ $ml^{-1}$. This is prepared from a volumetric standard containing 1 mg $Ca^{++}$ $ml^{-1}$. First dry anhydrous calcium nitrate $Ca(NO_3)_2$ at 105°C for one hour and then cool this in a desiccator. Next dissolve 2.05 g in water in a 100 ml beaker and add 1 ml of HCL (approx. 36% HCL) as a preservative. Transfer with washings to a 500 ml volumetric flask and make up to the mark with water. Pipette 25 ml into a 100 ml volumetric flask and make up to the mark, again using water.

Pipette 10 ml of the irrigation water into a conical flask and then add to this 2 ml of the buffer solution and then a few drops of murexide indicator. Titrate this with 0.005 M EDTA until the colour changes. The volume of EDTA used can be inserted into the equation below to determine the number of moles of EDTA used. As one mole of $Ca^{++}$ reacts with 1 mole of EDTA, the amount of calcium in the sample is therefore equivalent to the number of moles of EDTA used.

$$\text{No. of mol of EDTA used} = 0.005\ \text{mol l}^{-1}\ \text{x}\ \frac{\text{vol. of EDTA used}}{1000}\ \text{l}$$

Reference: Rowell, D. L., Soil Science, Methods and Applications, pg 268, 143, 144, Longmann, London.

**_Chloride_**

Equipment: Magnetic stirrer
Titration assembly (10 ml buret)

The Mohr volumetric method can be used for determination of chloride in water samples and also aqueous soil extracts. The chloride is titrated with a standard silver nitrate solution, using potassium chromate as the indicator. As the equivalence point is passed, the excess silver combines with the chromate to form a red or reddish brown precipitate of silver chromate. This colour change is easily recognised and serves as the end point of the titration.

Reagents: Potassium chromate ($K_2CrO_4$) indicator: First dissolve 5 g of $K_2CrO_4$ in 75 ml of water, and add to this a saturated solution of $AgNO_3$ until a small quantity of red $Ag_2CrO_4$ precipitates. Leave this solution in the dark overnight and then filter it to remove the $Ag_2CrO_4$, and make the volume up to 100 ml.

Standard silver nitrate ($AgNO_3$) solution, 0.025M: Dissolve 4.2472 g of $AgNO_3$ in water, and dilute the solution to a volume of 1 litre. Check molarity by titrating an aliquot of 0.01M KCl conductivity reference solution reagent. (This is made up by dissolving 0.7456 g of KCl in distilled water, and add water to make 1 litre at 25°C.

Sodium bicarbonate ($NaHCO_3$), saturated solution.
Before chloride can be tested for, a carbonate-bicarbonate titration has to be undertaken (Instructions for this can be found in 'Methods of soil analysis' pg 945).

To test for chloride: First place the solution from the carbonate-bicarbonate titration in the titration assembly, and start the stirrer. Adjust the pH with the $NaHCO_3$ solution so that the solution is alkaline to methyl orange but acid to phenolphthalein (usually one drop is sufficient). Next add the $K_2CrO_4$ indicator, 1 drop per 5 ml of solution, and titrate the solution with the standard silver nitrate until the appearance of a red or reddish-brown precipitate. Determine a blank correction by titrating a like volume of Cl-free distilled water. The equation below is used for determining the meq. of Cl per litre.

***meq of Cl per litre***

$$= \frac{1000}{\text{ml. of sample}} \text{ x (ml. of } AgNO_3 \text{ - blank) x Normality of } AgNO_3$$

Reference: Bower, C. A. & Wilcox, L. V. in Methods of Soil Analysis, Chemical & Microbiological Properties (1979), Monograph No. 9, Part 2 Black, C. A. (ed), pg 947-948, American Society of Agronomy.

### *Magnesium*

The same method as described above for determining calcium should be used, although using lanthanum chloride as the releasing agent. Where available a more accurate measure can be determined using an atomic absorptiometer.

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 286, 144, Longmann, London.

### *pH*

Equipment: pH meter
Buffer tablets (4 & 7 or 7 & 9) (Buffer tablets are temperature dependant. Instructions are normally supplied with the tablets).

First wash the electrodes with water from a wash bottle, and then dry. When dry, place the electrodes into the pH 4 buffer solution and adjust the pH meter to pH 4 using the buffer control. Repeat this again using the pH 6.9 buffer solution. Repeat these readings, as necessary, until they are correctly set for both of the buffer solutions. The pH meter should then be calibrated so that it can be used to measure the pH value of any solution. The pH of the irrigation water can thus be read straight from the meter.

Note: At pH 7 there are $10^{-7}$ mole per litre of hydrogen in solution, whereas at pH 4 this increases to $10^{-4}$ mole $1^{-1}$.

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 159, Longmann, London.

### *Boron*

To determine the boron content of the irrigation water, first add mannitol to the water, which will cause the solution to become acid. Then the quantity of standard alkali required to titrate the solution back to the initial pH is an accurate measure of the boron present. Boron can also be tested for using Atomic Absorption Spectrometry (See description under Trace Elements).

For a detailed description of the titration process see reference:
Diagnosis and improvement of Saline & Alkali Soils, United States Department of Agriculture, (1954) Agriculture Handbook No. 60, Pg 140-141.

## Soil

Before most laboratory tests can be carried out on soils, it is necessary, first, to make a saturation paste. This is done in the following way:

### *Saturated paste*

Begin by air drying the soil sample and passing it through a 2 mm sieve. Then weigh 300 g of air dry soil into a weighed 500 ml plastic beaker and add distilled water (whilst stirring) until the soil is near saturated. The paste should then be left to stand for a few hours to wet thoroughly. More water should then be added to form a saturated paste. This is not a precisely defined end point but saturation is defined by the following subjective descriptions:

- The paste glistens as it reflects light
- It flows slightly when the beaker is tipped
- It slides cleanly and freely off a spatula
- It is consolidated easily by tapping if a groove is formed in the surface

Once the paste is ready, cover the beaker and leave it standing overnight. More distilled water or dry soil can be added if necessary. The paste and beaker should then be weighed to determine the mass of water added to the soil.

A solution is then normally extracted from the saturation paste, which is termed the saturation extract. Most laboratory tests are then carried out on this extract.

***Saturation extract***

Reagent: Sodium hexametaphosphate, 0.1%. Dissolve 0.1 g of $(NaPO_3)_6$ in 100 ml water.

First place a Whatman No. 50 filter paper into a Buchner funnel. Next place the paste in the funnel and apply a vacuum. The filtration is finished when air starts to pass through the paper. Then add the sodium hexamethaphosphate solution to the filtrate (one drop per 25 ml of filtrate). This is to prevent precipitation of calcium carbonate.

The saturation percentage is the mass of water in the saturated paste expressed as a percentage of oven-dry mass of soil. To calculate the total water content, the mass of water in the air-dry soil is added to the mass of water which has been added to make the paste. The resulting figure should be expressed as mass of water per 100 g of oven dry soil.

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 287, Longmann, London.

***Sodium***

The same method as described earlier for measuring sodium content in irrigation water should be used. Dilute the saturation extract by 1000 and then multiply the resulting figure by 1000. Dilution is required because of the higher concentrations found in extracts.

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 287, Longmann, London.

***Calcium***

The same method as described earlier for measuring calcium in irrigation water should be used, although titrate 5 ml of extract and adjust the calculation accordingly.

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 287, Longmann, London.

***Chloride***

The same method as described earlier for measuring chloride in irrigation water should be used.

Reference: Methods of Soil Analysis, (1979) Chemical & Microbiological Properties, Monograph No. 9, Part 2, pg 947-948, American Society of Agronomy.

***Magnesium***

The same method as for determining magnesium content of irrigation water should be used. Titrate 5 ml of extract and adjust the calculation accordingly.

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 287, 286, Longmann, London.

### *Sodium Adsorption Ratio (SAR)*

The Sodium Adsorption Ratio (SAR) is worked out using the following equation:

$$\text{SAR} = \frac{[\text{Na}^+]}{\sqrt{\dfrac{[\text{Ca}^{2+}] + [\text{Mg}^{2+}]}{2}}}$$

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 287, Longmann, London.

### *Exchangeable Sodium Percentage (ESP) of soil directly*

Reagent: Alcoholic ammonium chloride, 1M. First dissolve 53.5 g $NH_4Cl$ in 300 ml of water and add 600 ml of ethanol (95% v/v). Then adjust the pH to 8.5/8.6, using concentrated ammonia solution and make up to 1 litre. This should then be stored in a stopped bottle to prevent access of $CO_2$.

The soil should then be leached to enable the leached sodium to be measured. First weigh 5 g of <2mm air dry soil into a 100 ml beaker, and add 20 ml of ammonium chloride solution. Next stir this and leave it to stand over night. Transfer the suspension to a filter funnel fitted with a Whatman No. 44 filter paper, which should be standing in a 250 ml volumetric flask. Next leach the soil with successive 25 ml volumes of ammonium chloride, allowing the funnel to drain between each addition. This should be continued until nearly 250 ml of filtrate has been collected. Make up to the mark with ammonium chloride. This extract is then used for determining sodium using the flame photometer as described earlier. (The funnel and suspension should be kept, as further tests need to be undertaken to determine Cation Exchange Capacity (CEC). A set of standards should be made up which have a concentration range of 0-10mg $Na^+$ per litre, and are made up in 1 M alcoholic ammonium chloride rather than water. Dilute the extract by 10 (pipette 10 ml into a 100 ml volumetric flask and make up to the mark with alcoholic ammonium chloride). Finally measure the concentration using a flame photometer to give the value for leached $Na^+$.

The soluble $Na^+$ is determined from the saturation extract (using the method described earlier for determining sodium content using the flame photometer).

Exchangeable sodium is found using the following equation:

$$\text{Exchangeable sodium} = \text{leached Na}^+ - \text{soluble Na}^+$$

The next step is to measure the Cation Exchange Capacity. Once the extract has been removed for determining leached sodium, place the funnel in a rack over a 250 ml beaker. Next the interior of the funnel, the soil and the paper should be washed with five 25 ml volumes of ethanol. These washings should then be discarded. This is to ensure that all of the ammonium ethanoate solution is removed. Then place the funnel in a 100 ml volumetric flask, and leach with successive 25 ml volumes of potassium chloride solution. This should be continued until nearly 100 ml has been collected and then make up to the mark.

To determine the cation exchange capacity, pipette 25 ml of the KCl extract into a distillation unit, distil it and then titrate it against 0.01 M HCL. This should also be expressed in terms of oven dry soil.

ESP is then determined using the following equation:

$$\text{ESP} = 100 \text{ x} \left( \frac{\text{Exchangeable Na}^+}{\text{CEC}} \right)$$

Reference: Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 289-290, Longmann, London.

***Soil salinity ($EC_e$)***

Electrical conductivity can be determined from the saturation extract using the same method as given for irrigation water.

***Potassium***

| | |
|---|---|
| Equipment: | Flame photometer<br>Potassium filter |

Potassium content of the saturation extract is determined using a flame photometer. As for sodium, it is necessary to prepare standard potassium solutions, 0-10 $\mu g \; K^+ \; ml^{-1}$. These are prepared as follows: First dry potassium nitrate, $KNO_3$, at 105°C for one hour and then cool it in a desiccator. Next dissolve 1.293 g in water in a 100 ml beaker and if the solution is going to be stored for a number of days then add 1 ml of hydrochloric acid (approx. 36% HCL) as a preservative. Next, transfer with washings to a 500 ml volumetric flask and make up to the mark. Pipette 10 ml of this solution into a 100 ml flask and make up to the mark using ethanoate solution. This will now contain 100 $\mu g \; K^+ ml^{-1}$. Pipette 0, 2, 4, 6, 8 and 10 ml of this solution into 100 ml flasks and make up to the mark with ammonium ethanoate solution. These contain 0, 2, 4, 6, 8 and 10 $\mu g K^+ \; ml^{-1}$. Read on a flame photometer after putting a $K^+$ filter in place. It is suggested that the extract is diluted by 1000 and then the resulting figure multiplied by 1000.

| | |
|---|---|
| Reference: | Rowell, D. L., (1994) Soil Science, Methods and Applications, pg 141, Longmann, London. |

***Trace elements***

Most of the trace elements can be measured using Atomic Absorption Spectrometry (AAS). The Varian 1475 Atomic Absorption Spectrometer consists of a slit burner, normally using an air-acetylene fuel mixture. A small sample of the solution is drawn through an atomiser which mixes it with air or nitrous oxide and is drawn into the flame. In the absorbance mode, the instrument measures the reduction in light intensity of a beam aligned through the flame and hitting a sensitive photomultiplier. This reduction in light penetration is inversely proportional to the concentration of an element in solution. The light derives from a hollow cathode tube which produces radiation at the wave length coincident with that of the element being atomised in the flame. In the Varian AAS, the relationship between known concentrations and the instrument reading is worked out by an internal computer which produces results directly in the concentration units required. The AAS is usually accurate to within 2% or better and once the machine is calibrated determination is rapid.

As trace element levels can change significantly over a short period of time and also due to changes in the temperature or sunlight, it is often required that they are tested for in the field. Hand held digital photometers can be purchased which are used in conjunction with manufactured reagent tablets.

***Soil texture and particle size analysis***

The classification of texture in terms of particle distribution is normally shown as a triangular diagram, the three variables being sand, silt and clay. (See Figure 4.1). These diagrams can be used to determine soil texture if particle size distribution is known.

Before particle size analysis is undertaken, it is necessary to first remove the organic matter. This is done by destroying the organic matter using hydrogen peroxide. The remaining soil is then dispersed using sodium hexametaphosphate, and analysed by sieving and sedimentation.

| | |
|---|---|
| Reagents: | Hydrogen peroxide: Transfer 200 ml of 100 vol $H_2O_2$ into a 1 litre measuring cylinder and then make up to the mark. (30g $H_2O_2$ per ml). As hydrogen peroxide is corrosive it is necessary to use gloves and safety glasses.<br>Octan-2-ol<br>Sodium hexametaphosphate:<br>Anhydrous sodium carbonate: |

Equipment: Sieves: 212 and 63 µm apertures, which should be mounted in 100 mm diameter frames. These should have a cover and a collecting pan.

The organic matter is destroyed as it hinders dispersion by binding mineral particles together. To do this, place 10 g of <2mm sieved air-dry soil in a 500 ml beaker. Next add to this 10 ml of $H_2O_2$ and a few drops of octan-2-ol (to reduce frothing). Once the frothing has ceased then add another 10 ml of $H_2O_2$. Once there is no reaction with fresh $H_2O_2$, then gently heat it over a low bunsen flame whilst adding further $H_2O_2$. (In total about 100 ml of the peroxide solution should have been used). Finally to complete the destruction of organic matter, raise the temperature to boiling and then leave to cool.

The next step is to disperse the soil. The dispersing agent is prepared by dissolving 50g of sodium hexametaphosphate and 7g of anhydrous sodium carbonate in water and then making it up to 1 litre. (This contains 0.57g of total reagent per 10 ml of solution). Next transfer the peroxide treated soil into a 500 ml bottle, by pouring the suspension through a funnel (the sides of the beaker should be washed with water, and if necessary, material should be dislodged from the sides of the beaker with a rod and transferred into the beaker). The next stage in the process is to shake the soil overnight on a mechanical shaker, hence the beaker should only be half full.

The next day, place a funnel in the top of the 500 ml measuring cylinder, and in that a 63 µm sieve. Transfer the contents of the shaking bottle through the sieve and wash the residue in the sieve with about 200 ml of water. Then transfer the residue into a 250 ml beaker, dry at 105°C and weigh. This should then be separated into coarse and fine sand by dry brushing the residue into a 212 µm sieve (which should be over a 63 µm sieve and a collecting pan). This should be covered and shaken for 15 minutes. Once finished, transfer the contents of each sieve into separate dry weighed beakers. Place these beakers into an oven at 105°C and then reweigh them. Any residue which has collected in the pan after shaking is therefore less than 63 µm. This fraction should then be washed back into the 500 ml measuring cylinder and made up to 500 ml. This resulting suspension therefore contains the silt and clay fractions.

Stir this suspension and then take a 20 ml sample from a depth of 15 to 20 cm using a pipette. Transfer this to a weighed dish or beaker, and dry at 105°C, cool in a desiccator and then reweigh. This then gives the mass of silt and clay in the 20 ml sample of suspension. Leave the suspension to settle for 8 hours and then take another 20 ml from the same depth (15 to 20 cm). This should be dried, cooled in a desiccator and reweighed (as above), to give the mass of clay in the 20 ml sample (In theory all the silt should have settled after this length of time).

### *Infiltration*

Infiltration is used to describe the process of water entry into the soil through the soil surface. The maximum rate at which water soaks into or is absorbed by the soil is termed the infiltration capacity. When infiltration is proceeding at less than the infiltration capacity, then the term infiltration rate is used.

Infiltration can be measured in the field using a double ring infiltrometer. First insert two concentric metal rings about two inches into the ground surface. The rings should have diameters of 300 mm and 600 mm respectively. Water should be applied to both rings at the same time to maintain the same of water in the outer annular compartment, as in the inner compartment. This is therefore forming a buffer area and is thus preventing the water from the inner ring spreading laterally below the ground surface. Place a gauge in the inner cylinder to measure the fall in water level in millimetres as water infiltrates into the soil. The time in minutes is also recorded as each water level measurement is taken. (The rate at which water must be applied to the inner ring to maintain a constant head of about one quarter of an inch is often taken to represent the infiltration rate).

Reference: R C Ward., (1967) Principles of Hydrology, Pg 193, McGraw-Hill
M Kay., (1986) Surface Irrigation, Systems and Practice, Pg 17, Cranfield Press.

### *Organochlorine pesticides*

Organochlorine pesticides are often found in water that has been affected by agricultural discharge.

The liquid-liquid extraction gas chromatographic procedure described below is suitable for quantitative determination of many pesticides, namely: BHC, Lindane, heptachlor, aldrin, heptachlor epoxide, dieldrin, endrin, captan, DDE, DDD, DDT, methoxychlor, endosulfan, dichloran, mirex, pentachloronitrobenzene.

Using the liquid-liquid gas chromatographic procedure the pesticides are extracted with a mixed solvent such as diethyl ether/hexane or methylene chloride/hexane. The extract is concentrated by evaporation (cleaned by column adsorption-chromatography if necessary) and then individual pesticides are determined by gas chromatography. As each component passes through an electronic detector a change in electrical signal is measured on a strip-chart recorder. The retention time is indicative of the particular pesticide and the concentration of the pesticide is proportional to its peak height. Whether a substance is detected or not is dependant upon many factors such as: detector sensitivity, extraction and cleanup efficiency and concentrations.

Detection levels are different for individual pesticides. Lindane for example, can usually be determined at 10 ng/l, whereas DDT is normally higher, at 20 to 25 ng/l.

The major pieces of equipment needed are a gas chromatograph equipped with a glass lined injection port, an electron-capture detector and recorder and a borosilicate glass column.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 6-101

### *Chlorinated phenoxy acid herbicides*

As these compounds have been found to have detrimental effects on human health it is essential that they are closely monitored in water supplies.

These herbicides can be determined using the gas chromatographic method, with a hydrolysis step included, as they often occur in water. The hydrolysis step is to allow determination of the active part of the herbicide.

Ethyl ether is used to extract chlorinated phenoxy acids and their esters from the acidified water sample. The extracts are then hydrolysed and a solvent wash is undertaken to remove any extraneous material. The acids are then converted to methyl esters, cleaned up on a micro-adsorption column, and then the methyl esters determined by gas chromatography (as described in the section on organochlorine pesticides).

The lower limits for measurement of phenoxy acid herbicides depend on the sample size and the method used. For example, if the extract from a 1 litre sample is concentrated to 2.00 ml and then 5.00 µl of concentrate is injected into the electron-capture gas chromatograph, measurements of 50 ng 2,4-D/l and 10 ng 2,4,5-T/l are feasible.

The main pieces of equipment are: evaporative concentrator, synder columns, separator funnels, and gas chromatographic system.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 6-116

### *Surfactants*

Surfactants enter waters and wastewaters mainly through the discharge of aqueous wastes from industries, households, and other such places where cleansing is involved.

Note: When testing for surfactant it is necessary to avoid formation of foam as surfactant concentration is higher in the foam phase than in the associated aqueous phase. If a foam does form prior to testing then it is essential to let it subside by standing and to then remix the liquid phase.

Surfactant separation by sublation is the recommended method for determining surfactant levels in water. Sublation isolates the surfactant from the dilute aqueous solution, and produces a dried residue relatively free of non-surfactant substances. The process begins by bubbling a stream of nitrogen up through a column containing a sample with an overlying layer of ethyl acetate. The surfactant is then absorbed at the water-gas interfaces of the bubbles and is carried into the ethyl acetate layer. The bubbles then enter the atmosphere leaving the surfactant dissolved in ethyl acetate. The solvent is then separated, dehydrated and evaporated to leave the surfactant in a state suitable for analysis.

At present the method described can reasonably accurately determine surfactant levels below 1 mg/l.

The major pieces of equipment needed are a sublator, gas washing bottle, funnel, filtration equipment and gas flowmeter.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 5-33.

### *Polychlorinated biphenyls (PCBs)*

Polychlorinated biphenyls are mainly found in water supplies that have been contaminated by transformer oils in which PCBs were originally used as a heat-exchange medium.

The liquid-liquid extraction (LLE) gas chromatographic (GC) method, described above for determination of organochlorine pesticides is also the recommended method for determining levels of PCBs. As the method has such a good sensitivity, both pesticides and PCBs can be measured simultaneously.

For a brief overview of the procedure see section on organochlorine pesticides.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:
Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 6-95/6-101

### *Organic nitrogen*

Organic nitrogen can be determined using the kjeldahl method which determines nitrogen in the trinegative state. It does not determine nitrogen in the form of azide, azine, azo, hydrazone, nitrite, nitrate, nitro and oxime.

The main characteristic of this process is that it produces ammonia nitrogen. In the presence of $H_2SO_4$, potassium sulphate ($K_2SO_4$), and mercuric sulphate ($HgSO_4$) catalyst, the amino nitrogen of most organic materials is converted to ammonium sulphate. Free ammonia and ammonium nitrogen are also converted to ammonium sulphate. During sample digestion, a mercury ammonium complex is formed and then decomposed by sodium thiosulphate ($Na_2S_2O_3$). After decomposition the ammonia is distilled from an alkaline medium and absorbed in boric or sulphuric acid. The ammonia can then be determined either colorimetrically or by titration with a standard mineral acid.

As colorimetric methods are very sensitive, they can determine organic nitrogen levels below 5 mg/l. The titrimetric and selective electrode methods for measuring ammonia in the distillate are suitable for determining a wide range or organic nitrogen concentrations.

The main pieces of equipment needed are: digestion apparatus, distillation apparatus and apparatus for ammonia determination.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 4-94

### *Nitrite*

Nitrite ($NO_2$-) can be determined by the formation of a red/purple dye if diazotized sulphanilamide is coupled with NED dihydrochloride at pH of between 2 and 2.5.

A spectrophotometer is then used - the range for measurements is 10 to 1000 µg $NO_2^-$-mol/l. (Note that photometric measurements can be made in the range 5 to 50 µg  mol/l if a 5 cm light path and green filter are used.

The main equipment needed is either a filter photometer or a spectrophotometer.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 4-85

### *Nitrate*

Determination of nitrate is difficult as it requires the undertaking of complex procedures. Nitrate can be determined by ion chromatography.  A water sample is injected into a stream of carbonate eluent and passed through a series of ion exchangers. The anions of interest are separated on the basis of their relative affinities for a low capacity, strongly basic anion exchanger. The separated anions are directed through a hollow fibre cation exchanger membrane (fibre suppresser) or micro-membrane suppresser bathed in continuously flowing strong acid solution (regenerant solution).  In the suppresser the separated anions are converted to their highly conductive acid forms and the carbonate-bicarbonate eluent is converted to weakly conductive carbonic acid. The separated anions in their acid forms are measured by conductivity. They are identified on the basis of retention time as compared to standards. Quantification is by measurement of peak area or peak height.

The main equipment required is an ion chromatograph, an anion separator column, guard column and fibre suppressor.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 4-88 / 4-1

### *Potassium*

Potassium ions can be measured potentiometrically by using a potassium ion-selective electrode and a double-junction, sleeve type reference electrode.  Potentials are measured with either a pH meter having an expanded millivolt scale capable of being read to the nearest 0.1 mV or a specific ion meter having a direct concentration scale for potassium.  The electrodes are calibrated with solutions of known potassium concentration and sample potassium concentration is determined in a solution with the same background.  Addition of an ionic strength adjustor to both standards and samples maintains constant background ionic strength.

Samples containing 0.1 to 1000 mg K/l may be analyzed.

The main equipment required is a pH meter or ion-selective meter, potassium ion-selective electrode. Sleeve-type double-junction reference electrode, pH electrode and a mixer.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 3-81

### *Phosphorus*

Phosphorus occurs in natural waters and in wastewaters as phosphates. These phosphates can be classified as orthophosphates, condensed phosphates and organically bound phosphates, and can occur in solution, in particles, or in the bodies of aquatic organisms.

The process is in two parts:

1) conversion of the phosphorus to dissolved orthophosphate

2) colorimetric determination of dissolved orthophosphate

Phosphates that respond to colorimetric tests without preliminary hydrolysis or oxidative digestion of the sample are termed "reactive phosphorus".

Because phosphorus may occur in combination with organic matter, a digestion method to determine total phosphorus must be able to oxidise organic matter effectively to release phosphorus as orthophosphate. After digestion, liberated orthophosphate can then be determined.

The sulphuric acid nitrific digestion method is recommend for most samples. For more information on this method see: Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 4-112

Once the sulphuric acid nitrific digestion process has been undertaken then the Vanadomoleybdophosphoric acid colorimetric method is suggested to determine orthophosphate. In a dilute orthophosphate, ammonium moleybdate reacts under acid conditions to form a heteroploy acid. In the presence of vanadium, yellow vanadomoleybdosphoric acid is formed. The intensity of the yellow colour is proportional to phosphate concentration.
The minimal detectable concentration is 200 µg P/l in 1cm spectrometer cells.

The main equipment required is either a spectrophotometer or a filter photometer.

For a complete list of necessary equipment, reagents, and a full explanation of the determination process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 4-12

### *Heavy metals*

For the determination of: antimony, bismuth, cadmium, calcium, cesium, chromium, cobalt, copper, gold, iridium, iron, lead, lithium, magnesium, manganese, nickel, palladium, platinum, potassium, rhodium, ruthenium, silver, sodium, strontium, thallium, tin and zinc, the direct air-acetylene flame method is recommended.

An atomic absorption spectrometer is needed, which has a light source such as a hollow-cathode lamp, a flame for vaporising the sample, a filter or slit for isolating an absorption line, and a photoelectric detector.

For a complete list of necessary equipment, reagents, and a full explanation of the process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 3-13

### *Coliform*

The faecal coliform test differentiates between coliforms of faecal origin and coliforms from other sources. The faecal coliform test (using EC medium) is applicable to tests of drinking water, stream pollution, raw water sources, wastewater treatment systems, bathing waters, seawaters and general water-quality monitoring. Once the faecal coliform test has been undertaken then a multiple tube procedure can be carried out to give the Most Probable Number (MPN) of organisms present, which is the mean density of coliforms in the sample. (It should be noted that the precision of the test is dependant on the number of tubes used).

The faecal coliform test:

The EC medium is:

| | |
|---|---|
| Tryptose or trypticase | 20.0 g |
| Lactose | 5.0 g |
| Bile salts mixture or bile salts No. 3 | 1.5 g |
| Diptassium hydrogen phosphate, $K_2HPO_4$ | 4.0 g |
| Potassium dihydrogen phosphate, $KH_2PO_4$ | 1.5 g |
| Sodium chloride, NaCl | 5.0 g |
| Regent-grade water | 1 L |

The procedure is to add the dehydrated ingredients to the water, mix, heat and then dispense into fermentation tubes. Next, if gas is produced with growth in an EC broth culture within 24 hours, then it is a positive faecal coliform reaction. On the other hand, if there is no gas produced then is assumed that the coliforms are from a source other that the intestinal tracts of warm blooded animals.

Coliform density in terms of the Most Probable Number (MPN) can be determined from MPN tables, which use the number of positive tubes in the multiple dilutions and are based on the Poisson distribution.

For further information and MPN tables refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 9-45 to 9-53

### *Nematodes*

Nematodes are aquatic animals which breed in slow sand filters and wastewater treatment plants. They ingest bacteria such as human enteric pathogens.

The method for diagnosing nematodes is to first take a sample of the water, then filter it, concentrate the sample, and then use a microscope for diagnosis.

For a complete list of necessary equipment, and a full explanation of the processing techniques, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 9-131

### *Biochemical oxygen demand (BOD)*

The oxygen demand of a sewage is roughly the amount of oxygen required to oxidise the various organic chemicals within it.

The basic principle is to fill an airtight bottle with the sample (to overflowing). The sample is then incubated for a five day period. It is necessary to measure dissolved oxygen before and after the incubation period. BOD can then be calculated from the difference between initial and final dissolved oxygen.

This measure is called the $BOD_5$ and is related to the amount of biodegradable organic matter contained in the sewage. (Note: in most references where the acronym BOD is used this refers to $BOD_5$ unless otherwise stated).

Units of BOD are mg/L and also a loading in $g/m^3/day$.

The main pieces of equipment required are incubation bottles and an air incubator or water bath.

For a complete list of necessary equipment, reagents, and a full explanation of the process, refer to:

Standard Methods for the Examination of Water and Wastewater, 18th Edition, Edited by A. E. Greenberg, L. S. Clesceri, and A. D. Eaton, 1992, pp 5-2

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