
SOUTH AFRICAN WATER QUALITY GUIDELINES
Volume 4: Agricultural Water Use: Irrigation
Second Edition, 1996

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South African Water Quality Guidelines

Volume 4 Agricultural Use: Irrigation

**Department of Water Affairs
and Forestry**

**Second Edition
1996**

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This volume is the fourth in a series of eight volumes comprising the South African Water Quality Guidelines.

Volume 1: South African Water Quality Guidelines -
Domestic Water Use

Volume 2: South African Water Quality Guidelines -
Recreational Water Use

Volume 3: South African Water Quality Guidelines -
Industrial Water Use

***Volume 4: South African Water Quality Guidelines -
Agricultural Water Use: Irrigation***

Volume 5: South African Water Quality Guidelines -
Agricultural Water Use: Livestock Watering

Volume 6: South African Water Quality Guidelines -
Agricultural Water Use: Aquaculture

Volume 7: South African Water Quality Guidelines -
Aquatic Ecosystems

Volume 8: South African Water Quality Guidelines -
Field Guide

Foreword

The Department of Water Affairs and Forestry is the custodian of South Africa's water resources. Part of its mission is to ensure that the quality of water resources remains fit for recognised water uses and that the viability of aquatic ecosystems are maintained and protected. These goals are achieved through complex water quality management systems which involve role players from several tiers of government, from the private sector and from civil society.

A common basis from which to derive water quality objectives is an essential requirement that enables all role players involved in such a complex system to act in harmony in order to achieve the overarching goal of maintaining the fitness of water for specific uses and to protect the health of aquatic ecosystems. For these reasons the Department initiated the development of the *South African Water Quality Guidelines*, of which this is the second edition. The *South African Water Quality Guidelines* serve as the primary source of information for determining the water quality requirements of different water uses and for the protection and maintenance of the health of aquatic ecosystems.

The process that followed and the wide variety of organizations and individuals involved in the development of these guidelines ensured the acceptance and use of these guidelines by all significant role players, as the *South African Water Quality Guidelines*. These guidelines are technical documents aimed at users with a basic level of expertise concerning water quality management. However, the role players involved in the different water use sectors are expected to use these guidelines as a basis for developing material to inform water users in specific sectors about water quality and to empower them to effectively participate in processes aimed at determining and meeting their water quality requirements.

The Department recognises that water quality guidelines are not static and will therefore update and modify the guidelines on a regular basis, as determined by ongoing research and review of local and international information on the effects of water quality on water uses and aquatic ecosystems. The process of developing water quality guidelines, and the involvement of key role players, is a continuing one. The second edition is published in a loose leaf, ring binder format to facilitate the regular updating of the guidelines. All those who want to comment on and make suggestions concerning the *South African Water Quality Guidelines* are invited to do so at any time by contacting the Director: Water Quality Management, Department of Water Affairs and Forestry, Private Bag X313, Pretoria 0001.

Finally I wish to express my sincere appreciation to all those who have been involved in the development of these guidelines. I also look forward to their continued involvement in maintaining one of the cornerstones of the water quality management system in South Africa.

Professor Kader Asmal **MP**
Minister Of Water Affairs and Forestry

May 1996

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We also wish to thank the many people who provided administrative, secretarial and financial support services during the development and production of this handbook.

Introduction

Scope and Purpose of the Water Quality Guidelines

Scope The *South African Water Quality Guidelines for Irrigation Water Use* is essentially a user needs specification of the quality of water required for different irrigation uses. It is intended to provide the information to make judgements on the fitness of water to be used for irrigation purposes, primarily for crop production. The guidelines are applicable to any water that is used for irrigation purposes, irrespective of its source (municipal supply, borehole, river, etc.) or whether or not it has been treated.

Purpose The *South African Water Quality Guidelines* are used by the Department of Water Affairs and Forestry as its primary source of information and decision-support to judge the fitness for use of water and for other water quality management purposes.

The *South African Water Quality Guidelines* contain similar information to that which is available in the international literature. However, the information provided in these guidelines is more detailed, and not only provides information on the ideal water quality for water uses, but in addition provides background information to help users of the guidelines make informed judgements about the fitness of water for use.

Users of the Guidelines The *South African Water Quality Guidelines* are being developed as an important information resource, primarily for water quality managers. Nevertheless, educators and other interested and affected members of the general public are likely to find them a valuable source of information for many aspects of water quality and its management.

Ongoing Review The *South African Water Quality Guidelines* will be periodically reviewed. The purpose of the reviews is to:

- ! Add guidelines for constituents not yet included in the guidelines.
- ! Update the guidelines for constituents currently included in the guidelines as relevant new information from international and local sources becomes available on the water quality or support information for water quality constituents.

The loose leaf/ring binder format of the guidelines, as well as the footnotes at the bottom of each page which clearly indicate the exact version of a guideline, have been designed to facilitate regular updating of the guidelines.

Overview The *South African Water Quality Guidelines for Irrigation Water Use* is divided into six chapters:

- ! Chapters 1 - 4 provide an introduction to the guidelines, define some important water quality concepts, explain how irrigation water use was characterised for the purpose of developing these guidelines, describe how the guidelines were developed and provide some guidance on how they should be used.
- ! Chapter 5 provides the actual guidelines for the different water quality constituents.
- ! Chapter 6 consists of appendices which provide additional support information.

Water Quality

Introduction To use the *South African Water Quality Guidelines* correctly, it is important for users of the guidelines to understand how water quality and some related concepts were defined.

Definition The term *water quality* describes the physical, chemical, biological and aesthetic properties of water that determine its fitness for a variety of uses and for the protection of aquatic ecosystems. Many of these properties are controlled or influenced by constituents which are either dissolved or suspended in water.

Constituents The term *constituent* is used generically in this edition of the *South African Water Quality Guidelines* for any of the properties of water and/or the substances suspended or dissolved in it. In the international and local literature, several other terms are also used to define the properties of water or for the substances dissolved or suspended in it, for example *water quality variable; characteristic and determinand*; etc.

Examples of constituents which are used to describe water quality are:

- ! The temperature of the water is 20 EC.
- ! The colour of the water is green.
- ! The concentration of calcium is 60 mg/R.
- ! Thirty percent of the surface of the water body is covered with water hyacinth.

Note that none of the statements of water quality states anything about how desirable or acceptable it is for water to have the properties listed. Therefore, in addition to such statements, one also needs to judge how desirable or acceptable water of such a quality would be for a particular water use or for maintaining the health of aquatic ecosystems before the fitness of water for use can be determined.

Water Quality Criteria *Water quality criteria* are scientific and technical information provided for a particular water quality constituent in the form of numerical data and/or narrative descriptions of its effects on the fitness of water for a particular use or on the health of aquatic ecosystems.

No Effect Range For each water quality constituent there is a No Effect Range. This is the range of concentrations or levels at which the presence of a particular constituent would have no known or anticipated adverse effects on the fitness of water for a particular use. These ranges were determined by assuming long-term continuous use.

Target Water Quality Range As a matter of policy, the Department of Water Affairs and Forestry (DWAF) strives to maintain the quality of South Africa's water resources such that they remain within the No Effect Range.

The DWAF encourages all stakeholders concerned with the quality of South Africa's water resources to join forces and aim to maintain water quality within the No Effect Range, where and whenever possible.

For this reason, the No Effect Range in the *South African Water Quality Guidelines* is referred to as the Target Water Quality Range (TWQR). It is included, and highlighted as such, in the water quality criteria provided for each of the constituents dealt with in the

guidelines.

Users of the *South African Water Quality Guidelines* should note that an important implication of setting the Target Water Quality Range equal to the No Effect Range is that it specifies good or ideal water quality, instead of water quality which is merely acceptable.

Water Quality Guidelines

A water quality guideline is a set of information provided for a specific water quality constituent. It consists of the water quality criteria, the Target Water Quality Range, and support information, such as the occurrence of the constituent in the aquatic environment, the norms used to assess its effects on water uses, how these effects may be mitigated and possible treatment options.

The *South African Water Quality Guidelines* consist of the guidelines for domestic, recreational, industrial and agricultural water (irrigation, livestock watering and aquaculture) uses, as well as guidelines for the protection of the health and integrity of aquatic ecosystems, and for the protection of the marine environment.

Fitness for use

Introduction

The Department of Water Affairs and Forestry is the custodian of South Africa's water resources. Part of its mission is to maintain the fitness for use of water on a sustained basis. The concept of fitness for use is therefore central to water quality management in South Africa and to the development and use of these guidelines.

Water Use

Four broad categories of water use are recognised in the South African Water Act, namely the use of water for

- ! domestic purposes;
- ! industrial purposes;
- ! agricultural purposes; and
- ! recreational purposes.

The DWAF's mandate also requires that the health of aquatic ecosystems be protected. The water quality requirements of these water uses and those for the protection of aquatic ecosystems form the basis on which the fitness for use of water is judged.

Characterisation of Water Uses

The broad water use categories listed above can each be subdivided into a number of subcategories. The subcategories of a particular water use can have quite different water quality requirements, hence the need to characterise water uses into subcategories or components and to specify water quality requirements at a subuse level.

The characterisation of water uses involves determining and describing those characteristics which will indicate its significance as well as those which dictate its water quality requirements, for example:

- ! The significance of each water use is determined by considering issues such as the volume of water used, the socio-economic benefits and costs associated with the use; and the nature of the use, i.e. whether it is consumptive or not, or whether it is abstractive or not.

- ! The water quality requirements of a water use are determined by considering:

- Typical water quality problems associated with a particular water use or the role that water quality plays in sustaining the use;
- The nature of the effects of poor water quality on the use;
- The norms which are commonly used as yardsticks to measure the effect of water quality on a particular water use;
- The water quality constituents which are generally of concern;
- Any other site- or case-specific characteristics of the water use which may influence its water quality requirements.

Fitness For Use The fitness for use of water, is a judgement of how suitable the quality of water is for its intended use or for protecting aquatic ecosystems.

To be able to make judgements about fitness for use, one needs to:

- ! characterise the water uses and/or a particular aquatic ecosystem from a water quality perspective;
- ! determine the quality requirements of the intended uses and/or that of an aquatic ecosystem;
- ! obtain information on the key constituents which determine the fitness of water for intended uses and/or that affect the integrity of aquatic ecosystems;
- ! establish how, and how much, the intended use or an aquatic ecosystem will be affected by the prevailing water quality; and
- ! determine whether the undesirable effects of water quality on a particular use can be mitigated against.

The fitness for use of water can range from being completely unfit for use to being 100 % or ideally fit for a specific use. Descriptions commonly used to express judgements about the fitness of water for use are:

- ! ideal; 100 % fit for use; desirable water quality; target water quality range;
- ! acceptable;
- ! tolerable, usually for a limited time period only;
- ! unacceptable for use; and
- ! completely unfit for use.

Effects and Norms Water quality can affect water uses or the health of aquatic ecosystems in many different ways. For example, it can affect the

- ! health of an individual drinking the water or swimming in it;
- ! productivity or yield of irrigated crops;
- ! cost of treating water before it can be used in an industrial process;
- ! sophistication of technology required to treat water to adequate quality; and
- ! biodiversity of aquatic ecosystems.

It is therefore necessary to use different norms, such as health effects; crop quality; cost of treatment; type and level of treatment technology; and the effects on biodiversity, as yardsticks for making judgements about the fitness for use of water.

Sustained use The sustained use of water is an important objective for agricultural development. The long-term sustainability of water uses was an important consideration in the development of the guidelines. For example, the water quality criteria for some constituents for irrigation use are based on the assumptions of water use of a given quality for long-term, intermediate,

and short-term periods.

The assumptions underlying the development of the guidelines must be taken into account, particularly when making judgements about the fitness of water required for short-term use only.

Approach to Guideline Development

Rationale, Approach and Methodology

Rationale Many different water quality criteria and guidelines have been published in the international and local literature. Different approaches and methodologies have often been used to derive criteria and guidelines, for example some guidelines specify maximum concentrations for constituents fit for use, whereas others attempt to define the ideal concentration of a constituent, often with the inclusion of safety factors. Therefore, depending on which guidelines or criteria are used to establish water quality requirements, one can arrive at answers which sometimes differ by a factor of a hundred or more.

The rationale for developing the *South African Water Quality Guidelines* was to:

- ! Develop a single set of guidelines and criteria that are appropriate for South Africa, and that are based on a consensus of South African expertise and other role players in water quality. One of the intentions of this approach was to limit the confusion that often arises from the use of different criteria and guidelines to establish the water quality requirements for a particular water use by the stakeholders of water supply and utilization in South Africa;
- ! Modify international guidelines in the light of local research and experience.

Approach The approach used to develop the *South African Water Quality Guidelines* for irrigation use was that the guidelines should as far as is practically possible serve as a stand-alone source of information and support base for decisions for water resource managers to make judgements about the fitness for use of water used for different irrigation purposes. It is accepted that, in many cases, the user will also have to consult different sources or obtain expert opinion before reaching a final conclusion as to the fitness of water for use. However, the guidelines should in these cases at least indicate to the users what kinds of information to look for.

Therefore, the guidelines developed consist not only of the water quality criteria for a specific constituent, but also include a substantial amount of information to support the user of the guidelines in making judgements about the fitness of water for irrigation use.

In order to decide what information to include in the *South African Water Quality Guidelines* an analysis was done of the DWAF's different water quality management processes. Those that required the guidelines to be used as a source of information and/or "decision-support" were identified and their typical information needs determined. The product specification of the *South African Water Quality Guidelines*, delineating the information requirements of the guidelines was provided to the technical teams responsible for the development of the guidelines.

Methodology The methods used to develop irrigation water quality guidelines for South Africa consisted of:

- ! Listing the various purposes for which irrigation water is used;
- ! Describing, for each water use, the water quality related problems or issues typically experienced in South Africa;

- ! Determining, for each water quality problem or issue, the appropriate norms to be used as yardsticks for assessing the effects of water quality on a particular use;
- ! Determining, for each norm, which water quality constituents in South Africa typically affect the fitness of water for use, and from this information, developing a list of constituents for the irrigation guidelines;
- ! Accessing international and local sources of information and expertise to develop draft guidelines for each constituent selected;
- ! Through a process of technical review and stakeholder participation finalise the guidelines as published in this edition.

Tentative Guidelines

The information available on the effects of some constituents on water uses is either very limited and/or unresolved differences in opinion exist on the effects these constituents may have on water uses. In these cases the guidelines have been included as tentative guidelines, and are clearly indicated as such.

During the ongoing review of the guidelines, it is intended that the status of the tentative guidelines eventually be changed to standard guidelines, when either sufficient information becomes available or sufficient consensus is reached concerning the effects of these constituents on water uses.

Sources of Information Used to Develop the Guidelines

Introduction

Because the *South African Water Quality Guidelines* are primarily aimed at South African water resource managers and water users, a greater emphasis was given to South African source documents. Opinions of a wide range of South African experts in water quality and water treatment, were used to supplement published sources. Due to the paucity of South African source documents, for some constituents international literature was also used as background and reference material.

Sources of Information

South African experts in water quality and water treatment were consulted during the development of the guidelines. The following criteria and guidelines published in the international literature were used as background and supplementary information in the development of the *South African Water Quality Guidelines* for irrigation use:

- ! ASCE Publication on Agricultural Salinity Assessment and Management (Tanjii, 1990)
- ! Australian Water Quality Guidelines for Irrigation Water Supplies (Hart, 1974; Hart *et al*, 1992)
- ! Canadian Irrigation Water Guidelines (Canadian Guidelines, 1987)
- ! FAO's Guide for Evaluating the Suitability of Water for Irrigation (Ayers and Westcott, 1985)
- ! USA Quality Criteria for Irrigation Water (US EPA, 1973)
- ! USDA Handbook on Diagnosis and Improvement of Saline and Alkali Soils (US Salinity Laboratory Staff, 1954)

The following criteria and guidelines published in the South African literature were used in the development of the SA Water Quality Guidelines for irrigation use:

- ! Department of Water Affairs and Forestry Guidelines for Irrigation Water Quality (Department of Water Affairs and Forestry, 1993)

Characterisation of Irrigation Water Use

Background Information

Introduction Irrigated agriculture is the largest consumer of available water in South Africa. Its importance as a water user has decreased dramatically from 80 % of available water resources 25 years ago, to the present level of 50 %. This trend will continue in future, and irrigators will experience increasing pressure to use less water. Since many irrigation schemes are situated at the lower end of drainage basins, they are often at the receiving end of upstream water quality degradation activities. It is therefore likely that many irrigation farmers will, in the future, have to contend with both deteriorating quality and a diminishing supply of irrigation water. The term irrigation water, as used in these guidelines, refers to water which is used to supply the water requirements of crops and plants which are not provided for by rain, and refers to all uses water may be put to in this environment. This includes water for

- ! the production of commercial crops;
- ! irrigation water application and distribution systems;
- ! home gardening;
- ! the production of commercial floricultural crops; and
- ! potted plants.

As irrigation water is used to supply the water requirements of a wide variety of plants, under widely varying degrees of intensification, with a range of different distribution and application systems, to a wide range of soils over all climatic ranges in South Africa, a wide spectrum of problems may be encountered where water does not meet requirements.

Sources of Water Water supplies for irrigation may originate from large reservoirs, farm dams, rivers, ground water, municipal supplies and industrial effluent. As such, irrigation water supplies span a wide range. On irrigation schemes, irrigators mostly rely on an adequate supply of fairly good water quality from untreated water, while home gardeners mostly receive a supply of conventionally treated water of high quality. The quality and quantity of water from rivers is highly variable, and is due to seasonal droughts or floods. The quality of ground water also varies greatly.

Water Quality Problems Irrigation water users may experience a range of impacts as a result of changes in water quality. These may be categorised as follows:

- ! reduced crop yield (as a result of increased salinity or the presence of constituents that are toxic to plants);
- ! impaired crop quality (this may result in inferior products or pose a health risk to consumers);
- ! impairment of soil suitability (as a result of the degradation of soil properties and accumulation of undesirable constituents or toxic constituents); and
- ! damage to irrigation equipment (corrosion or encrustation).

Constituents

The water quality problems and issues listed above can often be linked to the constituents that cause them. Some water quality problems are associated not only with the presence of a constituent, but with the interactions between constituents, for example, infiltration of water into the soil which is affected by both the sodium adsorption ratio and the total dissolved solids of the water.

Information Contained in the Guidelines

Overview

The information contained in a guideline for a particular constituent is organised in three sections.

- ! Background information. This section contains most of the support information required to make judgements about the fitness of water for use.
- ! Information on the effects of the constituent, the criteria, and the conditions for modification of the criteria.
- ! Information on additional sources of information.

The information in each section of a guideline for a constituent is organised under a series of labels in the left hand margin that identifies the type of information, and can assist users of the guidelines to quickly locate the information required.

Background Information

- | | |
|----------------------------|---|
| Introduction | The introduction to the guideline for each constituent includes a brief description of the constituent as well as a brief statement of its significance for irrigation water uses. |
| Occurrence | Information on the fate and occurrence of a constituent in the aquatic environment, as well as the natural and man-made sources thereof, are provided as background information to help the user to determine how widely, in what chemical and physical form and under what circumstances the constituent is likely to occur. |
| Interactions | The effects of a water quality constituent on the fitness of water for use can sometimes be significantly modified by its reaction with the irrigated soil and by synergistic or antagonistic effects caused by the presence or absence of other constituents in the water. These effects are described in the guideline and should be considered when making judgements about the fitness of water for use. |
| Measurement | The effect of many constituents on water uses depends on the state (dissolved or particulate) and the chemical species (oxidised or reduced) in which they occur. It is important for users of the guidelines to understand how measurements of the concentrations of constituents in water are obtained and which methodologies to use. |
| Data Interpretation | <p>The effects of water quality constituents on water uses vary from acute to chronic. In order to make judgements about the fitness of water for use, it is important that the appropriate statistics, depending on the types of effects that are likely, be estimated from data sets.</p> <p>For example, if the type of effect is acute, then statistics which estimate extreme values, such as maximal values, should be used to compare with the water quality criteria provided. However, if the effects are mostly chronic, then estimates of the average, such as the mean or median value, should be used.</p> |
| Treatment | There are a large variety of options, or combinations of options, to |

Options

- ! Improve, with the use of various treatments, the quality of raw water supplied to water users;
- ! Improve, with the use of various treatments, the quality of water on site, by the users themselves. For example, the filtering of raw water drawn from a river before using it for drip irrigation.

The information provided in the guidelines on treatment is very general and is simply provided to give a first indication of whether management intervention in the form of treatment is possible. It is expected that, if water treatment is to be pursued, the user will obtain expert advice.

The cost of, and the ease with which management interventions can be implemented are important factors which can influence judgements about the fitness of water for use. The feasibility of intervention depends on the

- ! availability of technological solutions;
- ! social acceptance;
- ! scale of the intervention;
- ! availability of institutional capacity to implement and sustain interventions;
- ! availability of suitably qualified people to implement and maintain interventions; and
- ! capital and operating costs of implementing the intervention; these are mostly too high to treat water intended for irrigation purposes.

The Effects of a Constituent

Norms

The norms that were used as yardsticks for assessing the effects of a particular water quality constituent on the fitness for use are described in this section of the guideline.

Effects

Water quality has different types of effects on specific water uses, for example, these effects can range from

- ! acute to chronic;
- ! reversible to irreversible;
- ! recoverable to irrecoverable.

In order to make informed judgements of the fitness of water for use, it is important that users of the guidelines take into account the information provided on the types of effects to be expected.

As a result of the hydrological characteristics of South African rivers, flow and consequently water quality, can be highly variable. The effects of water quality on water uses often depends on the duration of exposure to water of a given quality. Therefore, users of the guidelines must also consider information on the likely duration of the exposure to water of particular quality when judging the fitness of water for use.

Although the importance of soil characteristics (and their interaction with water characteristics) in determining the suitability of water for irrigation is recognised, the emphasis in these guidelines is placed on water characteristics. In order to concentrate mainly on water characteristics, it is necessary to make the assumption that suitable soils will be irrigated. The user of this document should therefore account for soil properties that determine sustainable use; as they are major considerations in the assessment of irrigability. For example, adequate internal drainage (natural or artificial), enables the leaching of salt from the soil profile and prevents the formation of elevated water tables. It is mostly

possible (although not necessarily economical) to modify shortcomings of a soil type so that it can be irrigated on a sustained basis. The question of soil irrigability is thus often reduced primarily to a question of economic feasibility, that concern the implementation of management of modifications. Although the guidelines concentrate on water, rather than soil, characteristics that determine irrigation water quality, they also consider (where necessary) the interactions between water and inherent, difficult-to-modify soil properties, such as, texture and clay mineralogy.

Balanced and adequate plant nutrition, pest control and other sound agronomic practices play a major role in determining the yield and quality of crops produced under irrigation. Another underlying assumption of the guidelines is that agronomic appropriate practices will be employed under prevailing conditions.

Climate plays an important role in the effects of irrigation water quality. It determines *inter alia* the crop water demand (the more water applied during an irrigation season, the sooner a dynamic equilibrium between soil and water constituents is established) and the degree to which irrigation water applications are diluted by rain.

Users of the guidelines need to take account of these environmental factors and interactions with other constituents when deciding on the fitness of water for use.

Mitigation

The undesirable effects of water quality on its fitness for a specific use can often be prevented or mitigated against by on-farm management interventions during use, or at the point of use. For example, these interventions may include larger-than-required irrigation applications to prevent the accumulation of salts in soil or by switching to a crop that is more tolerant of a particular constituent. The user of the guidelines is provided with relevant information on the availability of options for intervention, and the feasibility of implementing such interventions for making judgements about the fitness of water for use.

The information on mitigation in the guidelines is very general and is simply provided to give the user of the guidelines a first indication of whether management intervention is possible. It is expected that, if any options are to be pursued, the user will obtain expert advice.

Criteria

The water quality criteria for most of the constituents are provided in the form of tables, describing the effects of increasing concentrations of the constituents. The No Effect Range, designated in the *South African Water Quality Guidelines* as the Target Water Quality Range, is highlighted. It must be remembered that the Target Water Quality Range describes essentially what is considered good or ideal water quality and therefore water quality outside of this range may, under certain circumstances, still be acceptable.

Modifications

There are many site- and case-specific factors which modify the effects of water quality on specific water uses. Examples of such site- or case-specific factors are

- ! Soil salinity tolerance of crops; these may vary significantly.

- ! The limit placed on the heavy metal content of water in order to protect humans and animals does not apply to the irrigation of ornamental plants.

It is important that the information on site- and case-specific modifications be considered when making judgements about the fitness of water for use.

The information on modifications provided in the guidelines is very general and is simply provided to give the user a first indication of whether the criteria for a constituent may, in certain cases be modified. It is expected that, if the criteria need to be modified, the user of the guidelines obtain expert advice.

Sources of Information

It was simply not possible to either include all the constituents which may possibly affect the fitness of water for irrigation use, or to include all the relevant information on the constituents for which guidelines have been developed thus far.

The user is therefore referred to additional sources of information for each constituent. These same sources of information may in some cases also provide information on constituents which are not yet included in the *South African Water Quality Guidelines*.

Should the user of the guidelines require additional information it must be remembered that, besides the publications referenced in the guidelines, there is also a wealth of unpublished information available from a number of organisations and individuals in South Africa. The list of acknowledgements of people and organisations who participated in the development of the guidelines is a good starting point for accessing further information.

Chapter 5

Water Quality Constituents

Aluminium

Tentative Guideline

Background Information

Introduction Pure aluminium is a silvery-white, soft, light metal, resistant to corrosion by the formation of a thin protective layer of the oxide of aluminium. Aluminium does not appear to be an essential nutrient for humans and is for practical purposes non-toxic.

Occurrence Aluminium is the most common metal in the earth's crust, having an abundance of 81 g/kg. Aluminium does not occur in the elemental form, but its minerals, particularly the silicates of aluminium, are very widespread. Some important minerals containing aluminium are bauxite (hydrated aluminium oxide), spinel (magnesium aluminium oxide) and the kaolins (various aluminium silicates).

Aluminium occurs in water in two main phases, either as suspended aluminium minerals or as dissolved aluminium species. Aluminium occurs as a hydrated Al(III) cation, it hydrolyses and precipitates as insoluble aluminium hydroxide around neutral pH. The concentration of dissolved aluminium in unpolluted water at neutral pH is 0.005 mg/l or less. In acidic waters, or where soluble aluminium complexes are present, the dissolved aluminium concentration may be significantly higher.

Interactions Aluminium is one of the macro soil constituents. Upon being applied to the soil, the aluminium in the irrigation water mixes with the aluminium in the dissolved phase in the soil, which in turn is in dynamic equilibrium with aluminium in other phases. The concentration of aluminium in solution is largely determined by soil pH.

As a result of the enhanced solubility of aluminium oxides and the destruction of clay minerals and other aluminium silicates, the concentration of soluble aluminium in the soil solution increases as soil pH decreases. Consequently, the effect of aluminium on the productivity of plants is well correlated with soil pH. In acid soils (soil pH (water) less than 5.5) crop productivity is low. Aluminium precipitates in more alkaline soils (soil pH (water) higher than 7.0), thereby eliminating its toxic effects on plant productivity.

Freshly precipitated aluminium has a large capacity to fix phosphate fertilizers, rendering them unavailable to plants; it is one of the major plant nutritional problems experienced with acid ferralitic soils in South Africa.

Measurement The criteria refer to the dissolved aluminium concentration, i.e. aluminium which passes through a 0.45 µm membrane filter. The reference method for determining the concentration of aluminium is atomic absorption spectrometry using a nitrous oxide flame and addition of potassium as an ionisation suppressant. If other methods are used, such as colorimetric methods, their characteristics relative to the reference method should be known.

If total aluminium (the dissolved plus suspended fraction) is measured, the sample should be acidified before filtration. A vigorous digestion step is required since the acidification step will only dissolve species such as aluminium hydroxide and not aluminium silicate minerals.

Data Since aluminium is one of the macro soil constituents and its concentrations in soil solution

Interpretation are determined primarily by soil pH and soil aeration (determining the oxidation state, and thus solubility, of aluminium), it is uncertain whether its addition through irrigation water will have a significant additional effect on crop growth for normal soils. International guidelines for the concentration of aluminium in irrigation water have nonetheless been calculated in a manner similar to other trace elements.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The aluminium concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that aluminium does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The aluminium concentration that can be applied to *fine textured neutral to alkaline soils for a period of not more than 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that aluminium can be economically removed from water intended for irrigation use.* However, should it be required, the technologies available for removing aluminium from water include:

- ! The formation and precipitation of insoluble aluminium salts. Aluminium ions will react with alkalinity in the water to form aluminium hydroxide which is insoluble in the pH range of 6.7 - 7.6. The particles formed are very light and difficult to settle without the addition of a polyelectrolyte to flocculate and increase the specific gravity of the particles. An alternative is to dose the water with a phosphate solution and remove the aluminium as insoluble aluminium phosphate. High concentrations of aluminium in water can be reduced significantly by increasing the pH with a suitable alkali (mostly lime) and removing the aluminium hydroxide precipitate as a sludge.
- ! Substitution of aluminium with sodium in a cation exchange column along with calcium and magnesium.
- ! Removal of aluminium together with other dissolved components using desalination techniques such as demineralisation by ion exchange, membrane processes or distillation methods.

All of the methods described require skilled monitoring and control and generate a concentrated waste stream that may cause disposal difficulties.

The Effects of Aluminium

Norms The different norms used in the guideline to assess the effects of aluminium on irrigation water use are summarised in the tables that follows.

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to aluminium uptake through plant roots.
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected.
Maintenance of irrigation equipment	! No known effects

Effects

Aluminium is not a plant nutrient. Toxicity of aluminium to plants has been reported for both acid and alkaline conditions. It is, however, mostly associated with low pH values (less than 5.5) in natural soils. In nutrient solutions toxicities have been reported for a number of plants at a concentration range of 0.1 - 1.0 mg/R. Aluminium toxicity has been observed at concentrations range of 0.1 - 0.5 mg/R in soil solution. These values cannot be extrapolated directly to irrigation waters, because soil chemical interactions modify the aluminium concentration and species found in soil solution.

Mitigation

Common on-farm management practices to mitigate against uptake by plants on irrigated land, are to:

- ! Apply agricultural lime in order to raise (or maintain) soil pH at neutral to slightly alkaline values. This reduces aluminium concentrations to levels tolerated by most plants.
- ! Ensure that soil is well aerated and not waterlogged (the solubility of aluminium increases under reducing conditions such as those found in waterlogged soils).
- ! Switch to crops that are more tolerant of aluminium.

Criteria

Effects of Aluminium on Crop Yield and Quality

Concentration Range (mg/R)	Crop Yield and Crop Quality
<i>Target Water Quality Range # 5.0</i>	<i>Several crops show aluminium toxicity at concentrations as low as 0.1 - 0.5 mg/R in soil solution. Soils have the capacity to adsorb complex aluminium ions, thereby reducing their toxicity to plants</i>
5 - 20	Maximum acceptable concentration for fine textured, neutral to alkaline soils
> 20	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soils and the concentration range for fine textured neutral to alkaline soils are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.

Modifications

- ! The criteria given above may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods), because it is assumed that soil has a capacity to deactivate aluminium.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are grown for only limited periods the criteria for fine-textured neutral to alkaline soils are applicable.

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Arsenic

Tentative Guideline

Background Information

Introduction Arsenic is a greyish semi-metal and occurs in three oxidation states, namely (0), (III) and (V). In solution arsenic can exist as arsenite, As(III); arsenate, As(V); and as various organic complexes. Inorganic arsenates form arsenate salts with cations of calcium or iron. Soluble arsenic compounds are readily taken up by living organisms and at elevated concentrations can exert toxic effects.

Plants respond to the arsenic concentration in the soil solution. Similar to most trace elements, arsenic is strongly adsorbed by soil. The addition of arsenic to soils in relatively high concentrations over the short-term may not result in reduced crop growth or in its accumulation in plant parts to concentrations detrimental to humans or animals. However, continuous applications of arsenic over extended periods results in its accumulation in the surface soil layer, in practice, the cultivated or plough layer.

Occurrence Arsenic is fairly widespread in the environment, the average concentration in the earth's crust being approximately 2 mg/kg. It is found as arsenates, with sulphides and in association with many other metallic ores and occasionally in the elemental form.

Typically, the concentration of arsenic in fresh water is less than 1 Fg/R and in sea water, approximately 4 Fg/R. Elevated concentrations of arsenic occur where there is pollution from industrial sources, or where geological outcrops of arsenic minerals occur. For example, new borehole water supplies in areas where arsenic minerals are known to occur should be tested for arsenic content.

Arsenic is used in metallurgy, in the manufacture of glassware and ceramics, and as a pesticide and wood preservative.

Interactions Elevated concentrations of arsenic can occur in agricultural soils, due to previous use of organo-arsenic pesticides that persist as long-lasting residues in the soil. Arsenic concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex, and by coprecipitation with metal oxides. Sorption dominates at the relatively low concentrations that are of concern for water quality criteria for irrigation use.

Only a small fraction of the total arsenic present in soil is available to plants. Arsenic is present primarily in the arsenate ((As)V) and arsenite ((As)III) forms in soil. Both these forms are subject to chemically and/or microbiologically mediated oxidation-reduction and methylation reactions in soil. Soils have a high capacity to reduce the toxicity of dissolved arsenic through adsorption to clay and through the chemical speciation of arsenic as a result of reactions with phosphorus. The higher the clay content the more arsenic is adsorbed.

Soil pH affects the concentration of arsenic in the soil solution; solubility decreases with increasing pH. At high pH values, in the presence of calcium or magnesium, oxy-anions of arsenic are precipitated from solution.

Implications for irrigation with water containing arsenic, involve the following:

- ! Arsenic can be expected to be retained in the soil surface layers because of strong sorption by the soil exchange complex; in cultivated land it accumulates in the plough layer.
- ! Significant downward movement to below the plough layer and hence contamination of ground water with arsenic is unlikely.
- ! The larger the soil's cation exchange capacity (determined by clay content and clay mineral type), the more arsenic can generally be sorbed.
- ! Soils with a neutral to alkaline pH are able to accept a greater arsenic load than acidic soils before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the total arsenic concentration in units of mg/R. The reference method for the determination of arsenic is atomic absorption spectrometry with hydride generation. The various forms of arsenic are converted to As(V) in an acid digestion and then reduced to As(III), prior to the generation of arsine gas with borohydride. If other methods are used to measure arsenic, their characteristics relative to the reference method should be known.

Data Interpretation Because arsenic is retained by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions is reached. In order to prevent its accumulation, the total load applied to soil needs to be limited. International criteria for the concentration of arsenic in irrigation water have been calculated (using limited available information) to ensure that it does not accumulate to either phytotoxic levels or levels that are toxic to consumers, within a given time period. The calculations assume that arsenic accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality have been accounted for.

The *arithmetic mean concentration* of the applied water (preferably application volume weighted) is given in the criteria for:

- ! the arsenic concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that arsenic does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! the arsenic concentration that can be applied to *fine textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that arsenic can be economically removed from water intended for irrigation use.* However, should removal of arsenic be required, it can be most effectively removed in its pentavalent form. Trivalent arsenic is first converted to the pentavalent form using an appropriate oxidising agent such as chlorine or potassium permanganate. Pentavalent arsenic is effectively removed from water using conventional coagulation and flocculation processes followed by settlement and filtration. Suitable coagulants include aluminium sulphate, ferric salts and lime. The process requires monitoring to ensure the arsenic is effectively removed. The process will also generate a watery sludge rich in arsenic, that may present disposal problems.

The Effects of Arsenic

Norms The different norms used in the guideline to assess the effects of arsenic on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<p>! Crop yield as affected by crop sensitivity to arsenic element uptake through plant roots</p> <p>! Crop quality as determined by toxicity to consumers</p>
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects Although very low concentrations of arsenic stimulate plant growth, it is not an essential plant nutrient and crop yields are depressed at high concentrations. The main effect of arsenic in plants appears to be the destruction of chlorophyll in the foliage, as a consequence of inhibition of reductase enzymes. Since arsenic is toxic to humans, consumption of edible plant parts containing accumulated arsenic is dangerous.

Nutrient concentrations of 0.5 - 10 mg/R have been found to be toxic to various plant species. Potatoes and radishes have been shown to accumulate arsenic. Since plant growth is retarded before significant accumulation may occur, the edible parts of plants do not usually accumulate arsenic to levels dangerous to consumers. Yield decreases and crop failures are the most common effects of high arsenic concentrations in soils.

Mitigation

- ! The only effective management practice for soils with toxic concentrations of arsenic is to switch to more tolerant crops.
- ! A precautionary on-farm practice is to irrigate only soils with a high sorptive capacity (mainly soils with a high clay content). This will not always be feasible, as clay soils may not be available and may also have other undesirable characteristics, such as poor drainage.

Criteria

Effects of Arsenic on Crop Yield and Quality

Concentration Range (mg/R)	Crop Yield	Crop Quality
<i>Target Water Quality Range # 0.1</i>	<i>Depending on plant species, nutrient solutions containing 0.5 - 10 mg/R can induce arsenic toxicity. Only a fraction of the total arsenic in soil is available to plants</i>	<i>Yield reduction and crop failure are the main effects of arsenic contaminated soils. Generally arsenic does not accumulate in edible parts of plants to levels that are dangerous to consumers (root crops such as potatoes and radishes have been shown to concentrate arsenic)</i>
0.10 - 2.0	Maximum concentration acceptable for fine-textured neutral to alkaline soils	
> 2.0	Acceptable for irrigation only over the short term on a site-specific basis	

Note:

- ! The TWQR and the concentration range given for fine-textured neutral to alkaline soils is similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! The criteria assume that the soil to be irrigated contains only negligible amounts of arsenic. Should this not be the case, the period of irrigation needs to be reduced accordingly.
- ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because it is assumed that soil has a capacity to deactivate arsenic.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils generally applies.
- ! Rice on flooded soils is extremely sensitive to small amounts of arsenic. The maximum acceptable limit may be too high.

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Beryllium

Tentative Guideline

Background Information

Introduction Beryllium is a very light, greyish metal. Plants respond to the beryllium concentration in the soil solution. Similar to most trace elements, beryllium is strongly adsorbed by soil. Addition to soils in relatively high concentrations, over the short term, may not result in reduced crop growth, or may not concentrate beryllium in plant parts to a level detrimental to human or animal consumption. However, continuous application to the soil over extended periods results in its accumulation in the surface soil layer, in practice, the cultivated or plough layer.

Occurrence Beryllium is found in various silicate and oxide minerals, the most abundant of which is beryl, a beryllium aluminium silicate. Typically, the beryllium concentration in

- ! unpolluted waters is around 0.3 µg/l;
- ! in sea water is in the mg/l range; and
- ! in surface waters is in the µg/l range. Higher concentrations can occur in association with mining or industrial activities.

Beryllium silicates and carbonates are insoluble in water and bind to sediments. The natural silicate concentration of most waters will tend to limit the beryllium concentration in solution.

Beryllium metal is used in X-ray equipment. Beryllium salts are used in electrical equipment, in various alloys, in optical glasses, in ceramics, in the nuclear industry and in the plating industry.

Interactions Beryllium concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex. Sorption reactions dominate at the relatively low concentrations that are of concern for water quality criteria for irrigation.

Soil pH affects the concentration of beryllium in the soil solution; solubility decreases with increasing pH. Beryllium also associates with silicates and adsorbs onto the aluminosilicates in clay particles.

The implications for irrigation with water containing beryllium include the following:

- ! Beryllium can be expected to be retained in the soil surface layers because of its strong sorption by the soil exchange complex. In cultivated land it accumulates in the plough layer.
- ! Significant downward movement to below the plough layer and hence contamination of ground water with beryllium, is highly unlikely.
- ! The larger the soil's cation exchange capacity (determined by clay content and clay mineral type), the more beryllium can generally be sorbed.
- ! Soils with a neutral to alkaline pH will be able to accept a greater beryllium load than

acidic soils before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the total beryllium concentration, in units of mg/R. The reference method for the determination of beryllium is inductively-coupled plasma emission spectrometry. Where other methods are used, their characteristics relative to the reference method should be known.

Data Interpretation Because beryllium is retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions is reached. In order to prevent its accumulation, the total load applied to soil needs to be limited. International criteria for the concentration of beryllium in irrigation water have been calculated (using limited available information) to ensure that accumulation to either phytotoxic levels or levels toxic to consumers within a given time period does not occur. The calculations assume that beryllium accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality have been accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! the beryllium concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that beryllium does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! the beryllium concentration that can be applied to *fine textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a. The arithmetic mean concentration of the applied water (preferably application volume weighted) is used for this purpose.

Treatment Options *It is highly unlikely that beryllium can be removed economically from water intended for irrigation use.* However, should it be required, beryllium is commonly removed from water using an oxidising process which converts the beryllium into an insoluble oxide removable by filtration. The reaction is considerably more difficult to achieve than that with iron and normally requires the use of a strong oxidising agent. Agents commonly used include

- ! chlorine
- ! hydrogen peroxide
- ! potassium permanganate
- ! ozone

Where the oxidant used leaves a residue, as is the case with chlorine, the residue should be removed before the water is used.

Removal of beryllium is difficult to achieve on a small scale, but some removal will be obtained by adding sodium hypochlorite (bleach) to the water. On an industrial scale the process usually needs to be closely controlled and monitored, because the consequences of incomplete treatment may be severe.

The Effects of Beryllium

Norms

The different norms used in the guideline to assess the effects of beryllium on irrigation water use are summarised below.

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to beryllium uptake through plant roots ! ! Crop quality as determined by beryllium toxicity to consumers
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects

Beryllium is not a plant nutrient and is in fact, even at low concentrations, toxic to both plants and animals. Its toxicity to plants varies widely, ranging from 0.5 mg/R for bush beans to 5 mg/R for kale in nutrient solutions. Beryllium is not readily translocated from the roots to the foliage of plants growing in either soil or nutrient solutions. Therefore, it usually does not accumulate to toxic levels in foliage and other plant parts above the ground.

Mitigation

Common on-farm management practices to mitigate against beryllium uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline, and/or
- ! switch to a crop that is more tolerant to beryllium.

Criteria

Effects of Beryllium on Crop Yield

Concentration Range (mg/R)	Crop Yield and Quality
<i>Target Water Quality Range # 0.10</i>	<i>Beryllium is toxic to both plants and animals. Its toxicity to plants varies greatly. It is not readily translocated from the roots to foliage</i>
0.10 - 0.5	Maximum of range, acceptable as concentration for fine textured neutral to alkaline soils
> 0.5	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR given for relatively unrestricted use on all soils and the concentration range for fine textured and neutral to alkaline soils for irrigation periods of up to

20 years, is similar to most international criteria.

- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! The criteria were derived with the assumption that the soil to be irrigated contains only negligible quantities of beryllium. Should this not be the case, the period of irrigation needs to be reduced accordingly.
- ! The above criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods), because it is assumed that the soil has a capacity to deactivate beryllium.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils can mostly be used.

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Boron

Background Information

Introduction Amorphous boron is a dark-brown semi-metal and is relatively non-toxic. Its compounds, however, range from being moderately to highly toxic to all living organisms. Although boron is an essential plant nutrient, it is toxic to plant growth at very low concentrations. Compounds of boron such as boric acid and sodium borate are of commercial importance.

Occurrence Boron is found in nature in the form of various borates and borosilicate minerals. Common minerals include borax ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$), found in salt deposits of saline lakes, calcium borate (colemanite) and various borosilicate minerals such as tourmaline (an aluminium borosilicate). Boron tends to occur in association with saline conditions. Typically, the concentration of boron in

- ! sea water is 4.6 mg/R;
- ! fresh water is usually less than 0.1 mg/R; and
- ! surface water can be as high as 1 mg/R or more, especially if in association with arid, saline conditions.

Once in solution, boron is not easily removed and tends to concentrate in solution on evaporation of water. Hence, the ubiquitous finding of elevated boron concentrations in conjunction with saline hydrogeological conditions.

Industrial uses of boron include

- ! use in metallurgy to harden other metals;
- ! use in semi-conductors;
- ! use in the nuclear industry, as a neutron absorber;
- ! use of sodium borate (borax) as a preservative, in the manufacture of glasses and glazes, and in weather-proofing fabrics;
- ! use of organic complexes of boron as catalysts; synthetic organoboron compounds tend to be more toxic than the naturally occurring borates; and
- ! use of boric acid as a general household antiseptic agent.

Its relatively high concentration in sea water is the source of the high content of boron in argillaceous sediments of marine origin. Upon weathering the boron contained in these sediments is released into the aquatic environment.

Interactions Boron concentrations in the soil solution are largely determined by sorption and desorption reactions with soil particles. Boron can be specifically adsorbed by different clay minerals, hydroxy oxides of aluminium and iron, and by organic matter. The adsorption reactions are strongly pH-dependant with maximum adsorption occurring in a pH range of 7 - 11. Due to these interactions, the boron concentrations in a soil solution are largely buffered against rapid changes and the implications thereof include the following:

- ! Boron requires much longer time periods than unreactive ions, such as chloride, to attain equilibrium conditions. The time required to reach steady state concentrations depends on the boron load (boron concentration and volume of water applied), the leaching fraction and the sorptive capacity of the soil. The time required to establish equilibrium conditions has been calculated to vary from 3 to 150 years.

- ! Relatively longer time periods than for unreactive ions are required for boron toxicity to manifest itself after irrigation with boron-containing water (leaching with low boron water similarly takes longer to achieve a comparable reduction in the boron concentration in the soil solution).
- ! The boron concentration in the soil solution remains relatively constant between irrigations compared to the concentration of unreactive ions, such as chloride. (Boron is adsorbed onto soil particles when water uptake by plants reduces the soil water content and concentrates the soil solution. Boron is desorbed when the soil water content is replenished during irrigation with water of low boron content). Since plants respond to the boron concentration in the soil solution, solution and sand culture data can be used to evaluate the response of plants to boron.
- ! Similar to salt (see TDS), boron is also concentrated in the soil solution of deeper soil layers. The degree to which it is concentrated depends largely on the leaching fraction which is applied. However, most international water quality criteria are derived by assuming that boron concentrations in soil water are approximately equal to those in the irrigation water. This assumption, which was used in deriving the criteria, means that the criteria are only applicable under conditions where high leaching fractions exist. Where low leaching fractions exist, the boron criteria given are too high.

Measurement The criteria are given in terms of the total dissolved boron concentration, in units of mg/R. The reference method for the determination of boron is by curcumin colorimetry. Where other methods are used, their characteristics relative to the reference method should be known.

Data Interpretation Plants respond to root uptake of boron and are not sensitive to short-term variations in the concentration of boron in irrigation water. However, they are very dependent on the boron-supplying capacity of the soil, which, in turn, is largely determined by soil properties and previous boron applications. Two indices to interpret the effects of boron in irrigation water are used:

- ! A time series of annual mean boron concentration (preferably application volume weighted) is used to detect trends and potential residual effects of earlier irrigation applications.
- ! The annual mean boron concentration (preferably application volume weighted) is used to obtain the long-term mean boron concentration with which the soil will equilibrate.

No information is available for the interpretation of potential boron absorption by foliage when plant leaves are wetted by irrigation.

Treatment Options

It is highly unlikely that boron can be economically removed from water intended for irrigation use. However, should it be required, it is most easily removed from water along with other ions comprising the TDS. General methods for TDS removal include:

- ! Ion exchange in a mixed-bed ion exchange column, usually where the feed TDS is up to around 2 000 mg/R. On a commercial or industrial scale banks of large ion-exchange filter beds are used, which are capable of being regenerated.
- ! Treatment by membrane processes such as reverse osmosis or electrodialysis, where the TDS concentration is in the range of 2 000 - 3 500 mg/R. Large-scale water treatment is achieved using banks of reverse osmosis modules in parallel.
- ! Distillation, in cases where the TDS concentration is 10 000 mg/R or more.

All of the process alternatives are easily fouled by suspended matter in the water and may suffer from severe scaling with hard waters. All processes on a large-scale require high levels of design, operator and maintenance skills.

All of the processes produce a concentrated waste stream of the salts that may cause disposal difficulties.

The Effects of Boron

Norms

The different norms used in the guideline to assess the effects of boron on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop yield or appearance as affected by crop sensitivity to uptake through roots
Application to sustain suitability of irrigated soil	! No known effects of boron on soil itself. Effects are indirect since boron content of soil affects crop yield. These indirect effects are covered under crops
Maintenance of irrigation equipment	! No known effects

Effects

Boron is an essential plant nutrient (in the $\mu\text{g/R}$ range), but becomes toxic to plant growth at higher concentrations (in the mg/R range). Due to the fact that boron concentrations in the soil solution are largely buffered by sorption to and desorption from the soil, several seasons may be required before the effects of boron in irrigation water manifest in plant responses.

The symptoms of boron toxicity usually occur first on older leaves as yellowing (chlorosis), spotting or drying of leaf tissue at the tips and edges. As boron accumulates with time, the symptoms often progress towards the centre between the veins (inter-veinal) until finally leaf drop occurs. Some sensitive fruit crops, such as stone and pome fruit, may be damaged without leaf symptoms. A gum or exudate on the limbs or trunk and twig die-

back are often seen on trees without typical leaf symptoms.

The yield response of plants to increasing boron concentrations is similar to their response to increasing salinity. The yield remains unaffected until a threshold concentration is reached, after which yield declines linearly. However, quantitative data have only been determined for a few plants.

Plants also vary in their sensitivity to boron toxicity. The threshold concentration at which plants are affected varies over a considerable range. (See Table 2).

It takes time for boron to accumulate in the leaves. The leaves of vegetative crops (for example lucerne and lawns) that are cut frequently may therefore not accumulate sufficient boron to display toxic symptoms before they are harvested.

Earlier boron tolerance research was based on visual toxicity symptoms and reductions in growth. Unfortunately these do not always correlate with the yield of the marketable product.

Mitigation

Common on-farm management practices to cope with increasing levels of boron in irrigation water are to

- ! apply surplus irrigation to leach accumulating boron out of the soil (increase the leaching fraction). Since the boron concentration in the soil solution is strongly buffered, this approach is not as effective as for unreactive ions such as chloride (two to three times as much irrigation water as for chloride is required to achieve comparable reductions in the boron concentration of the soil solution); and/or
- ! accept a reduced crop yield; and/or
- ! switch to crops which are more boron-tolerant; and/or
- ! apply extra nitrogen to stimulate vegetative growth in cases where boron toxicity-induced leaf drop reduces the photosynthetic capability of a tree crop.

Criteria

Table 1: Effects of Boron on Crop Yield and Appearance

Concentration Range (mg/R)	Crop Yield and Appearance
<i>Target Water Quality Range # 0.5</i>	<i>Should prevent the accumulation of boron to toxic levels (through root uptake) in all but the most sensitive plants</i>
0.5 - 1.0	Crops very sensitive to boron accumulate toxic levels (through root uptake). They start to display symptoms of foliar injury and/or yield decreases
1.0 - 2.0	Crops sensitive to boron accumulate toxic levels (through root uptake). They start to display symptoms of foliar injury and/or yield decreases
2.0 - 4.0	Crops moderately sensitive to boron accumulate toxic levels (through root uptake). They start to display symptoms of foliar injury and/or yield decreases
4.0 - 6.0	Crops moderately tolerant to boron accumulate toxic levels (through root uptake). They start to display symptoms of foliar injury and/or yield decreases
6.0 - 15.0	Crops tolerant to boron accumulate toxic levels (through root uptake). They start to display symptoms of foliar injury and/or yield decreases
> 15.0	Crops very tolerant to boron accumulate toxic levels (through root uptake). They start to display symptoms of foliar injury and/or yield decreases

Modifications

Limitations to setting criteria for boron include the following:

- ! A paucity of information on boron sensitivity of crops.
- ! The numerical criteria assume equilibrium conditions between the boron concentration in irrigation water and that sorbed by soil, that is, equilibrium conditions after prolonged irrigation. Depending on the soil sorption capacity for boron and its concentration in the irrigation water, extensive periods may, however, be required to reach equilibrium conditions. Since boron is relatively strongly sorbed by soil, higher boron concentrations can be tolerated during the preceding period.
- ! The numerical criteria assume that at equilibrium conditions, the boron concentrations in soil water and in the upper root zone will be similar to those of the irrigation water and that the crop response will be determined primarily by these concentrations. The boron concentration in the soil water of the upper root zone will, however, be somewhat higher than that of the irrigation water. The boron concentration in the lower root zone will also be higher than that of the upper root zone (as determined by the leaching fraction). The numerical criteria in Table 1 will therefore be too high, once equilibrium conditions are attained.

- ! Table 2 provides a list of commercial crops grouped into boron tolerance classes.
- ! The effect of boron on woody crops is determined largely by the rootstock that is used. Table 3 provides a list of citrus and stone fruit rootstocks ranked in order of increasing boron accumulation and transport to scions.
- ! Leaf symptoms and vegetative growth are important yardsticks for ornamental plants. Soil water concentrations at which these are affected for a number of ornamental plants are given in Table 4.
- ! Potted plants usually receive water applications in excess of the assumptions used to derive the criteria. Practically no leaching occurs, with the result that boron will accumulate faster and to higher concentrations than under field conditions.
- ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because the criteria assume that the soil has the capacity to deactivate boron.

Table 2: A List of Crops Grouped into Boron Tolerance Classes according to Threshold Boron Concentrations (mg/l) in Soil Solution

Very sensitive # 0.5	Sensitive 0.5 - 1.0	Moderately Sensitive 1.0 - 2.0	Moderately Tolerant 2.0 - 4.0	Tolerant 4.0 - 6.0	Very Tolerant 6.0 - 15.0
Lemon* Blackberry*	Lemon* Avocado* Grapefruit* Orange* Apricot* Peach* Cherry* Plum* Persimmon* Fig, kadota* Grape* Walnut* Pecan* Onion Garlic Sweet potato Wheat Sunflower Bean, mung* Sesame* Lupine* Strawberry* Artichoke, Jerusalem* Bean, kidney* Bean, snap Bean, lima* Peanut	Broccoli Pepper, red Pea* Carrot Radish Potato Cucumber Lettuce*	Cabbage* Turnip Bluegrass, Kentucky* Barley Cowpea Oats Maize Artichoke* Tobacco* Mustard* Clover, sweet* Squash Muskmelon* Cauliflower	Lucerne* Vetch, purple* Parsley* Beet, red Sugar beet Tomato	Sorghum Cotton Celery* Asparagus*
* Tolerance based on reductions in vegetative growth rather than marketable product					

Note: The crops are listed in approximate order of increasing tolerance.

Table 3 : Rootstocks of Citrus and Stone Fruit Ranked in order of Increasing Boron Accumulation and Transport to Scions

Citrus	Stone fruit
Alemow Gajanimma Chinese box orange Sour orange Calamondin Sweet orange Yuzu Rough lemon Grapefruit Rangpur lime Troyer citrange Savage citrange Cleopatra mandarin Rusk citrange Sunki mandarin Sweet lemon Trifoliolate orange Citrumelo 4475 Ponkan mandarin Sampson tangelo Cuban shaddock Sweet lime	Almond Myrobalan plum Apricot Marianna plum Shalil peach

Table 4: A List of Ornamental Plants Grouped into Boron Tolerance Classes according to Threshold Boron Concentration (mg/l) in Soil Solution

Very sensitive # 0.5	Sensitive 0.5 - 1.0	Moderately sensitive 1.0 - 2.0	Moderately tolerant 2.0 - 4.0	Tolerant 6.0 - 8.0
Oregon grape Photinia Xylosma Thorny elaeagnus Laurustinus Wax-leaf privet Pineapple guava Spindle tree Japanese pittosporum Chinese holly Juniper Yellow sage American elm	Zinnia Pansy Violet Larkspur Glossy abelia Rosemary Oriental arborvitae Geranium	Gladiolus Marigold Poinsettia China aster Gardenia Southern yew Brush cherry Blue dracaena Ceniza	Bottlebrush California poppy Japanese boxwood Oleander Chinese hibiscus Sweet pea Carnation	Indian hawthorn Natal plum Oxalis

Notes:

- ! Plants are listed in order of increasing tolerance, based on appearance and growth reduction.
- ! Boron concentrations exceeding the threshold may cause leaf burn and loss of leaves.

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Cadmium

Tentative Guideline

Background Information

Introduction Cadmium is a soft, bluish-white metal chemically similar to zinc and highly toxic to living organisms. The presence of cadmium in the aquatic environment is of concern because it bioaccumulates. Cadmium has a low solubility under conditions of neutral or alkaline pH and is highly soluble under acidic conditions, where toxic concentrations can easily arise from the dissolution of cadmium from cadmium-plated materials.

Plants respond to the cadmium concentration in the soil solution. Similar to most trace elements, cadmium is strongly adsorbed by soil and its addition in relatively high concentrations over the short-term may not result in reduced crop growth or in its accumulation in plant parts to concentrations detrimental to humans or animals. However, continuous application of cadmium to soils over extended periods results in its accumulation in the surface soil layer, in practice, the cultivated or plough layer.

Occurrence Cadmium occurs in association with zinc ores and is also found as the mineral Greenockite (cadmium sulphide). Cadmium sulphide, carbonate and hydroxide salts are insoluble in water, whereas cadmium chloride, nitrate and sulphate salts are highly soluble in water. Cadmium binds strongly to sulphhydryl groups, hence, the pronounced tendency of cadmium to bioaccumulate in the food chain. Cadmium is not usually found in water at concentrations greater than 1 Fg/R, unless the water has been subject to pollution from industrial effluents containing cadmium.

Cadmium is used in electroplating, in alloys, in certain solders and in nickel-cadmium batteries. Salts of cadmium are used in photography, pottery, the electronics industry and as pigments in many different applications.

Interactions The soil chemical behaviour of cadmium is similar to that of copper, lead, nickel and zinc. Cadmium is strongly adsorbed by soil clay minerals and coprecipitated with iron and manganese oxides and oxy-hydroxides. It is for these reasons that cadmium has a limited vertical movement through neutral to alkaline soils. Its availability to plants increases at low pH levels and with increasing chloride concentrations. Plant availability is reduced when the concentration of organic matter is high.

Cadmium concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex. Sorption dominates at the relatively low concentrations that are of concern for water quality criteria for irrigation. Soil pH has a major effect on the concentration of cadmium in the soil solution and solubility decreases with increasing pH.

Implications for irrigation with water containing cadmium include the following:

- ! Cadmium can be expected to be retained in the soil surface layers because of its strong sorption by the soil exchange complex.
- ! Significant downward movement to below the plough layer and hence contamination of ground water with cadmium is unlikely.

- ! The larger the soil's cation exchange capacity (determined by clay content and clay mineral type), the more cadmium can generally be sorbed.
- ! Soils with a neutral to alkaline pH will be able to accept a greater cadmium load than acidic soils, before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the total cadmium concentration, in units of mg/R. The reference method for the measurement of cadmium is atomic absorption spectrometry. If other methods of analysis are used, their characteristics relative to the reference method should be known.

Data Interpretation Because cadmium is retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions is reached. In order to prevent its accumulation, the total load applied to soil needs to be limited. International criteria for the concentration of cadmium in irrigation water have been calculated (using limited available information) to ensure that accumulation to either phytotoxic levels or levels that are toxic to consumers, within a given time period, do not occur. The calculations assume that cadmium accumulates within the surface 150 mm of soil. As such the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for

- ! the cadmium concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that cadmium does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! the cadmium concentration that can be applied to *fine textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that cadmium can be economically removed from water intended for irrigation use.* However, should it be required, cadmium can be most conveniently removed by raising the pH and precipitating the insoluble cadmium salts after the addition of lime or iron salts in the pH range of 8.5 - 11.5. Precipitation is followed by settlement and filtration as in conventional water treatment. The precipitation process requires careful monitoring to ensure that removal is complete. A watery, cadmium-rich sludge or concentrate stream is generated in the processes that may present disposal difficulties.

To achieve very low residuals, it may be necessary to pass the stream through an ion exchange column charged with the appropriate resin.

The Effects of Cadmium

Norms The different norms used in the guideline to assess the effects of cadmium on irrigation water use are summarised in the following table.

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<p>! Crop yield as affected by crop sensitivity to cadmium uptake through plant roots</p> <p>! Crop quality as determined by cadmium toxicity to consumers</p>
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects

Cadmium is readily taken up by plants, even though it is not an essential plant nutrient. Due to its chemical similarity to zinc (an essential plant nutrient), cadmium can readily interfere with some plant metabolic processes and is therefore toxic to many plants. Plants, however, do vary in their sensitivity to cadmium. Nutrient solution concentrations of 0.1 mg/l reduce the yields of bean, beets and turnips by 25 %, whereas cabbage and barley yields are reduced by 20 % - 50 % in a 1 mg/l solution. A 25 % reduction in the yields of field crops grown in soil were found at cadmium concentrations varying from 4 mg/kg for spinach to 640 mg/kg for rice. The regular consumption of cadmium-enriched foods over decades results in the accumulation of cadmium to concentrations that are detrimental to human health.

Mitigation

Common on-farm management practices to mitigate against cadmium uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline; and/or
- ! switch to a crop that is more tolerant to cadmium; and/or
- ! ensure an adequate supply of zinc, manganese and copper - the uptake of cadmium is reduced by an adequate supply of these elements.

Criteria

Effects of Cadmium on Crop Yield and Quality

Concentration Range (mg/R)	Crop Yield and Quality
<i>Target Water Quality Range # 0.01</i>	<i>Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/R in nutrient solutions. Conservative limits are needed because of cadmium's potential for accumulation in plants and soils to concentrations that may be toxic to humans and animals</i>
0.01 - 0.05	Maximum acceptable as concentration for fine-textured neutral to alkaline soils
> 0.05	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soils and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! The criteria were derived with the assumption that the soil to be irrigated contained only negligible quantities of cadmium. Should this not be the case, the period of irrigation needs to be reduced accordingly.
- ! More cadmium is absorbed by plants in the presence of chlorides. Lower cadmium concentrations need to be applied when irrigation water contains appreciable chloride concentrations.
- ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods), because the criteria assume that the soil has the capacity to deactivate cadmium.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils, can mostly be used.

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Chloride

Background Information

Introduction Chloride is the anion of the element chlorine. Chlorine does not occur in nature, but is found only as chloride. The chlorides of sodium, potassium, calcium and magnesium are all highly soluble in water. Chloride is an essential plant micronutrient. Unlike most other micronutrients it is, however, relatively non-toxic to most crops.

Occurrence Chloride is a common constituent in water, is highly soluble, and once in solution tends to accumulate. Typically, concentrations of chloride in fresh water range from a few to several hundred mg/R. In sea water the concentration is approximately 19 800 mg/R. Chloride inputs to surface waters can arise from irrigation return flows, sewage effluent discharges and various industrial processes. Chloride can only be removed from water by energy-intensive processes.

Interactions Being an anion, chloride is only very weakly sorbed by the soil exchange complex (which is mainly a cation exchanger). The movement of chloride in soil is considered to be unaffected by exchange reactions since chlorides leach freely and their relative concentration and distribution in the soil profile is largely determined by the leaching fraction (see TDS).

Measurement The criteria are given in terms of the dissolved chloride concentration, in units of mg/R. Dissolved chloride is usually determined colorimetrically by means of ferricyanide. This is a reference method. If other methods are used, their characteristics relative to the reference method should be known.

Data Interpretation The chloride concentration of irrigation water provides an indication of the concentrations at which

- ! root uptake (that is, when foliage is not wetted by the irrigation method) by crops can be expected to result in the uptake of chloride to plant toxic levels. The *arithmetic mean concentration* during the active growing season (preferably application volume weighted) is used.
- ! leaf uptake (that is, when foliage is wetted by the irrigation method) by crops can be expected to result in the uptake of chloride to plant toxic levels. The *arithmetic mean concentration* during the active growing season (preferably application volume weighted) is used.
- ! leaf burn (foliar damage) of crops can be expected to occur when crop foliage is wetted by irrigation water. The *maximum concentration* during the active growing season is used.
- ! chloride will accumulate in consumable plant parts for which a *maximum chloride concentration* from a quality perspective has been defined. The *arithmetic mean concentration* during the active growing season (preferably application volume weighted) is used.

Chloride concentrations should also be interpreted in conjunction with the concentrations

of the other major cations and anions.

Treatment Options

Chlorides are highly soluble and cannot be precipitated at concentrations usually present in water. *Removal of chloride from water intended for irrigation purposes is not economically feasible.* However, should it be required, chloride can be removed from water by electrolysis to form chlorine gas liberated at the anode. Electrolysis is not effective where the conductivity and the chloride concentration is low.

More commonly, chloride is removed together with other ions using

- ! anion exchange resin beds, in which all significant anions will be removed; and
- ! desalination techniques such as reverse osmosis and electrodialysis.

The concentrated waste streams generated from ion exchange and desalination processes may cause disposal difficulties. Desalination techniques require skilled operation, control and maintenance. Capital and operating costs are typically high.

The Effects of Chloride

Norms

The different norms used in the guideline to assess the effects of chloride on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<ul style="list-style-type: none"> ! Crop yield as affected by crop sensitivity to uptake through crop roots ! Crop yield as affected by crop sensitivity to uptake through foliage ! Crop quality as determined by damage to marketed produce or by limits on concentration in final product
Application to sustain suitability of irrigated soil	! No known effects of chloride on its own
Maintenance of irrigation equipment	! No known effects

Effects

When the accumulated chloride concentration in leaves exceeds the crop's tolerance, injury symptoms develop in the form of leaf burn. This starts at the tips of leaves and progresses from the tip back, along the edges, as the severity increases. In extreme cases chloride toxicity manifests itself in early leaf drop.

With a few exceptions (notably some soybean cultivars), non-woody plants are not specifically sensitive to chloride. When irrigated with water with a high concentration of

chloride, yield decreases because the osmotic threshold of total salinity (see TDS) has been exceeded, but no obvious injury symptoms occur.

On the other hand, many of the economically important woody plants are susceptible to chloride concentrations lower than the salinity threshold. Chloride can be absorbed either singly through plant roots or plant foliage, or through a combination of both.

Absorption through plant roots

Chlorides are very soluble and are not adsorbed to any significant degree by soil, but are readily transported with the soil water, and are taken up by roots and conveyed in the transpiration stream, where they accumulate in the leaves. Plants vary in their ability to restrict the transport of chloride to the shoots. The tolerance of avocado, citrus and grapes relates closely to the ability of rootstocks to exclude or accumulate chloride.

Crops vary in their sensitivity to chloride and suffer yield reduction once the threshold concentration in the soil solution is exceeded. The yield response of crops to chloride has, as yet, not been well characterised. Chloride-crop response curves for crops that are not specifically sensitive to chloride have been developed, using the results of the experiments that derived TDS-crop curves, which were determined with artificial mixtures of sodium and calcium chloride.

Absorption through plant foliage

Crops wetted by saline water are exposed not only to root zone salinity but also to absorption directly through the leaves. Experiments to quantify the additional impact of foliar damage from sprinkler irrigation to crop yield, indicate that the effects can be substantial. Crop tolerances to foliar absorption have, as yet, not been well characterised and research in this regard is compounded by the pronounced influence of climatic conditions such as high temperatures, low humidity and wind, all of which aggravate adverse effects.

Further, the foliar absorption rate in crops also varies. The absorption rates of avocado leaves are low while those of citrus, stone fruits and almonds are high. This means that chloride concentrations as low as 70 - 105 mg/l can cause foliar damage.

Crop Quality

Crop quality is affected by chloride-induced leaf injury in plants whose leaves are the marketed product, or where fruit size and appearance are affected by chloride-induced yield decreases. These aspects of crop quality are covered by the criteria (to the extent that information is available) for yield decreases and foliar damage from chloride absorption through plant roots and/or foliage.

Tobacco is an exception. Neither the yield nor the foliar appearance of tobacco is detrimentally affected by moderate chloride concentrations. However, the burning properties and storage life (important quality criteria) of tobacco leaves are detrimentally affected even at relatively low concentrations of chloride in the leaves.

Mitigation

Chloride uptake through either roots or foliage

Common on-farm management practices to cope with an increasing chloride content of water affecting crop yield and quality, are to

- ! accept a reduced crop yield or quality; and/or
- ! switch to crops that are more tolerant to chloride.

Chloride uptake through foliage

Common on-farm practices to cope with problems arising from the wetting of foliage, are to

- ! switch to an irrigation application method that does not wet the leaves; or
- ! switch to crops with a lower foliar adsorption rate; and/or
- ! reduce the possibility for foliar absorption of chloride by reducing the number of wetting and drying cycles (that is, reducing the irrigation frequency) and/or by irrigating at night when temperature (absorption rate) and evaporation (salt concentration rate) are lower; and/or
- ! rinse the leaves at the end of an irrigation application with low chloride water; and/or
- ! avoid irrigation during periods of high wind. (Wind is a major factor in the concentration and absorption of chloride. The downwind drift of sprinklers is more concentrated than the applied sprinkler water and thus more likely to cause foliar damage); and/or
- ! increase sprinkler rotation speed (sprinklers that rotate slowly allow appreciable drying between rotations); and/or
- ! increase application rate (within the limits posed by soil water storage capacity and infiltration rate, thereby reducing the time period available for foliar absorption); and/or
- ! increase droplet size (this results in less absorption compared to small drops).

Chloride absorption through roots

Common on-farm management practices to cope with increasing problems arising from chloride, are to

- ! apply surplus irrigation (in addition to the evapotranspirational requirement) in order to leach accumulating chloride out of the soil (increased leaching fraction); and/or
- ! select, for some horticultural crops (for example grapes, citrus, avocado), a more tolerant rootstock.

Table 1: Effects of Chloride on Crop Yield and Quality

Concentration Range (mg/l)	Crop Yield and Quality
<i>Target Water Quality Range # 100</i>	<i>Should prevent the accumulation of chloride to toxic levels in all but the most sensitive plants, even when chloride uptake is through foliar absorption, that is, crop foliage is wetted</i>
< 140	Should prevent the accumulation of chloride to toxic levels in all but the most sensitive plants, when chloride uptake is through root absorption, that is, water is applied to the soil surface, thereby excluding wetting of crop foliage
140 - 175	Only slight problems with the accumulation of chloride to levels toxic to crops can be expected when chloride uptake is through root absorption, that is, water is applied to the soil surface, thereby excluding wetting of crop foliage
100 - 175	Crops sensitive to foliar absorption accumulate toxic levels of chloride when crop foliage is wetted. They display foliar injury and yield decreases
175 - 350	<p>Some problems with the accumulation of chloride to levels toxic to moderately sensitive crops can be expected when chloride uptake is through root absorption, that is, water is applied to the soil surface, thereby excluding wetting of crop foliage</p> <p>Crops moderately sensitive to foliar absorption accumulate toxic levels of chloride when crop foliage is wetted. They display symptoms of foliar injury and yield decreases</p>
350 - 700	<p>All moderately sensitive crops and most moderately tolerant crops accumulate chloride to levels toxic to crops when chloride uptake is through root absorption, that is, water is applied to the soil surface thereby excluding wetting of crop foliage</p> <p>Crops moderately tolerant to foliar absorption accumulate toxic levels of chloride when crop foliage is wetted. They display symptoms of foliar injury and yield decreases</p>
>700	<p>Increasing problems with the accumulation of chloride to levels toxic to crops can be expected when chloride uptake is through root absorption, that is, water is applied to the soil surface thereby excluding wetting of crop foliage</p> <p>Crops tolerant to foliar absorption increasingly accumulate toxic levels of chloride when crop foliage is wetted. They display symptoms of foliar injury and yield decreases</p>

Note:

- ! Crop tolerance to chloride, when crop foliage is wetted by sprinkler irrigation, is not well established. Very little local confirmation of internationally published

experiments has taken place. The indicated concentration ranges apply to daytime sprinkling under conditions that are not too hot or too dry.

- Modifications**
- ! Environmental or other conditions causing an increased chloride concentration on foliage (e.g. hot, dry conditions) necessitate more conservative criteria for crop tolerance to foliar absorption, and *vice versa* (see Mitigation).
 - ! The relative susceptibility of some crops to foliar injury is presented in Table 2.
 - ! Potted plants usually receive water in excess of the assumptions used to derive the criteria. Practically no leaching occurs with the result that chloride will accumulate faster and to higher concentrations than under field conditions.
 - ! Water and plant nutrients are often recirculated in commercial floriculture (e.g. hydroponics and soilless growth media) with the result that salts accumulate. Since water application is mostly controlled to ensure minimal matric potentials, higher salt and chloride concentrations can be tolerated. It should, however, still be controlled to within plant tolerance levels.
 - ! The effect of chloride on woody crops is determined largely by the rootstock that is used. By choosing an appropriate rootstock, the chloride concentration that is transported to the scion can be reduced drastically.

Table 2 : Relative Susceptibility of Crops to Foliar Injury from Saline Sprinkling Waters

Chloride Concentration (mg/l) Causing Foliar Injury in Crops of Varying Sensitivity to Foliar Absorption			
Sensitive # 175	Moderately sensitive 175 - 350	Moderately tolerant 350 - 700	Tolerant > 700
Almond Apricot Citrus Plum Grape	Pepper Potato Tomato	Barley Maize Cucumber Lucerne Safflower Sesame Sorghum	Cauliflower Cotton Sugar beet Sunflower

Note:

- ! The data in the above table are general criteria for daytime sprinkling under conditions that are not too hot or too dry.
- ! Tobacco presents a special case of chloride-sensitivity. Even at low concentrations, chloride in tobacco leaves affects the burning properties and storage life, and thus quality and price, of the leaves. Even though chloride in water and soil does not affect yield, it plays a deciding role in the economy of tobacco production. The quality of tobacco can be

affected by chloride concentrations exceeding 25 mg/R in irrigation water.

! Table 3 indicates the susceptibility of some crops in chloride tolerance classes, grouped according to their threshold chloride concentration in saturated-soil extracts. It should be used only as a guideline for relative crop tolerances. The tolerance classes used in Table 3 agree approximately with those used in Table 1. It can therefore be used as an indication of the crops that are referred to in Table 1.

Although the chloride concentration in the saturated-soil extract is largely determined by that of the irrigation water, several other factors have a moderating effect. Expert advice should be sought to derive criteria for site-specific conditions.

Table 3: Annual Crops Grouped into Chloride Tolerance Classes according to Threshold Chloride Concentrations (mg/R) in Saturated-soil Extracts

Sensitive # 350	Moderately sensitive 425	Moderately tolerant 700 - 1 200	Tolerant 400 - 2 100	Very tolerant 2 450 - 2 800
Strawberry Bean Onion Carrot Radish Lettuce Turnip	Pepper Clover, strawberry Clover, red Clover, alsike Clover, ladino Corn Flax Potato Sweet Potato Broad bean Cabbage Foxtail, meadow Celery Clover, Berseem Orchardsgrass Sugarcane	Trefoil, big Lovegrass Spinach Alfalfa Sesbania* Cucumber Tomato Broccoli Squash, scallop Vetch, common Wild rye, beardless Sudan grass Wheat grass, standard crested	Beet, red Fescue, tall Squash, zucchini Hardinggrass Cowpea Trefoil, narrow- leaf bird's foot Ryegrass, perennial Wheat, Durum Barley (forage)* Wheat	Sorghum Bermuda grass Sugar beet* Wheat grass, fairway crested Cotton Wheat grass, tall Barley*

* Less tolerant during emergence and seedling stage

Note: Crops are listed in columns in order of increasing tolerance from top to bottom.

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Chromium(VI)

Tentative Guideline

Background Information

Introduction Chromium(VI) is a highly oxidated state of metal chromium. It occurs as the yellow-coloured dichromate salt under neutral or alkaline conditions, and as the orange-coloured chromate salt under acidic conditions. Chromium(VI) is highly water soluble at all pH values. The reduced forms of chromium, namely chromium(II) and chromium(III), are less soluble than chromium(VI), have much lower toxicity indices than chromium(VI) and do not constitute as serious a health hazard.

Chromium is not essential for plant growth, but is toxic at high concentrations. Similar to most trace elements, chromium is strongly adsorbed by soil. Its addition in relatively high concentrations over the short-term may not result in reduced crop growth or in its concentration in plant parts that is detrimental to human or animal consumption. However, continuous applications of chromium to the soil over extended periods result in its accumulation in the surface soil layer, in practice, the cultivated or plough layer.

Occurrence The most common ore of chromium is chromite, in which chromium occurs in the trivalent state. Minerals containing chromium(VI) do occur, but are not common. Elevated concentrations of chromium(VI) found in the environment are due to industrial pollution. Because chromium(VI) is highly water soluble it is mobile in the environment and moves through the soil profile, resulting in contamination of ground water supplies. Chromium(VI) can be reduced to chromium(III) under suitable pH and reducing conditions. However, chromium(III) can also be re-oxidised to chromium(VI) under oxidising conditions. Chromium(VI) is not normally found in water at concentrations greater than 0.01 mg/R. Higher concentrations potentially occur wherever industrial activity using chromium(VI) compounds are located.

In water, chromium(II) and chromium(III) are not normally found at near-neutral pH, since the hydroxides of these two oxidation states are insoluble. However, they may occur in water under acidic conditions.

Chromic acid or hexavalent chromium salts are used in alloys in the metal pickling and plating industry, in the leather industry and in the manufacture of paints, dyes, explosives, ceramics and paper.

Interactions Chromium concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex. Sorption dominates at the relatively low concentrations that are of concern for water quality criteria for irrigation.

Depending on the prevailing redox conditions in soils, chromium(III) can be oxidised to chromium(VI) and *vice versa*. Chromium(III) oxidises readily to chromium(VI) under field soil conditions; organic matter and manganese oxides are important electron acceptors in this reaction.

Soil pH has a major effect on the concentration of chromium in the soil solution and its solubility decreases with increasing pH. At high pH values chromium(III) hydroxide, which has a low solubility, is precipitated from solution.

The implications for irrigation with water containing chromium are as follows:

- ! Chromium(III) can be expected to be retained in the soil surface layers, because of its strong sorption by the soil exchange complex. In cultivated land it accumulates in the plough layer.
- ! Significant downward movement of chromium(III) to below the "plough layer" and hence contamination of ground water, is unlikely. However, chromium(VI) is more mobile in soils and can thus be leached into ground water.
- ! The larger the soil's cation exchange capacity (determined by clay content, clay mineral type and amorphous sesquioxide content), the more chromium can generally be sorbed.
- ! Soils with a neutral to alkaline pH can accept a greater chromium load than acidic soils before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the total chromium concentration, in mg/R. The reference method for the determination of chromium(VI) is diphenyl carbazide spectrophotometry. Where other methods are used their characteristics relative to the reference method should be known.

Data Interpretation Because chromium(III) is retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions is reached. To prevent its accumulation to phytotoxic concentrations, the total load applied to soil must be limited. International criteria for the concentration of chromium in irrigation water have been calculated (using limited available information) to ensure that it does not accumulate to either phytotoxic levels or levels that are toxic to consumers, within a given time period. The calculations assume that chromium accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The chromium concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that chromium does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The chromium concentration that can be applied to *fine textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that chromium can be economically removed from water intended for irrigation use.* However, should its removal be required, trivalent chromium can be removed by various processes including:

- ! **Precipitation and flocculation** as chromium(III) hydroxide with lime and alum or a ferric salt, followed by settlement and filtration. The process needs careful monitoring to ensure effective removal of chromium.
- ! Removal with **reverse osmosis** or **ion exchange**.

The above methods are based on the fact that chromium(VI) is the most soluble of the chromium species and removal thereof requires pretreatment of chromium(VI) to a more easily precipitable species. As such, removal of chromium(VI) from water requires the reduction of the chromium(VI) to the trivalent form with ferrous sulphate, or by reaction with oxidisable organic matter.

Alternative methods are available for absorbing chromium(VI) onto ferric hydroxide precipitates. However, these are not as efficient as methods which rely on the reduction of chromium(VI), followed by precipitation of chromium(III) or chromium(II) hydroxides when the pH is raised.

All processes produce a watery sludge or concentrate stream that may be rich in chromium and present disposal difficulties.

The Effects of Chromium(VI)

Norms The different norms used in the guideline to assess the effects of chromium on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<p>! Crop yield as affected by crop sensitivity to chromium uptake through plant roots</p> <p>! Crop quality as determined by chromium toxicity to consumers</p>
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects Chromium has no known plant physiological function and is not an essential plant nutrient but, at low concentrations it has been found to have a beneficial effect on plant growth. At high concentrations, chromium becomes toxic to plant growth. In nutrient solutions chromium(III) and chromium(VI) have been found to be equally available to plants although plants do vary in their sensitivity to chromium.

Depending on the variety and species, reduced plant yields have been found at concentrations of 0.5 - 10 mg/l in nutrient solutions. Since chromium(VI) remains mobile in soil it is more available to plants than chromium(III), which is immobilised by absorption and complexation in soil. The toxic limit in soils therefore ranges from 5 - 500 mg/kg for chromium(VI) and from 50 - 5000 mg/kg for chromium(III).

Chromium is not readily translocated within the plant from the roots to the leaves to the fruit. Over 90 % of the chromium absorbed by plants remains in the roots. Accumulation of chromium in plants grown for human or livestock consumption is rare. Generally, foods contain insufficient chromium for toxicity to be induced from consumption.

Mitigation Common on-farm management practices to mitigate against chromium uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline; and/or
- ! switch to a crop that is more tolerant to chromium.

Criteria **Effects of Chromium(VI) on Crop Yield and Quality**

Concentration Range (mg/R)	Crop Yield and Soil Sustainability
<i>Target Water Quality Range</i> # 0.10	<i>Depending on plant species, nutrient solutions containing 0.1 mg/R can induce chromium toxicity</i>
0.10 - 1.0	Maximum acceptable concentration for fine-textured neutral to alkaline soils
> 1.0	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soils for irrigation periods up to 100 years and the concentration range for fine-textured neutral to alkaline soils for irrigation periods up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

- Modifications**
- ! The criteria were derived with the assumption that the soil to be irrigated contained only negligible quantities of chromium. Should this not be the case, the period of irrigation needs to be reduced accordingly.
 - ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because the criteria assume that the soil has a capacity to deactivate chromium.
 - ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
 - ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are, however, grown for only limited periods, the criteria applicable to fine-textured neutral to alkaline soils can mostly be used.

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Cobalt

Tentative Guideline

Background Information

Introduction Cobalt is a hard, grey, magnetic metal. The name cobalt derives from the German "kobelt", a term for gnomes and goblins; the toxic effects from the inhalation of dusts in cobalt mines was originally thought to be the work of goblins.

Similar to most trace elements, cobalt is strongly adsorbed by soil. The addition of cobalt to soils in relatively high concentrations over the short-term may not result in reduced crop growth or in its accumulation in plant parts to concentrations detrimental to humans or animals. However, continuous application over extended periods results in its accumulation in the surface soil layer, that is, the cultivated or plough layer. Accumulation in sediments can also occur as the sulphide of cobalt.

Occurrence The elemental form of cobalt is not found in nature. Cobalt occurs in various sulphide ores often associated with arsenic, iron, nickel and copper. Important ores include cobaltite (CoAsS), linnaeite (Co₃S₄) and smaltite (CoAs₂). Cobalt also occurs as the insoluble carbonate (sphaerocobaltite) and rarely as the soluble sulphate (bieberite).

The typical concentration of cobalt in unpolluted surface water is 0.0002 mg/l and in sea water is approximately 0.00002 mg/l. Elevated cobalt levels may occur in the vicinity of mines that process ores containing cobalt.

Cobalt is used in special alloys and magnets and cobalt salts are also used as pigments. The element has various uses in the nuclear industry, and radioactive Cobalt-60 is used in medical treatments as a radiation source to treat malignancies.

Cobalt tends to be concentrated on particles of manganese oxide in soils. The low levels of cobalt in natural waters may be due to an adsorption reaction of this type. The level of cobalt in herbage is dependent primarily on the soil concentration and soil pH. Nitrogen fertilizers may increase the uptake of cobalt by plants. Increasing soil pH (5.4 - 6.4) can reduce cobalt concentrations in pastures.

Interactions The chemical properties of cobalt are similar to those of iron and nickel. Unlike iron(II), the cobalt(II) ion is quite stable in the oxidated form. Cobalt(III) is a strong oxidising agent, unstable in soil.

Cobalt concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex. Sorption is more prevalent at the relatively low concentrations that are of concern for water quality criteria for irrigation.

Soil pH has a major effect on the concentration of cobalt in the soil solution and its solubility decreases with increasing pH.

The implications for irrigation with water containing cobalt are as follows:

! Cobalt can be expected to be retained in the soil surface layers, because of its strong sorption by the soil exchange complex. In cultivated land it accumulates in the plough layer.

- ! Significant downward movement to below the plough layer and hence contamination of the ground water is unlikely.
- ! The larger the soil's cation exchange capacity (determined by clay content and clay mineral type), the more cobalt can generally be sorbed.
- ! Soils with a neutral to alkaline pH can accept a greater cobalt load than acidic soils before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the total cobalt concentration, in mg/R. Total cobalt is normally measured after acidification of the sample. The reference method for the determination of cobalt is atomic absorption spectrometry. If other methods are used for measuring cobalt, their characteristics relative to the reference method should be known.

Data Interpretation Because cobalt is retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions are reached. In order to prevent its accumulation, the total load applied to soil needs to be limited. International criteria for the concentration of cobalt in irrigation water have been calculated (using limited available information) to ensure that it does not accumulate to either phytotoxic levels or levels that are toxic to consumers, within a given time period. The calculations assume that cobalt accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality have been accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The cobalt concentration that can be applied *to any soil on a continuous basis*. This concentration is calculated such that cobalt does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The cobalt concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that cobalt can be economically removed from water intended for irrigation use.* However, should it be required, cobalt can be removed by precipitation at alkaline pH, with lime, or by flocculation and coprecipitation with a ferric salt. Alternatively ion exchange can be used.

The waste stream produced will have elevated levels of cobalt, and will require appropriate disposal.

The Effects of Cobalt

Norms The different norms used in the guideline to assess the effects of cobalt on irrigation water use are summarised in the following table:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<ul style="list-style-type: none"> ! Crop yield as affected by crop sensitivity to cobalt uptake through plant roots ! Crop quality as determined by cobalt toxicity to consumers
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects

Cobalt is not generally considered a plant nutrient, but appears to be essential for some plant species. Cobalt concentrations in the range of 0.1 - 5 mg/R have been found to be toxic to a variety of food crops when added to nutrient solutions. A concentration of 0.1 mg/R was found to be toxic to tomatoes; this concentration also approximates the toxicity threshold for many other plants. An application of 0.05 mg/R seems to be satisfactory for continuous use in all soils. The occurrence of cobalt toxicity is rare under field conditions, presumably because it is strongly sorbed by soil.

Mitigation

Common on-farm management practices to mitigate against cobalt uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline; and/or
- ! switch to a crop that is more tolerant to cobalt.

Criteria

Effects of Cobalt on Crop Yield and Quality

Concentration Range (mg/R)	Crop Yield and Quality
<p><i>Target Water Quality Range</i> # 0.05</p> <p>0.05 - 5.0</p> <p>> 5.0</p>	<p><i>A satisfactory concentration for continuous application is 0.05 mg/R; 0.1 mg/R is near the toxicity threshold of many plants. Generally cobalt does not accumulate in edible parts of plants to levels that are dangerous to consumers</i></p> <p>Maximum acceptable as concentration for fine-textured neutral to alkaline soils</p> <p>Acceptable for irrigation only over the short term on a site-specific basis</p>

Note:

- ! The TWQR for relatively unrestricted use on all soils and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! The criteria were derived with the assumption that the soil to be irrigated contained negligible quantities of cobalt. Should this not be the case the period of irrigation needs to be reduced accordingly.
- ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because the criteria assume that the soil has a capacity to deactivate cobalt.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the guidelines. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils can mostly be used.

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Coliforms (Faecal)

Tentative Guideline

Background Information

Introduction Field crops and vegetables can become contaminated with human and animal pathogens and parasites when irrigated with water containing these organisms. These organisms may be transferred to humans when they are retained and survive on the surfaces of produce that are eaten raw, and to animals in their feed. Organisms transferred this way may lead to various bacterial enteric diseases, such as cholera (*Vibrio cholera*), typhoid fever (*Salmonella typhi*), salmonellosis (*Salmonella spp.*) and bacillary dysentery (*Shigella spp.*). Viruses are also important agents of waterborne diseases and can cause illnesses such as gastroenteritis, hepatitis, poliomyelitis and respiratory illness. The risk of Helminth (intestinal nematodes) and protozoan parasite (e.g. *Giardia spp.*) transmission by wastewater is also considered to be high.

A feature of bacterial pathogens is that a high infective dose of 10 - 1 000 or more organisms is required to cause infection, whereas a much lower infectious dose for both viruses and protozoan parasites causes infection.

Detection of pathogens in water is methodologically complex, time-consuming and expensive. Given the low density of pathogens in environmental waters and the large number of potential pathogens which may be associated with polluted water, it is common practice to monitor and control microbiological water quality on the basis of concentration of indicator organisms, rather than of the pathogens themselves. See Volume 1: Domestic Use.

Faecal coliforms, and more specifically *Escherichia coli* (*E.coli*), are the most common bacterial indicators of faecal pollution. This indicator group is used to evaluate the quality of wastewater effluents, river water, sea water at bathing beaches, raw water for drinking water supply, treated drinking water, water used for irrigation and aquaculture and recreational waters. The presence of *E. coli* is used to confirm the presence of faecal pollution by warm-blooded animals (often interpreted as human faecal pollution). Some organisms detected as faecal coliforms may not be of human faecal origin but are almost definitely from warm-blooded animals.

Occurrence Many of the micro-organisms that are pathogenic to animals and humans are carried in waters derived from surface sources. They originate from municipal and industrial waste, including food processing plants, slaughter houses, poultry processing operations, feed lots and runoff from unserviced high density housing areas. Indicator organisms are excreted by healthy individuals and form part of the natural flora of human faeces. Water polluted by human and/or animal faecal matter will show the presence of indicator organisms.

Faecal coliforms have been shown to represent 93 % - 99 % of coliform bacteria in faeces from humans, poultry, cats, dogs and rodents. Some faecal coliform tests also enumerate *Klebsiella spp.*, which can originate from non-faecal sources, and a few other bacterial strains also of non-faecal origin. *Escherichia coli* may comprises up to 97 % of coliform bacteria in human faeces. The remainder include other *Escherichia spp.*, *Klebsiella spp.*, *Enterobacter spp.*, *Enterobacter spp.* and *Citrobacter spp.*

Interactions Numerous physical and biological factors influence the rate of die-off or disappearance of

bacteria in water. Among the most significant are the type of organism, sunlight, temperature, pH, salinity, competition, predation, algae, nutrient deficiencies, toxic substances, organism density in the discharge, settling of organisms after discharge, resuspension of particulates and aftergrowth, and multiplication of organisms in the water body. Extremes in pH, elevated temperatures and solar radiation promote microbial decay, while elevated nutrient concentrations and lower temperatures promote microbial survival. Polluted water may contain enough nutrients to support the growth of some of the bacterial indicator organisms, especially in temperate waters.

Micro-organisms demonstrate increased survival in sediments and when aggregated to particles, possibly due to reduced predation and parasitism. The nature and stability of aggregates are highly dependent on environmental conditions and the physical and chemical nature of the particles.

Measurement Faecal coliforms are usually enumerated as counts (number of colony forming units)/100 mL of water. Water samples must be refrigerated immediately after collection and should be analysed within 24 hours. Analysis may be by membrane filtration (0.45 µm diameter pore size) or by multiple tube fermentation techniques. Faecal coliform bacteria are all bacteria which produce typical blue colonies on m-FC agar within 20 - 24 hours of incubation at 44.5 °C. *Escherichia coli* are considered to be all the faecal coliforms which test indole-positive at 44.5 °C.

Data Interpretation Strictly speaking, faecal bacterial indicators should be used to indicate the presence of bacterial pathogens only. However, although inappropriate, they are widely used to indicate the microbial quality of water in general, which includes viruses and parasites. The faecal coliform (specifically *E. coli*) content is used as indication of the microbial quality of irrigation water.

Geometric mean values (based on not less than six samples over a growing season) should be used to compare with the criteria given and should be interpreted as maximal values, not to be exceeded. *To assess the effect on crop quality, more importance should be attached to the faecal coliform concentrations of irrigation applications immediately preceding harvesting, compared to those earlier during the season.*

The geometric mean concentration of the applied water (preferably application volume weighted) should be used to assess the effect of faecal coliforms on irrigation equipment.

Treatment Options *In practice treatment is mostly too costly an option to remove human and animal pathogens and parasites from irrigation water.* However, should their removal be required, several conventional water purification processes, including sedimentation, absorption, coagulation and flocculation can be used for partial removal. These treatment processes do not necessarily inactivate the micro-organisms and additional disinfection processes need to be applied.

The most common and practical treatment options for irrigation water are:

- ! Disinfection of the water - mostly with chlorine. Disinfection requires careful process control of dosage and contact time.
- ! Filtration which physically removes the pathogens and parasites.

The Effects of Faecal Coliforms

Norms

The norms used in the guideline to assess the effects of faecal coliforms on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop quality as determined by the likelihood of negative health effects being transmitted by crops irrigated with the water
Application to sustain suitability of irrigated soil	! Soil quality as determined by the likelihood of negative health effects being transmitted through human or crop contact with the soil, as a result of irrigation with contaminated water. (No criteria given)
Maintenance of irrigation equipment	! Faecal coliforms and other micro-organisms can cause the clogging of irrigation equipment when secondary growth (which often collects suspended particles) takes place under growth stimulating (sufficient nutrients) conditions

Effects

Faecal coliforms are primarily used to indicate the presence of bacterial pathogens such as *Salmonella spp.*, *Shigella spp.*, *Vibrio cholerae*, *Campylobacter jejuni*, *Campylobacter coli*, *Yersinia enterocolitica* and pathogenic *E. coli*. These organisms can be transmitted via the faecal/oral route by eating raw produce that has been irrigated with contaminated water and may cause diseases such as gastroenteritis, salmonellosis, dysentery, cholera and typhoid fever.

The risk of being infected by microbial pathogens correlates with the level of contamination of the water and the amount of contaminated produce consumed. Higher concentrations of faecal coliforms in water will indicate a higher risk of contracting a waterborne disease, even if small amounts of produce are consumed.

The criteria are therefore based on the contamination level of the irrigation water and the likelihood of consumer exposure (e.g. ingestion of contaminated raw produce). The likelihood of clogging micro-irrigation equipment is linked to the total number of micro-organisms. Although individual micro-organisms are too small to cause clogging of drip irrigation systems, the presence of rough areas or particles to which they can adhere to and multiply in the presence of nutrients may give rise to secondary growth of micro-organism clusters which can cause clogging when dislodged.

Mitigation

Common on-farm management practices to mitigate against the transmission of human and animal pathogens as a result of irrigation with contaminated water, are to

- ! irrigate only crops that will be disinfected (cooked) before eaten, that is, crops that are not eaten raw;
- ! use an application method that does not wet the produce (e.g. drip irrigation); and
- ! allow as much time as possible to pass between the last irrigation and harvesting in order to maximise the natural die-off of pathogens. The survival rate of pathogens varies greatly depending on the type of pathogen and environmental conditions.

Common on-farm management practices to mitigate against the clogging of irrigation equipment, are to

- ! switch to an alternative application system; and
- ! regularly disinfect dripper lines to prevent secondary regrowth of micro-organisms which can cause clogging when dislodged.

Criteria

Table 1: Effects of Faecal Coliforms (*E.Coli*) on Crop Quality

Concentration Range (<i>E. coli</i> counts/100 mL)	Crop Quality
<i>Target Water Quality Range # 1</i>	<i>Irrigation water can be applied with any irrigation method to any crop with little likelihood that this will lead to the spread of human pathogens</i>
1 - 1 000	<p>Likelihood of contamination from vegetables and other crops eaten raw and of milk from cows grazing on pastures will result in the transmission of human pathogens</p> <p>Fruit trees and grapes may be irrigated provided that the fruits are not wetted</p> <p>Crops and pastures not consumed raw can be irrigated with any method provided crops and pastures are allowed to dry before harvesting and grazing</p>
> 1 000	<p>Provided water treatment quality is equivalent to or better than primary and secondary treated waste water, and that no contact is allowed to take place with humans, water can be used in irrigation for the production of fodder, tree plantations, nurseries, parks, etc.</p>

Note:

- ! The above criteria are based largely on the existing criteria of the Department of Health for the disposal of treated effluent from waste water treatment works.
- ! Since there is only limited consensus on the faecal coliform concentrations that can be allowed in water used to irrigate crops for human consumption, these criteria must be treated as tentative.

Table 2: Effect of Faecal Coliforms (and other bacterial populations) on Irrigation Systems (primarily drip irrigation)

Concentration Range (bacterial count/m℞)	Clogging of irrigation equipment (primarily drip irrigation systems)
<i>Target Water Quality Range # 10 000</i>	Practically no problems with clogged drip irrigation equipment
10 000 - 50 000	Slight to moderate likelihood of clogging of drip irrigation equipment
> 50 000	Increasingly likely that clogging of drip irrigation equipment will occur

Modifications Crop Quality

- ! The World Health Organization recommends that the faecal coliform limit be relaxed to 1 000 faecal coliforms/100 m℞ for vegetables eaten raw. In recognition of the greater risk posed by helminthic diseases, however, they also recommend a limit of one or less helminthic eggs and one or less protozoan parasite cyst/℞.
- ! Aerosolation of bacteria may occur during spray irrigation and may require precautionary measures.

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Copper

Tentative Guideline

Background Information

Introduction Copper occurs in three oxidation states, as metallic copper(0), cuprous copper(I) and cupric copper(II). Copper is an essential micro-nutrient for plants but at high concentrations becomes toxic to plants. Plants respond to the copper concentration in the soil solution. Similar to most trace elements, copper is strongly adsorbed by soil. Its addition to soils, in relatively high concentrations over the short-term, may not result in reduced crop growth or in its accumulation in plant parts detrimental to humans or animals. However, continuous application over extended periods results in its accumulation in the surface soil layer, in practice, the cultivated or plough layer.

Occurrence Many minerals containing copper are known, some of which are important semi-precious minerals, such as malachite, azurite and turquoise. Copper is also sometimes found in the elemental state. Copper(II) carbonate, hydroxide and sulphide are insoluble in water, while copper sulphate, nitrate and chloride are soluble. Ammonium complexes of copper are also soluble in water. At neutral and alkaline pH, the concentration of copper in surface waters is usually low, typically, around 0.003 mg/l, whereas in acidic waters, copper readily dissolves, and substantially higher concentrations may occur. The concentration of copper in sea water is approximately 0.0003 mg/l. Copper is readily adsorbed and precipitated in sediments at alkaline pH. Re-mobilisation of copper to underlying water occurs on acidification.

Copper has excellent conducting properties. One of the most important industrial uses of copper is in the electrical industry.

Interactions Soils were previously treated for years with copper sulphate as a fungicide. The fact that they mostly do not display toxicity symptoms is often quoted as evidence that copper combines strongly with most soils.

The soil chemical behaviour of copper is similar to those of cadmium, lead, nickel and zinc. Copper concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex. Sorption dominates at the relatively low concentrations that are of concern for water quality criteria for irrigation.

Soil pH has a major effect on the concentration of copper in the soil solution and its solubility decreases with increasing pH. At high pH values copper hydroxide, which has a low solubility, is precipitated from solution. Copper availability to plants is reduced when the soil organic matter content is high and at high concentrations of phosphate, zinc and manganese.

Implications for irrigation with water containing copper involve the following:

! Copper can be expected to be retained in the soil surface layers because of strong sorption by the soil exchange complex. In cultivated land it accumulates in the plough layer.

! Significant downward movement to below the plough layer is unlikely, as is resultant

contamination of ground water with copper.

- ! The larger the soils cation exchange capacity (determined by clay content and clay mineral type), the more copper can generally be sorbed.
- ! Soils with a neutral to alkaline pH can accept a greater copper load than acidic soils before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the total copper concentration, measured in mg/R. Total copper is measured after acidification of the water sample. The reference method for the determination of copper is atomic absorption spectrometry. If other methods are used for measuring copper, their characteristics relative to the reference method should be known.

Data Interpretation Because copper is retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions are reached. In order to prevent its accumulation, the total load applied to soil needs to be limited. International criteria for the concentration of copper in irrigation water have been calculated (using limited available information) to ensure that it does not accumulate to either phytotoxic levels or levels that are toxic to consumers within a given time period. These calculations assume that copper accumulates within the top 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality have been accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The copper concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that copper does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The copper concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that copper can be economically removed from water intended for irrigation purposes.* However, should its removal be required, copper can be removed by raising the pH and precipitating the insoluble copper carbonate and hydroxide complexes with lime treatment. The precipitation is followed by settlement and filtration as in conventional water treatment.

The precipitation process requires careful monitoring to ensure complete removal. A watery, copper-rich sludge is generated in the process; this may present disposal difficulties.

The Effects of Copper

Norms The different norms used in the guidelines to assess the effects of copper on irrigation water use are summarised in the following table:

Irrigation water uses	Norms for measuring water quality effects
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Application to commercial crops	<p>! Crop yield as affected by crop sensitivity to copper uptake through plant roots</p> <p>! Crop quality as determined by copper toxicity to consumers</p>
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects

Copper is an essential plant micro-nutrient and is an important component of several plant enzymes. Copper deficiency symptoms occur in plants grown in soil that have a low copper concentration. Approximately 6 mg/kg of copper in soil is the lower limit for healthy plant growth. Copper toxicity is usually associated with soil concentrations in the range of 150 - 400 mg/kg. Depending on plant species, copper toxicity occurs in nutrient solutions at concentrations between 0.1 and 1 mg/R.

Mitigation

Common on-farm management practices to mitigate against copper uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline; and/or
- ! switch to a crop that is more tolerant to copper;
- ! apply ample phosphate fertilisers or iron salts; the addition of either has been reported to reduce copper toxicity.

Criteria

Effects of Copper on Crop Yield and Quality

Concentration Range (mg/R)	Crop Yield	Crop Quality
<p><i>Target Water Quality Range # 0.2</i></p> <p>0.2 - 5.0</p> <p>> 5.0</p>	<p><i>Depending on plant species, nutrient solutions containing 0.1 - 1.0 mg/R can induce copper toxicity</i></p> <p>Maximum acceptable as concentration for fine textured neutral to alkaline soils</p> <p>Acceptable for irrigation only over the short term on a site-specific basis</p>	<p><i>Yield reduction and crop failure are the main effects of copper-contaminated soils. Generally copper does not accumulate in edible parts of plants to levels that are dangerous to consumers (root crops such as potatoes and radishes have been shown to concentrate copper)</i></p>

Note:

- ! The TWQR for relatively unrestricted use on all soils and the concentration range for fine-textured neutral to alkaline soil for irrigation for periods up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! The criteria were derived with the assumption that the soil to be irrigated contained only negligible quantities of copper. Should this not be the case the period of irrigation needs to be reduced accordingly.
- ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods), because it is assumed that the soil has a capacity to deactivate copper.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the values may need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine textured neutral to alkaline soils, can mostly be used.

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Fluoride

Tentative Guideline

Background Information

Introduction Fluoride is the most electronegative member of the halogens and therefore the most reactive. It has a strong affinity for positive ions and readily forms complexes with many metals. In its elemental form, fluorine is a greenish-yellow gas which readily dissolves in water to form hydrofluoric acid. Fluorine is highly reactive and will attack most materials, including glass. Apart from the alkali metal fluorides, most fluorides are insoluble in water. Many soluble complexes are formed with silicates and the transition metals.

Plants respond to the fluoride concentration in the soil solution. Addition of fluoride to soil in relatively high concentrations over the short-term may not result in reduced crop growth or in its accumulation in plant parts to concentrations detrimental to humans or animals. However, continuous applications over extended periods result in accumulation in the surface soil layer, in practice, the cultivated or plough layer.

Occurrence Common fluoride minerals are fluor-spar (CaF_2) and fluor-apatite, which is a calcium fluoro-phosphate. Others of importance are various fluoro-silicates and mixed fluoride salts, such as cryolite (Na_3AlF_6).

Typically, the concentration of fluoride in

- ! unpolluted surface water is approximately 0.1 mg/R;
- ! ground water up to 3 mg/R is common, but as a consequence of leaching from fluoride containing minerals to ground water supplies, a range of 3 - 12 mg/R and higher may be found; and
- ! sea water is approximately 1.4 mg/R.

Fluoride is present in many foods, and water is not the only source thereof. Drinking water is estimated to contribute between 50 % - 75 % of the total dietary fluoride intake in adult human beings.

In industry, fluorine and fluorides are used in the isotopic enrichment of uranium, in the manufacture of various fluorochemicals such as fluoro-chlorohydrocarbon refrigerants and in the etching of glass.

Interactions Fluoride is only very weakly sorbed by the soil exchange complex and its movement in soil is not affected by exchange reactions. Fluoride is, however, strongly adsorbed to iron and aluminium oxides and to clay minerals. The amount of fluoride plants remove from soil is generally unrelated to the fluoride content of the soil or the irrigation water. The controlling factors appear to be soil type, calcium and phosphorous content, and soil pH. Neutral and alkaline soils deactivate fluoride, and thereby restrict uptake by roots.

The implications of irrigating with water containing fluoride include the following:

- ! Retention in the soil surface layers due to sorption of fluoride by the soil. In cultivated land, accumulation will occur in the plough layer.

- ! Significant downward movement to below the plough layer and hence contamination of ground water with fluoride is unlikely under alkaline and neutral conditions. Under acidic conditions leaching to ground water occurs.
- ! Soils with a neutral to alkaline pH will be able to accept a greater fluoride load than acidic soils before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the dissolved fluoride concentration, in units of mg/l. The reference method for the determination of fluoride is the SPADNS colorimetric method. The SPADNS method is based on the formation of a red colour between the fluoride ion and a zirconium dye lake and relies on the tendency of fluoride to complex strongly to the zirconium ion. Where other methods are used, such as use of a fluoride-specific electrode or ion chromatography, their characteristics relative to the reference method should be known.

Data Interpretation Because fluoride is retained by soils, it may accumulate to phytotoxic concentrations. In order to prevent its accumulation the total load applied to soil needs to be limited. International criteria for the concentration of fluoride in irrigation water have been calculated (using limited available information) to ensure that accumulation to either phytotoxic levels, or levels that are toxic to consumers, within a given time period does not occur. The calculations assume that fluoride accumulates within the top 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The fluoride concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that fluoride does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The fluoride concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that fluoride can be economically removed from water intended for irrigation use.* However, should it be required, methods for the removal of fluoride include

- ! adsorption in a bed of activated alumina;
- ! removal in ion exchange columns along with other anions; and
- ! removal in membrane processes such as reverse osmosis and electrodialysis together with virtually all other ions.

Regeneration of the activated alumina or ion exchange bed produces a high fluoride stream which can pose disposal difficulties. A concentrated reject stream is also produced from reverse osmosis and electrodialysis, and needs careful disposal.

The techniques used are sophisticated and relatively expensive both in capital and operating costs. High levels of skills are needed in the design, operation and maintenance of the equipment.

The Effects of Fluoride

Norms The different norms used in the guideline to assess the effects of fluoride on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to fluoride uptake through plant roots ! Crop quality as determined by fluoride toxicity to consumers
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects The most serious effect of fluoride is usually not its effect on plant growth, but rather its effect on animals and humans that consume plants that have accumulated fluoride. Plant roots mostly exclude fluoride, but some accumulate large amounts. For the most part these plants are, however, not consumed by humans or animals. Plant roots and leaves of some plants are damaged when grown in nutrient solutions containing 0.02 - 0.5 mg/R fluoride. When present in the gaseous form, fluoride is most easily absorbed by plant foliage.

Mitigation Common on-farm management practices to mitigate against fluoride uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline (lime also adds calcium which reacts with fluoride); and/or
- ! switch to a crop that is more tolerant to fluoride;
- ! apply agricultural gypsum to raise the soil calcium content and promote the formation of fluoride which has a relatively low solubility. (Addition of gypsum to irrigation water will have a similar effect).

Criteria **Effects of Fluoride on Crop Yield and Quality**

Concentration Range (mg/R)	Crop Yield, Crop Quality and Soil Sustainability
<i>Target Water Quality Range # 2.0</i>	<i>No adverse effects on crops</i>

2.0 - 15.0	Maximum acceptable as concentration for fine textured neutral to alkaline soils
> 15.0	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soils, and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are the same as for most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! On acid sandy soils fluoride concentrations should be maintained at less than 1 mg/R.
- ! The criteria were derived with the assumption that the soil to be irrigated contains only negligible quantities of fluoride. Should this not be the case the period of irrigation needs to be reduced accordingly.
- ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because it is assumed that the soil has a capacity to deactivate fluoride.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the values may need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils can mostly be used.

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Iron

Tentative Guideline

Background Information

Introduction Pure iron is silvery in colour but usually appears as greyish-black or brown deposits as a result of oxidation. Iron is found in three oxidation states, namely, 0, II and III of which the III oxidation state is the most common. In water, iron can be present as dissolved ferric iron, Fe(III), as ferrous iron, Fe(II) or as suspended iron hydroxides. Biologically iron is an essential micro-nutrient required by all living organisms. Since most soils are naturally iron-rich, its concentration in the soil solution is determined primarily by soil pH, and soil aeration, which determine the oxidation state and thus solubility of iron. Therefore, the iron content of irrigation water has a negligible effect on the iron concentration in soil water, except in the case of soils with a low natural iron content. Iron dissolved in irrigation water gives rise to problems when it precipitates as damaging deposits on leaves or causes clogging of irrigation equipment.

Occurrence Iron is the fourth most abundant element and constitutes five percent of the earth's crust. It is found in many minerals, the most common of which is haematite (Fe_2O_3), widely used as an iron ore for metallurgical purposes. Other important iron minerals are pyrite (FeS_2), siderite (FeCO_3), magnetite (Fe_3O_4), goethite ($\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$), limonite ($2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) and a number of mixed ores, such as chalcopyrite (CuFeS_2) and arsenopyrite (FeAsS). Pyrite is often associated with coal formations and iron may also occasionally be found in the elemental form, either as terrestrial iron or as meteoric iron. The reddish colour of soil is due to iron, the median concentration in soil being four percent (m/m). Typically, the concentration of dissolved iron in :

- ! unpolluted surface water is in the range of 0.001 - 0.5 mg/R; and
- ! sea water is approximately 0.002 mg/R.

The speciation of iron is strongly related to the pH and the redox potential of the water. At neutral or alkaline pH, under oxidising conditions, the dissolved iron concentration is usually in the $\mu\text{g/R}$ range but under reducing conditions, soluble ferrous iron may be formed and substantially higher concentrations, in the mg/R range may be encountered. Where marked acidification of the water occurs and the pH is less than 3.5, the dissolved iron concentration can be several hundred mg/R, as may be the case with acid mine drainage.

There is a natural cycling of iron between the dissolved and precipitated phases at the water sediment interface, in which micro-organisms, particularly iron bacteria such as *Gallionella spp.*, play a significant role.

Interactions Iron is a major constituent in many soils. The iron concentration in soil water is determined primarily by its oxidation state and soil pH. Iron is precipitated as hydroxides in alkaline soils, that render the iron unavailable to plants, so that iron deficiency mostly develops in alkaline soils. Ferrous iron dissolved in irrigation water oxidises and precipitates upon aeration when applied to soil, and is therefore relatively unavailable to plants. Under waterlogged conditions iron is reduced and goes into solution. Precipitated iron in soil binds phosphorus and molybdenum (essential plant nutrients), thereby making them unavailable to plants.

Therefore, the iron content of irrigation water for most soil types has little effect on the iron concentration in the soil solution.

Measurement The criteria are given in terms of the total iron concentration, expressed in units of mg/l. The reference method is atomic absorption spectrometry (AAS) using an air acetylene flame. Measurement of the total iron concentration requires acidification followed by filtration prior to AAS analysis. Where other methods are used, their characteristics relative to the reference method should be known.

Data Interpretation International criteria for the concentration of iron in irrigation water have been calculated on a similar basis to that of other trace elements. In this guideline the criteria were calculated (using limited available information) to ensure that iron does not accumulate to either phytotoxic levels or levels that are toxic to consumers, within a given time period. The calculations assume that iron accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is used in the criteria for:

- ! The iron concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that iron does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The iron concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that iron can be economically removed from water intended for irrigation use.* However, should this be required, iron can be removed from water using an oxidising process which will convert the iron into an insoluble oxide removable by filtration. The following treatment approaches are used:

- ! The water can be aerated by devices such as fountains, cascades or mechanical aeration; and
- ! The water can be chemically oxidised by dosing with chlorine, hydrogen peroxide, ozone or other strong oxidants. On an industrial scale chlorine is commonly used as the chemical oxidant. Post-treatment, high levels of residual chlorine should be avoided since this may interfere with the quality of the water for the purpose intended.

For the optimisation of treatment processes it is important to determine both the total and dissolved iron species and their relative concentrations.

The Effects of Iron

Norms The different norms used in the guideline to assess the effects of iron on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<ul style="list-style-type: none"> ! Crop yield as affected by crop sensitivity to iron deposits on leaves ! Crop quality as affected by iron oxide spots on marketable product
Application to sustain suitability of irrigated soil	<ul style="list-style-type: none"> ! No known negative effect in natural soils
Maintenance of irrigation equipment	<ul style="list-style-type: none"> ! Iron precipitation can clog irrigation equipment

Effects Iron is an essential micro-nutrient. Chlorosis as a result of iron deficiency is often encountered on alkaline soils. Iron-rich irrigation water can cause a number of problems, namely:

- ! When sprinkler irrigated, an iron coating may be deposited on plant leaves or fruit. It could be in the form of light brown spotting, a silvery coating or a thick black coating. This interferes with normal photosynthesis, transpiration and respiration and may lead to damage and eventual plant death.
- ! Iron oxide spots or coatings on marketable plant products reduce their quality and thus the price that can be obtained for the produce.
- ! Iron precipitates can cause the clogging of irrigation equipment.

Mitigation Common on-farm management practices to mitigate against iron uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline; and/or
- ! ensure that soil is well aerated and not waterlogged; the solubility of iron increases under reducing conditions such as those associated with waterlogged soils; and/or
- ! switch to an irrigation system that does not wet plant leaves or marketable products.

Criteria

Table 1: Effects of Iron on Crop Yield and Quality

Concentration Range (mg/R)	Crop Yield and Quality
<i>Target Water Quality Range # 5.0</i>	<i>Not toxic to root uptake by plants in aerated soils. Plant foliage damaged or blemished by iron deposits when wetted during irrigation</i>
5.0 - 20.0	Maximum acceptable as concentration for fine-textured neutral to alkaline soils
> 20.0	Exceeds the maximum acceptable concentration used by most international guidelines

Note:

- ! The TWQR for relatively unrestricted use on all soils and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.

Table 2: Effects of Iron on Water Uses involving Irrigation Equipment

Concentration Range (mg/R)	Clogging of Irrigation Equipment
< 0.2	Only minor problems encountered with clogging of drip irrigation systems
0.2 - 1.5	Moderate problems encountered with clogging of drip irrigation systems
> 1.5	Severe problems encountered with clogging of drip irrigation systems

Modifications

- ! The criteria may not be protective for commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because the criteria assume that the soil has a capacity to deactivate iron.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
- ! Since potted plants are grown for only limited periods, the criteria applicable to fine-textured neutral to alkaline soils, can mostly be used, provided leaves are not wetted.

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Lead

Tentative Guideline

Background Information

Introduction Lead is a bluish-white, very soft metal, which is highly malleable and ductile. It is also highly resistant to corrosion. Plants respond to the lead concentration in the soil solution. Similar to most trace elements, lead is strongly adsorbed by soil and its addition to soils in relatively high concentrations over the short-term may not result in reduced crop growth or in its accumulation in plant concentrations detrimental to humans or animals. However, continuous application over extended periods results in its accumulation in the surface soil layer, in practice, the cultivated or plough layer.

Occurrence The most common mineral ores of lead are galena (lead sulphide), cerussite (lead carbonate) and anglesite (lead sulphate). The occurrence of lead in its elemental state is rare. Lead tends to accumulate in sediments and soils in the environment. Lead which has been absorbed by vertebrate organisms, is to a large extent deposited in the bony skeleton.

Typically, the concentration of lead in

- ! surface water is less than 0.010 mg/R;
- ! sea water is no more than 0.003 mg/R; and
- ! contaminated water may be several mg/R. Dissolution of lead from lead pipes occurs particularly with soft water low in calcium carbonate.

Lead has many industrial applications which can give rise to sources of lead contamination in water supplies. Lead is used in batteries, in domestic water distribution pipes, in paints and as an organic lead compound, alkyl lead, in gasoline.

Interactions The soil chemical behaviour of lead is similar to that of cadmium, copper, nickel and zinc. Lead concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex. Sorption dominates at the relatively low concentrations that are of concern for water quality criteria for irrigation. Soil pH has a major effect on the concentration of lead in the soil solution and its solubility decreases with increasing pH.

Implications for irrigation with water containing lead include the following:

- ! Due to the strong sorption of lead by the soil exchange complex, it can be expected to be retained in the soil surface layers.
- ! Significant downward movement to below the plough layer and contamination of ground water with lead is unlikely.
- ! The larger the soil's cation exchange capacity (determined by clay content and clay mineral type) the more lead can generally be sorbed.
- ! Soils with a neutral to alkaline pH will be able to accept a greater lead load than acidic soils before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the total lead concentration, in units of mg/R. Lead can be measured colorimetrically at low concentration (0 - 30 Fg/R) using the dithizone method

to form the cherry red lead dithizonate, which is measured spectrophotometrically. Alternatively, lead may be measured by atomic absorption spectrophotometry. These two methods constitute the reference methods for lead. If other methods are used, their characteristics relative to the reference methods should be known.

Data Interpretation

Because lead is retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions are reached. In order to prevent its accumulation, the total load applied to soil needs to be limited. International criteria for the concentration of lead in irrigation water has been calculated (using limited available information) to ensure that it does not accumulate to either phytotoxic levels or levels that are toxic to consumers, within a given time period. The calculations assume that lead accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The *arithmetic mean concentrations* of the applied water (preferably application volume weighted) are given in the criteria for two concentration ranges, namely:

- ! The lead concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that lead does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The lead concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options

It is highly unlikely that lead can economically be removed from water intended for irrigation use. However, should it be required, lead is most conveniently removed by applying conventional water treatment processes of coagulation with alum, ferric salts or lime followed by settlement and filtration.

The coagulation/flocculation process requires careful monitoring to ensure complete removal. A watery sludge containing lead is generated in the process; this may present disposal difficulties.

The Effects of Lead

Norms

The different norms used in the guidelines to assess the effects of lead on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<p>! Crop yield as affected by crop sensitivity to lead uptake through plant roots</p> <p>! Crop quality as determined by lead toxicity to consumers</p>
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects

Compared to other trace elements, lead has a fairly low phytotoxicity and is seldom encountered in the soil solution because lead is strongly sorbed by soil. Toxic effects have been observed in nutrient solutions at concentrations of 1 mg/l. Lead concentrations tend to be higher in roots than in leaves, or in the fruit parts of plants, suggesting that translocation does not occur readily. Plants are nonetheless capable of accumulating lead at concentrations that are potentially hazardous to humans and livestock, for example, potatoes, lettuce and hay.

Mitigation

Common on-farm management practices to mitigate against lead uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline; and/or
- ! switch to a crop that is more tolerant to lead.

Criteria

Effects of Lead on Crop Yield and Quality

Concentration Range (mg/l)	Crop Yield and Quality
<p><i>Target Water Quality Range</i> # 0.2</p>	<p><i>Application at the rate of 1 000 mm/annum for 100 years would result in lead accumulation to 89 mg/kg in the top 150 mm of soil. Few plants appear to be affected at this level</i></p> <p><i>Yield reduction and crop failure are the main effects of lead contaminated soils. Generally lead does not accumulate in edible parts of plants to levels that are dangerous to consumers (potatoes, lettuce and hay have, however, been shown to concentrate lead)</i></p>
0.2 - 2.0	Maximum acceptable as concentration for fine-textured neutral to alkaline soils
> 2.0	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soils and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! The criteria were derived with the assumption that the soil to be irrigated contains only negligible quantities of lead. Should this not be the case the period of irrigation should be reduced accordingly.
- ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because the criteria assume that the soil has a capacity to deactivate lead.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
- ! Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils can mostly be used.

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Lithium

Tentative Guideline

Background Information

Introduction Lithium is the lightest of all the metals; it is also lighter than water. It reacts with water, resulting in the release of hydrogen. Like sodium, higher concentrations tend to be found in hot springs associated with arid hydrogeological conditions.

Occurrence Lithium is found as the pearly-coloured spodumene (lithium aluminium silicate) and amblygonite (lithium aluminium fluorophosphate) in granite pegmatites. It also occurs as lilac-coloured lepidolite mica.

Typically, lithium concentrations in fresh waters are around 0.002 mg/R. Higher concentrations can be found in spring waters and mineral springs. Sea water contains approximately 0.18 mg/R lithium.

Lithium is used in the aerospace industry in the manufacture of light alloys. Lithium salts are used in lubricating greases and in metal cleaning and soldering fluxes. Lithium is also used in the manufacture of glazes and enamels, in alkaline batteries and in photography.

Interactions Lithium is a monovalent cation which takes part in cation exchange reactions. It is fairly easily displaced by all other cations and is therefore fairly mobile and leaches relatively easily. Its behaviour is similar to sodium but it is less strongly adsorbed and more mobile. However, the fact that it is adsorbed does not appear to have much effect on its availability to plants.

Over the long term (i.e. under conditions of chemical equilibrium) the lithium content of irrigation water determines the percentage of exchangeable lithium on the soil exchange complex. Since the quantity of cations in irrigation water is normally small compared to those adsorbed on a soil's cation exchange complex, the exchangeable lithium percentage of a soil profile changes only slowly towards that implied by its concentration in irrigation water. Several years to decades may be required before steady state conditions are established throughout the soil profile.

Measurement Lithium is very easily measured by flame emission photometry, by virtue of the intense red light emission of thermally-excited lithium atoms. This is the reference method. Where other methods are used, their characteristics relative to the reference method should be known.

Data Interpretation Since the exchangeable lithium percentage of a soil profile is well buffered against changes, plant and soil reactions with lithium in soil are not affected by short-term variations in the lithium content of irrigation water. The mean lithium concentration of water during the irrigation season (application volume weighted where possible) should therefore be used to assess the following plant and soil reactions:

- ! The degree to which the growth of lithium-sensitive plants is affected by root uptake of lithium.
- ! The negative effect of lithium on soil physical properties.

Treatment Options

It is highly unlikely that lithium can economically be removed from water intended for irrigation use. However, should it be required, lithium can be removed from water, together with other ions which constitute the TDS, by a number of desalination processes, including:

- ! Demineralisation in a mixed-bed ion exchange column, usually where the feed TDS is up to approximately 2 000 mg/R.
- ! Treatment by membrane processes such as reverse osmosis and electro dialysis, where the TDS concentration is in the range of 2 000 - 3 500 mg/R.
- ! Distillation, in cases where the TDS is 10 000 mg/R or more.

The Effects of Lithium

Norms The different norms used in the guideline to assess the effects of lithium on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to lithium uptake through plant roots
Application to sustain suitability of irrigated soil	! Accumulation in soil to levels where crop yield is affected ! Accumulation in soils to concentrations where soil physical properties are affected
Maintenance of irrigation equipment	! No known effects

Effects Irrigation with water containing lithium results in the retention of lithium by the soil exchange complex. Two negative effects are associated with lithium-affected soils, namely:

- ! reduced crop yield caused by lithium toxicity when lithium is taken up by plant roots; and
- ! impaired soil physical conditions (similar to the effects of sodium on soils).

The uptake of lithium by plant roots can result in the accumulation of lithium to levels that are toxic to plant growth. This can cause reduced yields or impaired crop quality. Crops sensitive to sodium are generally also sensitive to lithium. Most crops grown in nutrient solutions can tolerate up to 5 mg/R lithium. *Citrus is, however, very sensitive and shows toxic responses at concentrations of 0.06 - 0.1 mg/R.* Severe toxicity symptoms have been displayed by grapefruit irrigated with water containing 0.18 - 0.25 mg/R. Barley growth is reduced by 1 mg/R in nutrient solutions while cabbage displays a 30 % decrease in growth in a nutrient solution with 6.9 mg/R lithium. Increased potassium and decreased calcium uptake has been observed at high lithium concentrations, possibly due to changes in root membrane permeability.

Lithium has a similar (but more severe) effect than sodium on soil physical properties. This effect is, however, not noticeable at concentrations toxic to plants. Criteria which protect plant growth automatically protect soil physical properties as well.

Mitigation Common on-farm management practices to mitigate against the negative effects of an increasing lithium concentration in water affecting crop yield, are to

- ! accept a reduced crop yield; and/or
- ! switch to crops that are more tolerant; and/or
- ! apply calcium and/or magnesium to the soil to promote displacement of lithium from the soil exchange complex.

Criteria **Effects of Lithium on Crop Yield**

Concentration Range (mg/R)	Crop Yield
<i>Target Water Quality Range</i> # 2.5	Tolerated by most crops in nutrient solutions containing 5 mg/R. Some crops are more sensitive, e.g. sugar beet (3.5 mg/R), barley (1 mg/R) and citrus (0.075 mg/R).

Note:

- ! The TWQR for relatively unrestricted use on all soils is similar to most international criteria.
- ! The above criteria guideline is based on relatively limited information and should be viewed as tentative.

Modifications ! Citrus experience lithium toxicity at low levels. The limit for irrigating citrus is 0.075 mg/R.

- ! The criteria to prevent crop yield reduction is in most cases applicable for the prevention of lithium-induced soil physical degradation.
- ! Commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) may tolerate slightly higher lithium concentrations.
- ! Potted plants normally receive water applications in excess of irrigated crops and are not regularly leached.

Lithium can thus be expected to accumulate to higher concentrations than in irrigated soil. However, since potted soil can be leached fairly easily and is normally used for limited periods only, the same criteria as for commercial irrigated crops can be used.

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Manganese

Tentative Guideline

Background Information

Introduction Manganese is a grey-white, brittle metal and is found in several oxidation states, namely - III, -I, 0, I, II, III, IV, V, VI and VII. Plants respond to the manganese concentration in the soil solution. Manganese is an essential plant nutrient. It appears to be required as an enzyme activator. Its concentration is highest in the reproductive parts of plants (seeds) and lowest in woody sections.

Occurrence Manganese is a relatively abundant element, constituting approximately 0.1 % of the earth's crust. Commonly occurring minerals which contain manganese include pyrolusite (MnO_2), manganite ($Mn_2O_3 \cdot H_2O$), rhodochrosite ($MnCO_3$) and rhodonite ($MnSiO_3$). Manganese is found in solution predominantly as the manganous Mn(II) ion, which can be stabilised by complexation to humic acids. On oxidation to the manganic ion, Mn(IV), manganese tends to precipitate out of solution to form a black hydrated oxide, which is responsible for the staining problems often associated with manganese-bearing waters.

Typically, the median concentration of manganese in

- ! fresh water is 8 $\mu\text{g}/\text{R}$, with a range of 0.02 - 130 $\mu\text{g}/\text{R}$;
- ! soils is 1 000 mg/kg; and
- ! sea water is approximately 0.2 $\mu\text{g}/\text{R}$.

Manganese concentrations in the mg/R range can be found in anaerobic, bottom level waters, where manganese has been mobilised from the sediments. Industrial uses of manganese include

- ! the manufacture of steel and manganese alloys;
- ! the salts of manganese as drying compounds in varnishes and oils;
- ! manganese chloride in dry cell batteries;
- ! manganese carbonate as the pigment "manganese white"; and
- ! manganese dioxide in the manufacture of amethyst glass and decorative porcelain.

Interactions Manganese is a normal soil constituent. Its concentration in the soil solution is largely determined by soil pH and oxidation-reduction reactions. This is further modified by sorption and desorption reactions with the soil exchange complex. Manganese is reduced (and the solubility increased) under waterlogged conditions in association with low pH. Under these conditions the manganese concentration in the soil solution can increase to levels toxic to plant growth. The effect of soil pH is to decrease the manganese concentration in the soil solution as soil pH increases. Manganese toxicity seldom occurs at soil pH (water) above 5.5 - 6.0. In practice the concentration of manganese in irrigation water is therefore relatively unimportant in determining the concentration in soil solution.

Measurement Manganese is measured as total manganese, in units of mg/R. The reference method for the determination of manganese in water is atomic absorption spectrometry, using an air-acetylene flame. Samples should be acidified prior to analysis to dissolve manganese adsorbed to suspended matter. Where other methods are used, their characteristics relative to the reference method should be known.

Data

Interpretation

International criteria for the concentration of manganese in irrigation water have been calculated (using limited available information) to ensure that it does not accumulate to phytotoxic levels, within a given time period. The calculations assume that manganese accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The manganese concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that manganese does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The manganese concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options

It is highly unlikely that manganese can be economically removed from water intended for irrigation use. However, should it be required, manganese is commonly removed from water using an oxidising process which converts the manganese into an insoluble oxide removable by filtration. The reaction is considerably more difficult to achieve than with iron and normally requires the use of a strong oxidising agent. Agents commonly used include

- ! chlorine;
- ! hydrogen peroxide;
- ! potassium permanganate; and
- ! ozone.

Where the oxidant leaves a residual, as is the case with chlorine, the residual should be removed before the water is supplied for use.

On an industrial scale the process usually needs to be closely controlled and monitored because the consequences of incomplete treatment may be severe.

The Effects of Manganese

Norms

The different norms used in the guideline to assess the effects of manganese on irrigation water use are summarised in the table that follows:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to manganese uptake through plant roots
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where crop yield is affected
Maintenance of irrigation equipment	! Clogging of irrigation emitters and distribution system

Effects Plants vary in their sensitivity to manganese and toxicity has been observed at a fraction of a mg/l in nutrient solution. At fairly low concentrations manganese can cause the clogging of irrigation pipelines, drip and microjet emitters.

Mitigation Common on-farm management practices to mitigate against excessive manganese uptake by plants on irrigated land, are to

- ! apply agricultural lime, in order to raise or maintain soil pH to neutral to slightly alkaline; and/or
- ! maintain the aeration status of the soil to ensure oxidising conditions; and/or
- ! switch to a crop that is more tolerant to manganese.

Criteria **Table 1: Effects of Manganese on Crop Yield and Soil Sustainability**

Concentration Range (mg/l)	Crop Yield and Soil Sustainability
<i>Target Water Quality Range # 0.02</i>	<i>Depending on plant species, nutrient solutions containing a few tenths of a mg/l can induce manganese toxicity</i>
0.02 - 10.0	Maximum acceptable concentration for fine-textured neutral to alkaline soils
> 10.0	Acceptable for irrigation only over the short term on a site-specific basis

Note:

! The TWQR for relatively unrestricted use on all soils, and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to the most conservative international criteria.

! The above criteria are based on relatively limited information and should be

viewed as tentative.

- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Table 2: Effects of Manganese on Water Uses involving Irrigation Equipment

Concentration Range (mg/l)	Clogging of Irrigation Equipment
< 0.1	Only minor problems encountered with clogging of drip irrigation systems
0.1 - 1.5	Moderate problems encountered with clogging of drip irrigation systems
> 1.5	Severe problems encountered with clogging of drip irrigation systems

- Modifications**
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the values may need adjustment.
 - ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils, can mostly be used.

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Molybdenum

Background Information

Introduction Molybdenum is a silvery-white, very hard metal and is an essential micro-element for all living organisms, but is toxic in excess. Molybdenum plays a role in many enzymes, notably the flavoprotein enzyme, xanthine oxidase.

Molybdenum occurs in soil predominantly as the molybdate (MoO_4^{2-}) anion. Plants absorb molybdenum predominantly as molybdate from the soil solution. Plants concentrate molybdenum and are apparently able to tolerate concentrations of several 100 mg/kg in plant tissue without adverse effect. High molybdenum concentrations in feed is toxic to ruminants. The risk associated with molybdenum uptake by crops is related to adverse effects to livestock that consume these crops.

Occurrence The principle ore of molybdenum is molybdenite (MoS_2), frequently found in association with tungsten-bearing minerals. Molybdenum is also found in association with lead, as the mineral wulfenite (PbMoO_4). Typically, the concentration of molybdenum in

- ! freshwater is between 0.03 - 10 $\mu\text{g}/\text{R}$, with a median concentration of 0.5 $\mu\text{g}/\text{R}$;
- ! sea water is similar to that of freshwater; and
- ! soils is between 0.1 - 40 mg/kg, with a median concentration of 1.2 mg/kg.

Molybdenum tends to be associated with the suspended sediment fraction of water. Higher concentrations are generally found in sediments and soils and not in solution.

Molybdenum is used in the manufacture of hardened alloys and high strength steels and as a lubricant additive. It is used as a filament material in the electronics industry, in glass and ceramics, and as a corrosion inhibitor.

Interactions Because of the generally low anion exchange capacity of soils, molybdenum is similar to other anions which are mostly very mobile in soils. Anion exchange capacity generally increases with decreasing pH, especially in soils with high fractions of aluminium and iron oxides. Molybdenum is therefore retained by acid soils, making it unavailable to plants. Thus molybdenum availability to plants increases with increasing soil pH.

Measurement The criteria are given in terms of the total molybdenum concentration, in units of mg/R. The reference method for the measurement of molybdenum is by electrothermal atomic absorption spectrometry. Where other methods are used, their characteristics relative to the reference method should be known.

Data Interpretation Molybdenum concentrations in water should be interpreted in conjunction with molybdenum concentrations in soils and sediments, and also in relation to copper and sulphate concentrations. The arithmetic mean concentration of molybdenum in irrigation water (preferably application volume weighted) are given in the criteria for:

- ! The molybdenum concentration that can be applied to *any soil on a continuous basis*.
- ! The molybdenum concentration that can be applied to *acidic soils on a short-term*

basis.

Treatment Options

It is highly unlikely that molybdenum can be economically removed from water intended for irrigation use. However, should it be required, molybdenum is most conveniently removed by raising the pH and precipitating the insoluble salts, after adding lime or iron salts in the pH range of 8.5 - 11.5. The precipitation is followed by settlement and filtration as in conventional water treatment.

The precipitation process requires careful monitoring to ensure that removal is complete. To achieve very low residuals, it may be necessary to pass the stream through an ion exchange column charged with the appropriate ions.

A watery, molybdenum-rich sludge or concentrate stream is generated in the processes that may present disposal difficulties.

The Effects of Molybdenum

Norms

The different norms used in the guidelines to assess the effects of molybdenum on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop quality as determined by molybdenum toxicity to animals
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects

Molybdenum in low concentrations is an essential plant micro-nutrient, and plants can take up relatively large amounts of molybdenum without any apparent ill effect. Molybdenum uptake appears to be proportional to the amount added to the soil. The accumulation of molybdenum in plant tissue is of concern because of its toxicity to livestock (molybdenosis). Molybdenum concentrations of 0.01 mg/l in soil and nutrient solutions have been found to accumulate in legumes to levels that are toxic to cattle. The effects of molybdenum toxicity to livestock are aggravated by conditions of copper deficiency and high sulphur intake.

Mitigation

Common on-farm management practices to mitigate against excessive molybdenum uptake by plants on irrigated land, are to

- ! switch to a crop that is less absorbent of molybdenum; and/or
- ! acidify the soil (to reduce molybdenum availability);
- ! switch to crops that are not used as forage for livestock.

Criteria

Effects of Molybdenum on Water Uses involving Application to Commercial Crops

Concentration Range (mg/l)	Crop Quality
<p><i>Target Water Quality Range # 0.01</i></p> <p>0.01 - 0.05</p> <p>> 0.05</p>	<p><i>Threshold concentration to be used over the long term which will not cause the accumulation of molybdenum in plants to levels that are toxic to animals</i></p> <p>Maximum acceptable as concentration for fine-textured acidic soils</p> <p>Acceptable for irrigation only over the short term on a site-specific basis</p>

Note:

- ! The TWQR for relatively unrestricted use on all soils, and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! Commercial floricultural crops grown in greenhouses are mostly not fed to animals. They can tolerate higher levels than those given in the criteria.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are, however, grown for only limited periods, they can tolerate higher levels than those given in the criteria.

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Nickel

Tentative Guideline

Background Information

Introduction Nickel is a silvery-white, hard, semi-magnetic metal, and occurs most commonly as a sulphide ore. Plants respond to the nickel concentration in the soil solution and nickel, like most trace elements, is strongly adsorbed by soil. The addition of nickel in relatively high concentrations over the short-term may not result in reduced crop growth or in its accumulation in plant parts to concentrations detrimental to humans or animals. However, continuous applications of nickel over extended periods result in its accumulation in the surface soil layer, in practice, the cultivated or plough layer.

Occurrence Nickel is widespread in the environment, with a slightly higher occurrence than copper in the earth's crust. It tends to be concentrated on particles of manganese oxide in soils. Nickel occurs together with iron as a major constituent of most meteorites. Nickel minerals include sulphides and arsenides. Important minerals are millerite (NiS), niccolite (NiAs) and chloanthite (NiAs₂). The most common state is Ni(II). Most of the nickel released globally is from the burning of fossil fuels. Nickel is insoluble in water and other common solvents. Most soils tend to bind relatively large quantities of nickel.

Typically, the concentration of nickel in unpolluted fresh water is 0.0005 mg/R, and in sea water, is approximately 0.0006 mg/R. Higher concentrations may be found around mines where the ores contain nickel. Nickel is used for manufacturing a variety of alloys and is widely used for making coins, in armour plating and for burglar proof vaults. Nickel compounds are also used for catalytic properties in the chemical industry and in the hydrogenation of fats in the manufacturing of margarine.

Accumulation of nickel can occur in certain plants as well as in sediments, usually in the sulphide form.

Interactions The soil chemical behaviour of nickel is similar to that of cadmium, copper, lead and zinc. Nickel concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex. Sorption dominates at the relatively low concentrations that are of concern for water quality criteria for irrigation. Soil pH also has a major effect on the concentration of nickel in the soil solution. Its solubility decreases with increasing pH.

Implications for irrigation with water containing nickel, include the following:

- ! Due to the strong sorption of nickel by the soil exchange complex, nickel is expected to be retained in the soil surface layer.
- ! There is little significant downward movement through the soil profile, and hence contamination of groundwater is unlikely.
- ! Generally, the larger the soil's cation exchange capacity (determined by clay content and clay mineral type) the more nickel can be sorbed.
- ! Soils with a neutral to alkaline pH will be able to accept a greater nickel load than acidic soils, before concentrations in the soil solution become phytotoxic.

Measurement The criteria are given in terms of the total nickel concentration, in mg/R. Total nickel is normally measured by atomic absorption spectrometry after acidification of the sample. If other methods are used for the measurement of nickel, their characteristics relative to the reference method should be known.

Data Interpretation Because nickel is retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions is reached. In order to prevent nickel accumulation, the total load applied to soil needs to be limited. International criteria for the concentration of nickel in irrigation water have been calculated (using limited available information) to ensure that accumulation to either phytotoxic levels, or levels that are toxic to consumers, will not occur within a given time period. The calculations assume that nickel accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The nickel concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that nickel does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The nickel concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that nickel can be economically removed from water intended for irrigation use.* However, should this be required, nickel can be removed from water by precipitation at alkaline pH with lime, or by flocculation and coprecipitation with a ferric salt. Alternatively ion exchange can be used.

The waste stream produced will have elevated levels of nickel, and will require appropriate disposal.

The Effects of Nickel

Norms The different norms used in the guideline to assess the effects of nickel on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to nickel uptake through plant roots ! Crop quality as determined by nickel toxicity to consumers
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects Nickel can be translocated from soils through the human and animal food chain. It is not considered to be an essential plant nutrient. However, there is some evidence that nickel in small quantities may improve the growth of some plants, including oats and mustard. At high concentrations plant growth is reduced. In sand and solution cultures nickel has been found to be toxic to a number of plants at concentrations of 0.5 - 1.0 mg/R. Concentrations of 0.5 mg/R in water culture are toxic to flax, but symptoms are reduced in the presence of molybdenum.

Mitigation Common on-farm management practices to mitigate against nickel uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline conditions; and/or
- ! switch to a crop that is more tolerant to nickel.

Criteria **Effects of Nickel on Crop Yield and Quality**

Concentration Range (mg/R)	Crop Yield and Quality
<i>Target Water Quality Range</i> # 0.20	<i>Depending on plant species, nutrient solutions containing 0.5 - 1.0 mg/R can induce nickel toxicity</i>
0.20 - 2.0	Maximum acceptable as concentration for fine-textured neutral to alkaline soils
> 2.0	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soils, and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.

! The criteria are calculated to ensure soil sustainability for continued crop production.

- Modifications**
- ! The criteria were derived with the assumption that the soil to be irrigated contains only negligible quantities of nickel. Should this not be the case, the period of irrigation should be reduced accordingly.
 - ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods), because it is assumed that the soil has a capacity to deactivate nickel.
 - ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
 - ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils, can mostly be used.

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Nitrogen (Inorganic)

Background Information

Introduction Nitrogen, as used in this guideline, refers to all inorganic nitrogen forms present in water, that is, ammonia, ammonium, nitrite and nitrate. Ammonia (NH_3) and ammonium (NH_4), are the reduced forms of inorganic nitrogen and their relative portions in water are governed by water temperature and pH. Nitrite (NO_2^-) is the inorganic intermediate and nitrate (NO_3^-) the end product of the oxidation of organic nitrogen and ammonia. Nitrate is the more stable of the two forms, and usually, by far, the more abundant in the soil and water environment. In view of their co-occurrence and rapid interconversion, nitrite and nitrate are usually measured and considered together.

Nitrogen in irrigation water is primarily of concern because of :

- ! its stimulatory effect on plant growth when applied in excess of plant requirements,
- ! its potential to leach and contaminate ground water sources, and
- ! its stimulatory effect on nuisance growth of algae and aquatic plants in irrigation structures (canals, storage, dams, etc.), that can interfere with the efficient distribution of irrigation water (diminished carrying or storage capacity of irrigation structures and clogging of sprinklers and micro-irrigation openings)

Occurrence All nitrogen forms are interrelated by a series of reactions, collectively known as the nitrogen cycle, which regulate the flow of nitrogen from inorganic soil forms in soil, air and water into living systems, and then back again to inorganic forms. Organic nitrogen is also associated with other components of organic matter, such as total organic carbon (TOC) and total phosphorus. In aquatic systems, interactions with suspended matter and with other nitrogen species such as ammonia, nitrate and nitrite take place.

Inorganic nitrogen is seldom present in high concentrations in unimpacted natural surface waters. This is because inorganic nitrogen is rapidly taken up by plants and converted to protein and other organic forms of nitrogen in plant cells. Inorganic nitrogen concentrations in unimpacted aerobic surface waters are usually less than 0.5 mg/R. In highly enriched waters, concentrations may be as high as 5 - 10 mg N/R.

Oxidised forms of organic nitrogen (usually nitrate) can sometimes be present in very high concentrations ($> 150 \text{ mg NO}_3\text{-N/R}$) in ground water. Such high concentrations occur under natural conditions (e.g. mineral salts derived from rock and soil) or from seepage of sewage systems and leaching of fertilizers from soil.

Nitrogen in surface runoff from the surrounding catchment is the major inflow source to surface waters. This is supplemented by the discharge from effluent streams containing human and animal wastes, agricultural fertilizers and organic industrial wastes. In highly impacted catchments, the inorganic nitrogen arising from human activities can greatly exceed natural sources. In addition many groups of bacteria are able to transform organic nitrogen during the decomposition of organic material.

Interactions Nitrogen occurs predominantly as nitrate in irrigation water. The ammonium form is usually a result of contamination with waste water. The amounts of nitrate and ammonia added through the application of irrigation water, are usually small compared to that which is applied as fertilizer or released by the mineralisation of organic matter. The concentrations of nitrate and ammonia in soil water are determined primarily by the amounts added as fertilizer, sorption on the soil exchange complex (mainly ammonia), organic matter

transformations (where nitrogen can be either incorporated into, or released from soil organic matter) and nitrogen uptake by crops.

Being an anion, nitrate is only very weakly sorbed by the soil exchange complex (which is mainly a cation exchanger) and its movement in the soil is considered to be unaffected by exchange reactions. Therefore, nitrates leach freely, and their relative concentration and distribution in a soil profile is largely determined by the leaching fraction (see TDS). Ammonia takes part in normal cation exchange reactions. Its movement in the soil profile is largely determined by exchange reactions, and leaching of the ammonium ion occurs very seldom under normal conditions.

The interaction of nitrogen with soil is complicated by the fact that nitrogen is a major constituent of soil organic matter. Generally, the amount of nitrogen in soil organic matter is one order of magnitude greater than that present in the soil solution. The concentration and oxidation state of nitrate or ammonium in the soil solution is largely affected by organic matter transformations. For example, nitrogen is consumed by micro-organisms during the breakdown of fresh organic material (low concentrations in soil) and released when soil organic matter is decomposed. Acidity is released during the microbial oxidation of reduced sources of nitrogen, for example ammonium ions. High concentrations of reduced nitrogen sources in irrigation water can therefore cause soil acidification.

Since nitrogen is one of the major plant nutrients, plants actively absorb nitrate and ammonium ions from the soil solution, as do soil micro-organisms. Nitrate ions that remain in the soil solution can be leached by irrigation water applications, and thus may pollute ground water.

Measurement

The concentration of inorganic nitrogen in water is obtained by adding together the individual concentrations of ammonia ($\text{NH}_4 + \text{NH}_3$), nitrite and nitrate. No single analytical technique will provide a measure of the inorganic nitrogen. Nitrite and nitrate are determined by the cadmium reduction method followed by diazotisation and spectrophotometry. Nitrite alone is determined by diazotisation without prior reduction. Free ammonia (the sum of $\text{NH}_4 + \text{NH}_3$) is determined by the phenate hypochlorite method followed by spectrophotometry or colorimetry.

Where other analytical methods are used their characteristics relative to the reference methods should be known. Concentrations are usually expressed as mg N/R. Prior filtration may be required where water samples are turbid. Analysis, after the taking of the sample, should be as rapid as possible to minimise the effects of bacterial transformations and pH changes. Water samples should preferably not be preserved with acid before analysis; rather the samples should be kept at low temperature (4 EC).

Data Interpretation

The nitrogen concentration of irrigation water provides an indication of:

- ! The *arithmetic mean concentration* during the active vegetative growing season (preferably application volume weighted) which is used to determine levels at which nitrogen needs of crops may be exceeded. It is assumed that crops are fertilized according to their nitrogen requirements, and that the application of nitrogen through irrigation water can lead to an excess of nitrogen. Provided that the nitrogen concentrations are less than the crop's nitrogen requirement, fertilizer applications can be adjusted to compensate for unintended applications.
- ! The degree to which ground water is at risk of nitrate pollution; this can be expected when crops are supplied in excess of their needs, either during the active vegetative growing season, before, or thereafter. The arithmetic mean concentration (preferably

application volume weighted) is used during the *active vegetative growing season* and the *non-vegetative growing season*.

- ! The likelihood that nuisance growth of algae and aquatic plants will occur. The concentration during each irrigation release or where releases are near continuous, the average of weekly samples over a four-week period, should be compared with the criteria.

Treatment Options

It is highly unlikely that nitrate can be economically removed from water intended for irrigation use. However, should this be required, nitrate is not readily removed from water supplies. Some reduction of nitrate may be achieved using slow sand filtration, but the method is not reliable. Biological reduction of nitrate to nitrogen gas is feasible in the presence of a suitable carbon source. Non-specific methods of removing nitrate include:

- ! Passing the water stream through an ion exchange column which is selected for its affinity for nitrates. The method is expensive because other anions will also be removed, depending on the nature of the resin;
- ! Reverse osmosis will remove nitrate effectively from water, along with high percentages of virtually all other ions and many organic compounds.

On a large scale the processes described require competent operation, control and maintenance.

The Effects of Nitrogen

Norms

The different norms used in the guideline to assess the effects of nitrogen on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<ul style="list-style-type: none"> ! Crop yield as affected by crop sensitivity to uptake through roots or foliage ! Crop quality as determined by lodging and delayed crop maturity
Application to sustain suitability of irrigated soil	<ul style="list-style-type: none"> ! Groundwater contamination as a result of nitrate leaching ! No known negative effects of nitrogen on soil itself
Maintenance of irrigation equipment	<ul style="list-style-type: none"> ! Nuisance growth of algae and aquatic plants can cause clogging of irrigation equipment

Effects

Nitrogen is one of the essential macro plant nutrients and its presence in irrigation water is mostly viewed as beneficial. However, high concentrations may stimulate excessive vegetative growth and cause lodging, delayed crop maturity and poor quality (as is the case when too much nitrogenous fertilizer is applied). These effects are similar to excessive use

of fertilizers.

Crop sensitivity and the need for nitrogen varies with different growth stages. High nitrogen levels may be beneficial during early growth stages, whereas these may cause yield or quality losses during the flowering and fruiting stages. Crops that are supplied with too much nitrogen, or supplied with nitrogen on a continuous basis, continue to grow late into the season at the expense of fruit production, that is, yields are often reduced, fruit may be late in maturing and have a low sugar content. Excessive vegetative growth in grain crops produces weak stalks that are unable to support the grain.

Ruminants are sensitive to nitrogen. Heavy nitrogen applications to pastures used as livestock feed can cause the nitrogen to accumulate to levels that are hazardous to animals.

Sensitive crops such as grapes and most other fruit crops may be affected when total nitrogen concentrations in irrigation water exceed 5 mg/l. Most other crops remain relatively unaffected until nitrogen exceeds 30 mg/l. These concentrations, either nitrate or ammonium are equivalent to nitrogen applications of 50 and 300 kg/ha respectively for an irrigation application of 1 000 mm.

Nitrogen in irrigation water may stimulate the growth of algae and aquatic plants in irrigation canals and storage dams. During optimum growth conditions of sunlight, temperature and other nutrients, rapid growth of algae may occur. This can, in turn, result in clogged valves, pipelines, sprinklers and filtering equipment. Maintenance costs are also increased when algae and aquatic plants need to be cleared from irrigation canals, storage dams and drainage ditches.

Mitigation

On-farm management options available to deal with elevated nitrogen levels in irrigation water, are to

- ! reduce nitrogen fertilizer application by the amount added with irrigation water; and/or
- ! dilute the nitrogen-rich source if another water source is available, or to use the nitrogen-rich source only during vegetative plant growth stages when crop nitrogen requirements are high; and/or
- ! switch to crops with a high nitrogen requirement; and/or
- ! use a water source that is low in nitrogen during periods when crop nitrogen requirements are low;
- ! limit leaching as far as possible to reduce the likelihood of ground water contamination;
- ! control algae growth in irrigation structures chemically with copper sulphate;
- ! remove nuisance algae and water plants from irrigation water with screens and filters.

Criteria

Table 1: Effects of Nitrogen on Crop Yield and Quality and Ground Water Contamination

Concentration Range (mg/l)	Crop Yield and Quality	Ground Water Contamination
<i>Target Water Quality Range # 5</i>	<i>The unintended nitrogen application should, at normal irrigation applications, be low enough not to affect even sensitive crops such as grapes and most fruit trees</i>	<i>The unintended nitrogen application should, at normal irrigation applications, be low enough so that most of it would be utilised by the irrigated crop and little be available for leaching to ground water</i>
5 - 30	Sensitive crops increasingly likely to be affected (depending on magnitude of irrigation application). Other crops remain largely unaffected in the lower concentration range, but are increasingly affected as concentration increases	Likelihood of ground water contamination increases, depending on actual volume of irrigation water applied and uptake by irrigated crop
> 30	Most crops are affected. A limited range of crops can utilise the nitrogen applied. Severe restrictions are placed on the utilisation of these waters	Increasingly serious likelihood of ground water contamination

Table 2: Effects of Nitrogen on Irrigation Equipment

Concentration Range (mg/l)	Effects on Irrigation Equipment
<i>Target Water Quality Range # 0.5</i>	<i>Oligotrophic conditions. No nuisance growth of aquatic plants or blue-green algal blooms in irrigation structures (canals and storage dams)</i>
0.5 - 2.5	Mesotrophic conditions. Occasional growth of nuisance plants and blue-green algae in irrigation structures
2.5 - 10	Eutrophic conditions. Frequent growth of nuisance plants and blue-green algal blooms in irrigation structures, in the absence of other limiting growth factors
> 10	Hypertrophic conditions. Almost continuous growth of nuisance plants and blue-green algal blooms in irrigation structures in the absence of other growth-limiting factors

Modifications

- ! The criteria for the nitrogen content of irrigation water are calculated to prevent the oversupply of nitrogen to crops and to protect groundwater from nitrate pollution. Both can be met if the nitrogen supplied through irrigation does not exceed the crop requirement. Since crops vary in their total nitrogen requirement and the growth period during which it is required, criteria should preferably be calculated on a site-specific basis. The criteria presented above are for "average" conditions.
- ! Potted plants usually receive water applications in excess of the assumptions used to derive the criteria. Practically no leaching occurs with the result that more nitrogen will be applied than under field conditions. This may be acceptable when lush vegetative growth is required, but is detrimental to flower development.
- ! Plant nutrients are often added to irrigation water for commercial floriculture production. Care should be taken to adjust the nitrogen applications based on the nitrogen content of the irrigation water.

Sources of Information

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Background Information

Introduction The pH of a solution is the negative logarithm to the base ten of the hydrogen ion concentration, given by the expression

$$\text{pH} = -\log_{10}[\text{H}^+]$$

where $[\text{H}^+]$ is the hydrogen ion concentration.

At pH less than 7 water is acidic, while at pH more than 7 water is alkaline.

The pH of natural waters is a measure of the acid-base equilibrium of various dissolved compounds, and is a result of the carbon dioxide-bicarbonate-carbonate equilibrium which involves various constituent equilibria, all of which are affected by temperature. Conditions which favour production of hydrogen ions result in a lowering of pH, referred to as an acidification process. Alternatively, conditions which favour neutralisation of hydrogen ions result in an increase in pH, referred to as an alkalinisation process. The pH of water does not indicate the ability to neutralise additions of acids or bases without appreciable change. This characteristic, termed buffering capacity, is controlled by the amounts of acidity and alkalinity present.

The pH of water does not have direct consequences except at extremes. The adverse effects of pH result from the solubilisation of toxic heavy metals and the protonation or deprotonation of other ions.

Occurrence The geology and geochemistry of the rocks and soils of a particular catchment area affect the pH and alkalinity of the water. The pH of most raw waters lies in the range of 6.5 - 8.5. Biological activities and anthropogenic sources such as nutrient cycling and industrial effluent discharge, respectively, may give rise to pH fluctuations. Notably acid mine drainage, can have a marked effect on the pH. Further, acid-forming substances released into the atmosphere such as oxides of sulphur and nitrogen may ultimately alter the acid-base equilibria in natural waters and result in a reduced acid-neutralising capacity, and hence a lowering of the pH.

Interactions The hydrogen ion concentration is probably the single most important reactant in chemical reactions. It largely determines the solubility and availability of many plant nutrients and potentially toxic ions. Soil is much more strongly buffered against changes in pH than is water. Except in extreme conditions irrigation water will cause soil pH to change slowly with time and does not present a problem in itself over the short term. Extreme pH conditions in irrigation water can be corrosive or scale-forming to some of the components used in irrigation equipment.

Measurement Water pH is measured electrometrically using a pH meter. The pH meter should be calibrated against standard buffer solutions of known pH, prior to measurement of a sample. Fresh samples should be used to determine pH. The temperature at which measurements are made should always be reported since pH measurement is influenced by temperature.

Errors may be caused by the presence of sodium at pH values more than 10.

Data Interpretation Use of single-sample (maximal or minimal) or mean values to compare with the criteria given, depends on application. The pH should be interpreted in relation to the full analysis of the water sample and its use. The pH of irrigation water indicates the levels at which

- ! soil pH will equilibrate over the very long term. The *long term mean* pH (calculated from the hydrogen ion concentration of individual applications of the applied irrigation water) is used.
- ! leaf burn (foliar damage) of crops will occur when crop foliage is wet by irrigation water. The *maximum or minimum pH* during the active growing season is used.
- ! irrigation equipment may be damaged by either corrosion or encrustation. These effects are calculated with various indices; see Total Hardness. As a preliminary estimate of the potential to cause damage to equipment the *seasonal mean pH* (calculated from the hydrogen ion concentration of individual applications) is used.

Treatment Options Although seldom used, the pH of irrigation water can be adjusted up or down by the addition of an alkali or an acid respectively.

Agricultural lime is mostly used as an alkali reagent, whereas sodium carbonate and sodium hydroxide are mostly not used (see **sodium** and **sodium adsorption ratio**). Acidic reagents commonly used are carbon dioxide (a gas which forms carbonic acid in water), controlled burning of sulphur (which forms sulphuric acid in water) or sulphuric acid. Nitric acid and phosphoric acid are also used, in part because they are also a source of plant nutrients. The reagent is usually diluted using a dosing pump controlled by a pH monitor.

The adjustment of pH in water will inevitably increase the salinity of the water by adding ions such as calcium, carbonate, hydroxyl or sulphate. Reagents should be chosen to minimise secondary effects. For certain purposes the pH of the water will need to be stabilised to within a chosen range by the addition of buffering reagents.

The handling of acids and alkalis is often hazardous requiring special precautions in the form of protective clothing and in materials used in the manufacture of the dosing equipment.

The Effects of pH

Norms The different norms used in the guideline to assess the effects of pH on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<p>! Crop yield as affected by foliar damage due to wetting</p> <p>! Crop quality as affected by damage of marketable product due to wetting</p>
Application to sustain suitability of irrigated soil	! Soil pH as affected by long-term irrigation water application
Maintenance of irrigation equipment	! Damage to irrigation equipment

Effects

The solubility and bio-availability of many plant nutrients and potentially toxic constituents are highly dependent on pH. For example, most micro-nutrients and heavy metals are unavailable for plant uptake at high soil pH and available (often at toxic concentrations) at lower pH levels.

Soil microbial populations are also markedly affected by soil pH levels. The effect of soil pH on crop production is thus mostly indirect. Since soil is more strongly buffered against changes in pH than water, irrigation water will cause soil pH to change slowly and is seldom a problem in itself.

Direct contact with crop foliage by either high or low pH waters causes foliar damage, which can, depending on the severity and timing of the damage, result in a decreased yield or damage to fruit or other marketable products.

Extreme pH values are associated with corrosion and encrustation of irrigation equipment.

Mitigation

Since the negative effects of extreme pH in irrigation water on commercial crops is associated with damage due to wetting, the on-farm management practice to mitigate against the effects of extreme pH of irrigation water is to switch to a method of irrigation that will not cause wetting of the foliage or marketable products.

Common on-farm management practices to mitigate against the effects that irrigation water pH may have on soil sustainability, are to

- ! apply agricultural lime to maintain soil pH in the desired range when irrigating with low pH water; and/or
- ! apply soil acidifiers (e.g. sulphur, reduced nitrogenous fertilizers, etc.) to maintain soil pH in the desired range when irrigating with high pH water.

A common on-farm management practice to mitigate against the effects irrigation water pH may have on irrigation equipment, is to switch to irrigation equipment made of material (e.g. plastic) that is tolerant of pH over a wide pH range.

Criteria

Effects of pH on Crop Yield and Quality, Sustainability of the Soil and Irrigation

Equipment

pH Range	Crop Yield and Quality	Sustainability	Irrigation Equipment
< 6.5	Increasing problems with foliar damage when crop foliage is wet. This could give rise to yield reduction or a decrease in the quality of marketable materials	Increasing problems with the availability of several micro- and macro-nutrients in toxic concentrations are experienced in this range over the long term	Increasing problems with corrosion of metal and concrete in irrigation equipment are experienced in this range Practically no problems experienced with clogging of drip irrigation systems
<i>Target Water Quality Range 6.5 - 8.4</i>	<i>Even when crop foliage is wetted, this should not cause foliar damage in plants which will result in a yield reduction or a decrease in the quality of marketable products.</i>	<i>Soil pH within this range does not present major problems with either unavailability of plant nutrients or toxic levels of elements.</i>	<i>Mostly no major problem with either corrosion or encrustation of irrigation equipment is experienced within this range (see Total Hardness). Slight to moderate problems with the clogging of drip irrigation systems.</i>
> 8.4	Increasing problems with foliar damage affecting yield or decrease in visual quality of visual marketable products are experienced in this range.	Increasing problems with the unavailability of several micro- and macro-nutrients are experienced within this range over the long term.	Increasing problems with encrustation of irrigation pipes and clogging of drip irrigation systems are experienced in this range.

- Modifications** ! The severity of effects increase as the buffering capacity of the irrigation water increases. Water with an extreme pH and a low TDS concentration may have minimal effects because of the low quantity of neutralising agent it requires.
- ! Corrosion and encrustation are affected by several factors in addition to the pH of water (see **total hardness**).

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Scaling/Corrosion

Background Information

Introduction The equilibrium saturation point of water for calcium carbonate, as well as for other salts, is described by various indices which provide an indication of the scale-forming or corrosive potential of water. If the water is supersaturated it will be *scale forming*, whereas if it is undersaturated, it will be non-scale forming or *corrosive*. The Langelier index is often used to predict the potential of an irrigation water to be either scale forming or corrosive.

Distribution and application systems represent much of the capital outlay required for irrigation farming. Maintenance and replacement of corroded or scaled-up components of the system may incur unnecessary costs for the irrigator. The application of appropriate water treatment practices can minimise the adverse effects of scaling and corrosion. Ideally, water that is *stable*, i.e. non-corrosive and non-scaling, should be used for irrigation.

Occurrence Various indices are used to quantify the corrosivity or scaling tendency of water. The Langelier index provides a measure with which to assess the potential of an irrigation water to be either scale forming or corrosive, and it is calculated from the concentrations of calcium, alkalinity and total dissolved salts, the pH and the temperature of the water.

The corrosive/scaling properties of water can be manipulated during water treatment by the addition of various chemicals to the water. See Modifications for other indices that are often used to determine the scaling and corrosive potential of water.

Interactions The corrosive properties of water are influenced not only by the chemical composition of water, but by other determining factors such as the bacteriological activity, the presence of electrical fields and the conjunction of dissimilar metals.

Measurement The Langelier index (LI) is based on the calculation of the saturation pH (pH_s) of water with respect to the calcium carbonate concentration. It is calculated as the difference between the measured (or actual) pH of the water (pH_a) and the hypothetical pH (pH_s) of the water, if it were in equilibrium with solid calcium carbonate ($CaCO_3$) at the actual concentrations of bicarbonate ions and calcium ions present:

$$LI = pH_a - pH_s$$

A positive Langelier index indicates scale forming, and a negative Langelier index indicates a scale-dissolving tendency, with the possibility of corrosion. Calculation of the pH_s value is derived from the pH, temperature and concentrations of the alkalinity, calcium, and dissolved salts.

The Langelier index should be calculated for the water temperature (or range of temperatures) that is applicable to the particular site and distribution or application system. For example, the water temperature in black, slow-flowing, PVC dripper lines is much higher than in fast-flowing aluminium sprinkler lines.

Data Interpretation The Langelier index of irrigation water provides an indication of the

- ! likelihood for corrosion to occur in irrigation distribution and application systems (negative LI index values);

- ! likelihood for scale forming to occur in irrigation distribution and application systems (positive LI index values); and
- ! likelihood for irrigation distribution and application systems to be unaffected by the irrigation water quality (near-neutral LI values)

For practical purposes the arithmetic mean value of the applied water (preferably application volume weighted) can mostly be used to calculate the Langelier index. Where the water shows marked variation over time it is advisable to also calculate the extreme LI values, since both corrosion and scale forming are practically irreversible.

No single test or index is infallible and it is thus desirable to apply as many of the available indices and tests as possible and to use the most conservative (safest) values for planning purposes. (See Modifications).

Treatment Options

The tendency of a water to form a scaling film or be aggressive can be reduced by manipulation of the chemical composition of the water. *In practice, treatment is mostly too costly an option to overcome scale-forming or corrosive characteristics of irrigation water.* Mitigating measures are mostly preferred. However, each case has to be decided on its own merits.

- ! Scaling is commonly reduced by removal of alkalinity and calcium hardness from the water until it becomes slightly undersaturated with respect to the calcium carbonate concentration, and consequently slightly aggressive. (Alkalinity can be reduced by adding a weak acid solution, while calcium hardness can be reduced by base exchange softening, which is seldom practical for irrigation applications).
- ! Conversely, an aggressive water, which tends to attack unprotected structures, can be stabilised by increasing the alkalinity and calcium content. Poorly-controlled additions may result in a scaling water.
- ! A water which is corrosive to metal fittings can usually be rendered less corrosive by increasing its alkalinity and reducing the sulphate and chloride content. Alkalinity addition is the more simple procedure since removal of sulphate and chloride would necessitate using desalination techniques.
- ! The modifications necessary to achieve acceptably stable water may be very complex and require a high level of treatment skills and sophisticated analytical facilities. The amount of chemicals to be added can be determined by graphical methods, using manual calculations, or with computer software, such as Stasoft III.

The Effects of Total Hardness

Norms The different norms used in the guideline to assess the effects of a given value of the Langelier index on irrigation water use, are summarised in the table that follows:

Irrigation Water Uses	Norms for Measuring Water Quality Effects
Application to commercial crops	! No norms used
Application to maintain suitability of irrigated soil	! No norms used

Maintenance of irrigation equipment	<p>! Likelihood of corrosion to irrigation equipment</p> <p>! Likelihood of scale forming in irrigation equipment</p>
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Effects

For the irrigator, a corrosive (or aggressive) water may necessitate premature replacement of pipes, irrigation ditches and other irrigation equipment. A scaling water may result in impaired water flow rates and blocking or partial blocking of dripper and sprinkler orifices, which may in turn result in poor water distribution and reduced yields.

A scaling water mostly presents a problem of white scale formation on leaves and fruit when sprinklers are used. These deposits often build up on leaves, fruit and flowers and negatively affect the marketability of these products. No numerical criteria are provided for these effects.

The presence of oxidised iron as a result of corrosion can give rise to a red discolouration of the water and impact negatively on the aesthetic quality of irrigated fruits. (See **iron**).

Mitigation

Chemical Corrosion

- ! Chemical corrosion can be eliminated or alleviated by using corrosion-resistant coatings or materials (e.g. PVC pipes) for all elements of the water distribution system which come into direct contact with the water.
- ! Cathodic protection may be required in some instances, for example where pipelines run close to electrical cables, or close to electric railway lines.
- ! The resistance of concrete to corrosion as a result of dissolution of lime by low salinity soft water can be greatly increased by the use of good quality concrete compared to poor quality porous concrete.
- ! Corrosion can be avoided by preventing different metals from having contact with one another in the water distribution system.
- ! Chemical corrosion can be reduced by limiting sulphate and chloride concentrations in the water.

Scaling

- ! Scaling due to hard water may be alleviated by lowering the pH. Scale is extremely difficult to remove and even with the use of the stabilised acid wash procedure, removal is seldom effective.
- ! Electromagnetic anti-scaling devices are available on the market but have not been proven or widely accepted.
- ! Scaling due to increases in water temperature in the distribution system may be reduced by not irrigating in the middle of the day or, where practical, burying the distribution pipeline.

Biological Corrosion

- ! Biological corrosion is best prevented by commencing with a clean, sediment-free system that is maintained as such. Bacterial growth or other biological activity should be monitored and prevented if possible.
- ! The organic content of the water, and especially the Assimilable Organic Carbon (AOC) content should be kept as low as possible in order to deprive micro-organisms of nutrition. This in turn will limit the amount of post-disinfection required. However, post-disinfection using chlorination or chloramination is imperative at high AOC concentrations and/or in distribution systems having long retention times. Re-chlorination in multiple steps may be required to ensure the presence of adequate chlorine residual in all parts of the distribution system.

Criteria

Effects on Irrigation Equipment

Langelier Index Range	Irrigation Equipment
# -0.2	Increasing problems with corrosion of metal and concrete in irrigation equipment
<i>Target Water Quality Range</i> -0.2 - +0.2	<i>No major problem with either corrosion or scaling of irrigation equipment</i>
> +0.2	Increasing problems with scaling or encrustation of irrigation pipes, drippers and other openings

Modifications

Various indices are used to quantify the tendency of water to be either corrosive or scale forming. No single test or index is infallible. It is thus advisable to apply as many of the available indices and tests as possible and to use the most conservative (safest) for planning purposes. It is also advisable to obtain expert opinion. The following are the most well-known complementary scaling/corrosion indices.

! *Aggressiveness index*

The aggressiveness index (AI) formulated for evaluating corrosion in an asbestos cement pipe, is defined as

$$AI = pH + \log_{10}(AH)$$

where

A = total alkalinity in mg/RCaCO₃, and
H = calcium hardness as mg/R CaCO₃

Interpretation of the aggressiveness index is as follows

Aggressiveness Index (AI)	Water Property
\$ 12	Non-aggressive

10.0 - 11.9	Moderately aggressive
# 10	Highly aggressive

! *Ryznar index*

The Ryznar index (RI) is defined as

$$RI = 2pH_s - pH_a$$

where pH_s is the saturation pH as given by the Langelier method, and pH_a is the actual pH.

An alternate formula for the Ryznar index is

$$RI = pH_a - 2LI$$

where LI is the Langelier index.

Interpretation of the Ryznar index is as follows

Ryznar index	Effect
< 6.5	Scale-forming tendency
> 6.5	Corrosive tendency

! *Corrosion ratio*

The corrosion ration (R) is used to estimate the corrosive tendency of chloride and sulphate ions, and is given by

$$R = \{ me/R(Cl + SO_4^{2-}) \} / \{ me/R \text{ alkalinity as } CaCO_3 \}$$

A ratio below 0.1 indicates general freedom from corrosion in neutral to slightly alkaline oxygenated waters. Higher ratios indicate a tendency towards progressive corrosion, i.e. aggressive waters.

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Selenium

Tentative Guideline

Background Information

Introduction Selenium is a semi-metallic element with pronounced photoconductivity. At low concentrations it is an essential nutritional micro-element in humans and animals, and is an integral part of the enzyme glutathione peroxidase.

Occurrence Selenium occurs in association with sulphide ores of heavy metals such as copper, iron and zinc. Selenium forms insoluble metal selenides which tend to be incorporated into sediments, particularly under anaerobic conditions. Selenium is also bio-accumulated by certain plants which are used as indicators in the bio-measurement of selenium. Typically, the concentration of selenium in surface water is less than 10 Fg/R. Elevated concentrations can occur in ground waters in seleniferous areas.

Selenium is used in various industrial processes, such as the manufacture of glass and ceramics, ink and paint pigments, plastics, rubber, photoelectric cells and various alloys.

Interactions The chemistry of selenium is similar to that of sulphur. Selenium occurs in soil predominantly as selenite (SeO_3^{2-}) and selenate (SeO_4^{2-}). Under strong oxidising conditions, selenate is predominant, while selenite occurs under moderately oxidising conditions. Because of the generally low anion exchange capacity of soils, selenium is similar to other anions and is mostly very mobile in soils. In acid soils, containing high fractions of iron and aluminium oxides, selenite forms low solubility complexes with ferric and aluminium hydroxides. In alkaline soils selenium occurs as selenate which is leachable with water.

Measurement The criteria are given in terms of total selenium concentration in units of Fg/R. The reference method for the determination of selenium is atomic absorption spectrometry. Prior to analysis, digestion of the sample followed by reduction of Se(VI) to Se(IV) with hydrochloric acid, and the formation of selenium hydride using a borohydride reagent, is required. If other methods of measuring selenium are used, their characteristics relative to the reference method should be known.

Data Interpretation The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! the selenium concentration that can be applied to *any soil* on a *continuous basis*; and
- ! the selenium concentration that can be applied to *fine-textured soils* for a *period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that selenium can be economically removed from water intended for irrigation purposes.* However, should it be required, selenium is most effectively removed by one of the two processes:

- ! Coagulation and precipitation by treatment with lime or ferric chloride at pH values more than 8.5. Careful monitoring is needed to ensure effective removal.

! Adsorption on to activated alumina at low pH levels.

The processes involved require skilled operation and process control. Both processes produce a waste stream that may be rich in selenium, presenting disposal difficulties.

The Effects of Selenium

Norms The different norms used in the guideline to assess the effects of selenium on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop quality as determined by selenium toxicity to consumers
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentration where crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects Plants take up relatively large amounts of selenium without apparent adverse effects. Of more concern is the toxicity of selenium to animals eating plants containing too much selenium. Selenium is required in small quantities by livestock. Selenium concentrations of around 0.03 - 0.10 mg/kg in forage are required by cattle to prevent deficiencies. On the other hand, concentrations more than 3 - 4 mg/kg are considered toxic. This level of selenium may be absorbed by many plants from a solution containing 0.05 mg/l selenium. In most fruit and annual crops, selenium accumulation is generally restricted to the leaves.

Mitigation Common on-farm management practices to mitigate against selenium uptake by plants on irrigated land, are to

- ! leach excess selenium from the soil when selenium is in the selenate form; and/or
- ! apply sulphate to the soil to inhibit uptake of selenium; and/or
- ! switch to a crop that is less absorbent of selenium.

Criteria

Effects of Selenium on Crop Quality

Concentration Range (mg/l)	Crop Quality
<i>Target Water Quality Range</i> # 0.02	<i>The threshold concentration that can be used over the long term, and which does not result in the accumulation of selenium in plants to concentrations that are toxic to animals</i>
0.02 - 0.05	Maximum concentration range, acceptable for fine-textured soils
> 0.05	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soils and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to most international criteria.
- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

Modifications

- ! Commercial floricultural crops grown in greenhouses are mostly not fed to animals. They could thus tolerate higher levels than given in the criteria.
- ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the values may need adjustment.
- ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured soils can mostly be used.

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Sodium Adsorption Ratio

Background Information

Introduction The sodium adsorption ratio (SAR) is an index of the potential of a given irrigation water to induce sodic soil conditions. (Soil sodicity is usually measured by the percentage of a soil's cation exchange capacity that is occupied by sodium ions). It is calculated from the concentrations of sodium, calcium and magnesium in water, and gives an indication of the level at which the exchangeable sodium percentage (ESP) of the soil will stabilise after prolonged irrigation.

In addition to irrigation water, SAR is also determined on the saturated soil extract. In this case, the SAR gives an indication of the ESP of the soil, and the two values are approximately equal.

Occurrence The SAR is an index of the potential of water to induce sodic soil conditions, and is calculated from the sodium, calcium and magnesium concentrations in the water.

Interactions Over the long-term (i.e. under conditions of chemical equilibrium) the SAR of an irrigation water determines the ESP of the irrigated soil. Since the quantity of cations in irrigation water is normally small, compared to those adsorbed on a soil's cation exchange complex, the ESP over the depth of a soil profile only changes slowly towards that applied by irrigation water SAR. Several years to decades may be required before steady state conditions are established throughout the soil profile.

Changes to the ESP start in the topsoil and move progressively down to lower layers, therefore short-term variations in irrigation water SAR affects the soil profile ESP only marginally, but largely determines the ESP at the soil surface.

The SAR of an irrigation water increases in soil when its sodium, calcium and magnesium content increases together with that of other ions when water is lost through evapotranspiration. This gives rise to a progressive increase in soil ESP from the top to the bottom soil layers in tandem with the increasing salt concentration from top to bottom. By decreasing the leaching fraction both the salt concentration and ESP in the bottom soil layers are thus increased, and *vice versa*.

Since the sodium concentration of water is a common factor for both the SAR and the total salt content) is often found to increase with increasing salt content (EC), the SAR tends to increase with increasing EC. The EC also indirectly determines how soon the soil ESP will reach equilibrium conditions with the irrigation water SAR. The higher the irrigation water EC at a particular SAR, the sooner equilibrium ESP conditions will be established.

It has been found that irrigation water with high bicarbonate/carbonate concentrations gives rise to the precipitation of calcium as calcium carbonate (in soil). This causes the soil solution to become relatively enriched with sodium and, consequently, results in an effective increase in the SAR and the ESP. In order to compensate for this effect, a revised procedure for calculating SAR (the adjusted SAR) is used. The adjusted SAR values are higher for waters with appreciable bicarbonate concentrations and this has become a popular index for calculating the "effective" SAR.

In practice it has, however, been found to over-predict the sodicity hazard, and for this

reason has not been used in this guideline.

The presence of lime and other calcium sources in soil has an effect on the SAR of the soil solution. The effective SAR in the soil solution is reduced by such calcium sources. A calculating procedure to compensate for both this phenomenon and the increase in SAR as a result of lime precipitation from solution is recommended. It is termed the adjusted sodium ratio (adj. RNa) and is an improved index of the soil ESP that would be induced by irrigation water sodicity and can be used instead of SAR. Since SAR and adj. RNa values are normally given within 10 % of each other and adj. RNa requires a more elaborate calculating procedure, SAR is used in these guidelines.

Measurement

SAR is calculated from the total concentrations of sodium, calcium and magnesium in irrigation water by using the following formula.

$$\text{SAR} = [\text{sodium}] / ([\text{calcium}] + [\text{magnesium}])^{0.5}$$

where the concentrations of sodium, calcium and magnesium in solution are measured in mmol/l of sodium, calcium and magnesium in solution. The units in which SAR is measured are thus (mmol/l)^{0.5}. However, SAR values are mostly reported without units.

The SAR is used in preference to the adjusted SAR since it was found that the latter over-predicts the sodicity hazard.

For specific applications such as advanced water quality evaluation procedures which utilise chemical speciation models, the SAR is calculated using the "active" ion concentrations which exclude ion pairs.

Data Interpretation

The SAR of irrigation water provides an indication of the soil ESP that can be expected to develop in soil, once chemical equilibrium has been established.

The SAR is numerically approximately equal to the ESP which is established in the soil under equilibrium conditions. A relationship between ESP and SAR, with ESP approximately equal to $1.475 \text{ SAR} / (1 + 0.0147 \text{ SAR})$, has been derived by the United States Salinity Laboratory from a dataset for soils in the western USA. It is often used locally to calculate the approximate ESP of a soil under equilibrium conditions with a given irrigation water SAR. However, soils vary significantly in their relationship between ESP and SAR and further investigation is therefore required for site-specific applications.

Since the ESP of the soil profile is well buffered against change (see Interactions), plant and soil reactions that are determined by soil profile ESP are not affected by short-term variations in irrigation water SAR. These reactions can be predicted best by the mean SAR of the applied water. The mean SAR of water during the irrigation season (application volume weighted where possible) should therefore be used for the following plant and soil reactions:

- ! The degree to which the growth of sodium sensitive plants is affected by root uptake of sodium.
- ! The development of sodium-induced hardsetting in soils.
- ! The degree to which hydraulic conductivity in the soil profile will be reduced at a given

EC of the soil water.

Since the ESP at the soil surface (where "surface sealing" can develop) is mostly affected by the SAR of the most recent irrigation application (see **Interactions**), the maximum irrigation water SAR during the irrigation season is used to estimate

- ! the ESP-determined potential for the development of infiltration rate reducing surface seals.

Treatment Options

The SAR presents problems (and the need for treatment) only when its value is high. The SAR of a water can be reduced either by decreasing the sodium concentration or by increasing the calcium and/or magnesium concentrations. Sodium can be removed from water only by highly sophisticated physico-chemical separation techniques. Because of the high cost involved, the option of sodium removal is ruled out as uneconomic. The calcium and/or magnesium concentrations can be increased cost-effectively by the addition of calcium and/or magnesium salts to the irrigation water.

Any relatively soluble salt of calcium or magnesium can be added to irrigation water to decrease its SAR. In practice agricultural gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is most often used. Certain practical implications need to be considered:

- ! The addition of salt gives rise to an increase of the salt content of the water, which has potentially negative effects. See **TDS**.
- ! The complementary anions can have negative effects on crop response. For this reason the use of sulphate (which is not considered to be a potentially toxic ion) rather than chlorides (although more soluble) are usually recommended. (Chlorides are also more expensive).
- ! Plant nutritional imbalances can be introduced when large quantities of either calcium or magnesium are added to the soil.
- ! Impurities in the added salt (e.g. fluorides in some gypsum sources) can induce negative effects.
- ! Although reasonably soluble, agricultural gypsum has a limited solubility and special equipment is often required to ensure complete dissolution, such that it does not remain in particulate form; this can lead to the clogging of some irrigation equipment.

Several management alternatives, that can be applied at the point of use, to offset the negative effects of high sodium and SAR are available.

The Effects of the Sodium Adsorption Ratio

Norms The different norms used in the guideline to assess the effects of SAR on irrigation water use are summarised below:

Irrigation Water Uses	Norms for Measuring Water Quality Effects
Application to commercial crops	<ul style="list-style-type: none"> ! Crop yield as affected by crop sensitivity to sodium uptake through plant roots ! Crop quality as determined by damage to marketed product or by regulatory limits on the sodium concentration in the final product
Application to sustain suitability of irrigated soil	<ul style="list-style-type: none"> ! Infiltration rate (because of surface sealing) of soils varying in sensitivity as affected by increasing SAR ! Reduction in hydraulic conductivity of soil ! Hardsetting of soils which affect, <i>inter alia</i>, cultivation
Maintenance of irrigation equipment	! No known effects

Note :

Almost all available information on the effects of SAR when used for irrigation are on the effects on crop yield and water penetration (infiltration rate and hydraulic conductivity) into soil. Less information is available on hardsetting and practically no reliable information is available to link the SAR of irrigation water to crop quality.

Effects By irrigation with sodium-rich water, soil sodicity is induced. Negative effects associated with sodium affected soils, include

- ! reduced crop yield and quality as a result of sodium uptake through the roots of sodium sensitive plants;
- ! impaired soil physical conditions, as manifested by reduced soil permeability (infiltration rate and hydraulic conductivity) and an increased tendency for hardsetting; and
- ! reduced crop yield and quality.

The uptake of sodium by plant roots can result in the accumulation of sodium to levels that are toxic to plant growth, and may be the cause of reduced yield or impaired crop quality. The sodium concentration in the soil water (that which is taken up by plants) is determined by both the mean soil ESP in the root zone and the total salt concentration of the soil water. The higher the total salt concentration and/or the soil ESP, the higher the sodium concentration.

Typical symptoms of plants experiencing sodium toxicity are leaf burn, scorch, and

dead tissue along the outside edges of leaves. Symptoms appear first on older leaves, starting at the outer edges and, as severity increases, move progressively inwards between the veins towards the leaf centre.

Most experiments to determine the uptake of sodium at toxic levels by plant roots link sodium levels to the soil ESP. The criteria in this guideline are based on the results of these experiments. There are, however, indications that the nutritional effects of sodium in the soil are determined to a greater extent by the absolute sodium, calcium and magnesium concentrations in the soil solution rather than by ESP.

The toxic effects of absorption of sodium by plant foliage (see **sodium**) and root uptake of sodium are cumulative.

! Crop quality

Crop quality is affected by sodium-induced leaf injury in plants of which leaves are the marketed product, or where fruit size and appearance are affected by sodium-induced yield decreases. These aspects of crop quality are covered (to the extent that information is available) by the criteria for yield decreases and foliar damage as a result of sodium absorption through plant roots.

Crop quality is also affected by restrictions by users or regulating authorities on the sodium content of the final product. In South Africa the sodium content of wine is restricted to 100 mg/R.

! Soil physical conditions

The most prominent impairment to soil physical conditions under irrigation is *reduced soil permeability* which may, in turn, result in the soil not being able to absorb sufficient water to supply the crop water requirement. A reduction in soil permeability can be the result of a reduction in either *infiltration rate* or *hydraulic conductivity*. It could also be a combination of both. Both are reduced by increasing soil ESP.

Another impairment of soil physical conditions related to elevated ESP is the physical deterioration of primarily the ploughed layer of the soil profile. It is manifested by *soil hardsetting* which manifests as difficult cultivation conditions and poor tilth (slippery when wet and hard clods when dry).

Both soil permeability and hardsetting are determined by soil properties such as potential denseness of packing of soil particles as predetermined by their size distribution (i.e. soil texture), by the swell-shrink properties of the clay minerals, and by the soil ESP.

The degree to which the potential denseness of packing is realised, is determined by the degree to which the factors promoting the breakdown of the existing structure are counteracted by those soil properties that stabilise the existing structure. The soil organic matter and sesquioxenic content are properties that act to stabilise the existing soil structure. The breakdown of the existing structure is promoted by a decrease in soil organic matter, by an increase in ESP, and by mechanical destruction such as, ploughing and compaction by wheel traffic. Inherent soil properties therefore largely determine the permeability and hardsetting characteristics of a soil.

Soils with a low organic matter content with a large percentage silt and/or fine sand can be expected to be more prone to permeability and hardsetting problems than either sandy or loamy soil with a high organic matter content.

Under irrigation the inherent permeability and hardsetting characteristics of a soil are modified by the SAR and EC of the irrigation water. Increasing soil ESP (irrigation water SAR) gives rise to increasing swelling and dispersion of clay minerals, which destabilise soil structure. High salt concentrations in the soil solution, on the other hand, counteract swelling and dispersion.

The *infiltration rate* of soils is affected by both soil ESP and the EC of the infiltrating water. The infiltration rate, is therefore, much more susceptible to soil sodicity under rainfall conditions, than where only irrigation water (with a higher EC) is applied. Soils sensitive to sodium have been found to form surface seals or crusts and experience a significant reduction in infiltration rate even at low ESP values, when exposed to the combined effects of low salinity rain water, and the disruptive mechanical effect of falling rain drops. (Moderate EC levels in infiltrating water offset this effect and help to prevent the formation of infiltration rate-reducing surface seals). These surface seals are much less permeable than the underlying undisturbed soil.

For most of the summer rainfall areas of South Africa, it rains during the irrigation period. This is different from the situation in the western USA and Israel, where most of the published criteria originate from. The potential for the formation of surface seals is higher under South African conditions. This is reflected by more conservative criteria aimed at preventing surface seal formation.

The effect of SAR on infiltration rate is mainly a soil surface phenomenon. Depending on the concentration of the SAR constituents in the water and the soil buffering capacity, the ESP of the soil surface may often be determined by the SAR of the last irrigation. The risk of SAR-induced infiltration rate reduction, is therefore related to the maximum, rather than the mean, SAR.

Hydraulic conductivity determinations approximate the permeability of subsurface soil horizons. Because the disruptive effect of falling drops does not operate below surface, reductions in hydraulic conductivity are usually much less with the same combination of ESP and water EC, than for the infiltration rate. Reduced hydraulic conductivity presents problems in irrigated agriculture when it manifests itself as a reduction in hydraulic conductivity to below a critical value in one or more layers of an irrigated soil. Such a reduction gives rise to a decrease in the flow of irrigated water down a soil profile, and reaches critical values if it results in the establishment of a temporary or permanent water table, a decrease in the volume of soil available for root development, and/or the development of anaerobic conditions which are unfavourable for root development and metabolism.

Since hydraulic conductivity, as used in these guidelines, refers to reduced soil permeability within the soil profile, where ESP is fairly well buffered against rapid change, the risk of SAR-induced hydraulic conductivity changes is related to the *long-term mean SAR* during the irrigation season (preferably weighted by the irrigation volume). It is not affected by short-term variations in SAR.

Hardsetting of a cultivated soil involves slumping, a process of compaction that occurs without the application of an external load. Hardsetting involves the collapse of the aggregated structure during and after wetting, and a hardening without restructuring during drying.

Hardsetting is common in soils prone to dispersion and, therefore very sensitive to the electrolyte concentration of the soil solution. The potential for dispersion is enhanced where irrigation periodically supplements rainfall, or *vice versa*. The potential for

dispersion is further enhanced when sensitive soils are cultivated under wet conditions and low EC of the soil water. A soil need not have a high ESP for dispersion to occur. Soils with an SAR of less than three are found to disperse when a mechanical stress is applied.

Hardsetting was, up to now, only superficially investigated under South African conditions. Previous research dealt with crust strength (modulus of rupture) measurements as affected by *inter alia* ESP, and on soil compaction as a result of wheel traffic. Of these, only the research on modulus of rupture is applicable.

The effect of SAR on hardsetting is manifested mostly in the upper part of the soil profile. Because of the soil buffering capacity, the SAR-induced changes in soil ESP occur gradually with time. The risk of SAR-induced hardsetting is therefore related to the long-term mean SAR value during the irrigation season (preferably weighted by the irrigation volume). It is not significantly affected by short time variations in SAR.

! Guideline implications

The TWQR for the SAR, which aims to prevent surface sealing-induced reductions in infiltration rate, is lower than that for plant toxicity by root uptake, hydraulic conductivity and hardsetting. The SAR criteria for the latter three effects will only be used where the site-specific criteria to prevent surface sealing are higher.

Mitigation

Common on-farm management practices to mitigate against the negative effects of an increasing SAR of water affecting crop yield and quality are to

- ! accept a reduced crop yield or quality; and/or
- ! switch to crops that are more tolerant; and/or
- ! increase the leaching fraction; and/or
- ! ameliorate the water and/or soil with plant nutrients such as calcium, magnesium and potassium to overcome plant nutritional imbalances induced by the excess sodium associated with a high SAR.

Reductions in *infiltration rate* as a result of surface sealing which develops under the impact of rain drops, can be reduced by

- ! surface applications of easily dissolvable gypsum to increase the salt content of infiltrating water (especially rain water); and/or
- ! a surface mulch which reduces drop impact energy; and/or
- ! the application of huge quantities of organic matter; and/or
- ! soil stabilisers which can be applied on their own or in combination with each other and easily dissolvable gypsum.

Hardsetting and reduced soil *hydraulic conductivity* can be counteracted by

- ! gypsum applications designed to reduce soil ESP to acceptable levels by mixing it to the desired depth with the affected soil (gypsum applications also increase the EC of the soil solution); and/or

- ! the application of huge quantities of organic matter; and/or
- ! increasing the irrigation water salinity (TDS/EC) without increasing its SAR. This may have other negative effects (see **TDS**); and/or
- ! increasing the leaching fraction to enhance the ESP of the bottom soil layers;
- ! refraining from cultivation when the soil is wet, thereby reducing the likelihood of further hardsetting.

Criteria

Table 1: Effects of the SAR on Crop Yield and Quality

SAR Range	Crop Yield and Quality
<i>Target Water Quality Range # 2.0</i>	<i>Should prevent sodium toxicity from developing in plants sensitive to sodium, provided that irrigation water is applied to the soil surface (that is, crop foliage is not wetted), limiting sodium uptake to that through the roots</i>
2.0 - 8.0	The most sodium-sensitive crops absorb toxic levels of sodium through roots (that is, crop foliage is not wetted). Crops vary in sensitivity
8.0 - 15.0	Sodium-sensitive crops absorb toxic concentrations of sodium through roots (that is, if crop foliage is not wetted). Crops vary in sensitivity
> 15.0	All sodium-sensitive crops absorb toxic levels of sodium through root uptake (that is, crop foliage is not wetted). Crops that are more tolerant of sodium increasingly absorb toxic concentrations of sodium through root uptake. A number of economically important crops can be irrigated without developing sodium toxicity

Table 2 : Effects of the SAR on Soil Physical Conditions

SAR Range	Infiltration Rate	Hydraulic Conductivity and Hardsetting
<i>Target Water Quality Range # 1.5</i>	<i>Should ensure an adequate infiltration rate for soils sensitive to the formation of infiltration rate-reducing surface seals under conditions of rainfall during the irrigation season or irrigation with water having an EC < 20 mS/m</i>	No significant reduction in hydraulic conductivity below inherent soil hydraulic conductivity expected in this SAR range for any soil; no hardsetting above inherent hardsetting expected in any soil in this SAR range
1.5 - 3.0	Infiltration problems likely to occur in soils sensitive to the formation of infiltration rate-reducing surface seals under conditions of rainfall during the irrigation season or irrigation with water having an EC < 20 mS/m; no problem is expected with irrigation waters having on EC > 90 mS/m and slight to moderate problems at ECs in the range of 20 - 90 mS/m	No significant reduction in hydraulic conductivity below inherent soil hydraulic conductivity expected in this SAR range for any soil; no hardsetting above inherent hardsetting expected in any soil in this SAR range
3.0 - 6.0	Infiltration problems likely to occur in soils sensitive to the formation of infiltration rate-reducing surface seals when irrigated with water having an EC < 25 mS/m; no problem is expected with irrigation waters having an EC > 130 mS/m and slight to moderate problems at ECs in the range of 25 - 130 mS/m	Hydraulic conductivity reduction likely to occur in soils sensitive to hydraulic conductivity reduction. A low EC in the soil solution may cause hydraulic conductivity to be irreversibly reduced by up to 25 % for sensitive soils; Hardsetting increasingly likely to occur in sensitive soils at ECs < 60 mSg/m for SAR = 3 and < 120 mS/m for SAR = 6
6.0 - 12.0	Infiltration problems likely to occur in soils sensitive to the formation of infiltration rate-reducing surface seals when irrigated with water having an EC < 35 mS/m; no problem is expected with irrigation waters having an EC > 200 mS/m and slight to moderate problems at ECs in the range of 35 - 200 mS/m	Hydraulic conductivity reduction likely to occur in soils sensitive to hydraulic conductivity reduction. A low EC in the soil solution may cause hydraulic conductivity to be irreversibly reduced by > 25 % for sensitive soils and < 25 % in less sensitive soils, depending on the particle size distribution of the soil and the type of clay mineral present in the clay size fraction. Tolerant soils will show little or no effect Small and reversible changes in hydraulics occur in sensitive soils when EC is in the range of 100 - 200 mS/m; Hardsetting likely to occur in sensitive soils at ECs < 120 mS/m for SAR = 6 and < 240 mS/m for SAR = 12
12.0 - 20.0	Infiltration problems likely to occur in soils sensitive to the formation of infiltration rate- reducing surface seals when irrigated with water having an EC < 90 mS/m; no problem is expected with irrigation waters having an EC > 310 mS/m and slight to moderate problems at ECs in the range of 90 - 310 mS/m	Hydraulic conductivity reduction likely to occur in soils sensitive to hydraulic conductivity reduction. A low EC in the soil solution may cause hydraulic conductivity to be irreversibly reduced by > 25 % for sensitive soils and < 25 % in less sensitive soils, depending on the particle size distribution of the soil and the type of clay mineral present in the clay size fraction. Tolerant soils will show little or no effect Small and reversible changes in hydraulics occur in sensitive soils when EC is in the range of 100 - 200 mS/m; Hardsetting likely to occur in sensitive soils at ECs < 240 mS/m for SAR = 12 and < 400 mS/m for SAR = 20
> 20	Infiltration problems likely to occur in soils sensitive to the formation of infiltration rate-reducing surface seals when irrigated with water having an EC < 180 mS/m; no problem is expected with irrigation waters having an EC > 560 mS/m and slight to moderate problems at ECs in the range pf 180 - 560 mS/m	Hydraulic conductivity reduction likely to occur in soils sensitive to hydraulic conductivity reduction. A low EC in the soil solution may cause hydraulic conductivity to be irreversibly reduced by > 25 % for sensitive soils and < 25 % in less sensitive soils, depending on the particle size distribution of the soil and the type of clay mineral present in the clay size fraction. Tolerant soils will show little or no effect Small and reversible changes in hydraulics occur in sensitive soils when EC is in the range of 100 - 200 mS/m.

Modifications

A slightly improved index of the SAR in the soil solution can be obtained by calculating the adj. RNa or by using a computer programme to simulate the chemical equilibria.

Reduced crop yield and quality

- ! It should be noted that absorption of sodium by plant roots (described in this guideline) and absorption by crop foliage (see sodium) are additive to one another. The most restrictive guideline value should therefore be used when crop foliage is wetted (sprinkler irrigation).
- ! There is uncertainty whether SAR is the most appropriate index for the assessment of the sodium sensitivity of crops. However, the sodium concentration in the soil solution is largely determined by (and is in dynamic equilibrium with) soil ESP and the total salt content of the soil solution of which SAR is an index.
- ! Frequent water application in quantities exceeding that applied for commercial crops cause the soil in containers and under intensive cultivation for floricultural production to equilibrate faster with the SAR of applied irrigation waters than under commercial crops. The effects of SAR-induced reduction in crop yield and quality can thus be expected to become visible sooner than under commercial cropping practices.
- ! See Table 3 for a grouping of crops according to their relative sensitivity to ESP. The SAR of irrigation water provides a reasonable estimate of soil ESP after long-term irrigation.

Table 3: Relative Tolerance of Crops to ESP

ESP Range		
2 - 15 %	15 - 40 %	> 40 %
Avocado	Carrot	Lucerne
Deciduous Fruits	Clover, Landino	Barley
Grapes	Dallisgrass	Beet, garden
Nuts	Fescue, tall	Beet, sugar
Beans (green)	Lettuce	Bermuda grass
Cotton (at germination)	Sugarcane	Cotton
Maize	Berseem	Paragrass
Peas	Benji	Rhodes grass
Grapefruit	Raya	Wheatgrass, crested
Orange	Oat	Wheatgrass, fairway
Peach	Onion	Wheatgrass, tall
Tangerine	Radish	Karnal grass
Mungbean	Rice	
Mashbean	Rye	
Lentil	Ryegrass, Italian	
Groundnut	Sorghum	
Gram	Spinach	
Cowpeas	Tomato	
	Vetch	
	Wheat	

Note :

Tolerance decrease in each column from top to bottom

The tolerances which are listed are relative. Nutritional factors and adverse physical

conditions usually stunt growth before the higher levels are reached. (In most cases these tolerances were established by first stabilising soil structure).

Soil physical conditions

- ! Because soils are generally well buffered against changes in ESP when irrigated with water having a different SAR value, the effects mentioned in the criteria will not be visible immediately after SAR changes are introduced.
- ! Frequent water application in quantities exceeding that applied for commercial crops causes the soil in containers and under intensive cultivation for floricultural production to equilibrate faster with the SAR of applied irrigation waters than under commercial crops. The effects of SAR-induced reduction in soil physical conditions can thus be expected to become visible sooner than under commercial cropping practices.
- ! See Table 4 for a list of soil types classified according to their sensitivity to soil physical deterioration as determined by ESP - EC interactions.

Table 4 : The Susceptibility of South African Soil Types to Physical Deterioration due to ESP - EC Interactions

Soil Physical Reaction	Sensitivity of Different Soil Types*				
	Sensitive		Medium		Tolerant
Infiltration rate	G I E	B	D	A J	C F H
Hydraulic conductivity	G F	E I	B	J	A C H
Hardsetting	E G J		I	A B	C D F H

Note :

* Symbols refer to soil descriptions in table below

Several factors affect soil susceptibility to physical deterioration. The information given in Table 4 provides general guidance on how different soil types can be expected to react. The grouping of soil types into different classes requires modification as a result of difference in rainfall (degree of soil weathering) and parent material, e.g. the Oakleaf (J) soils of the Western Cape are mostly leached of stabilising sesquioxides and thus highly sensitive to infiltration. Furthermore it is often difficult to decide where to group a soil type. Cracking clay soils (F) is classed as tolerant to infiltration because their deep vertical cracks (when dry) allow for the infiltration of large volumes of water. However, when they are already wet, water intake is slow, with a sensitive rate for hydraulic conductivity.

Expert opinion should be sought when critical decisions about soil physical reaction to ESP - EC interactions need to be made.

Soil Type	Generic description	Typical South African Soil Forms
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A.	Freely drained, structureless and red-structured soils excluding those containing sand and loamy sand textures	Hutton, Clovelly, Shortland
B.	Red and yellow structureless soil with imperfectly drained plinthic horizons excluding sand textures	Avalon, Glencoe, Bainsvlei, Pinedene
C.	Exclusively drained soils (sandy)	Shepstone, Lamotte, Fernwood, Dundee
D.	Clay soils, usually dark, often swelling	Bonheim, Inhoek, Tambankul, Arcadia
E.	Soils with a blocky structured horizon	Vals River, Swartland
F.	Clay soils, often dark, imperfectly drained	Rensburg, Willowbrook
G.	Texture contrast soils with sandy topsoil overlaying structured clay horizon Poorly drained	Estcourt, Sterkspruit, Kroonstad
H.	Soils with a humic topsoil containing > 2 % organic carbon	Kranskop, Magwa, Inanda
I.	Poorly drained soils. Shallow with a plinthic horizon especially those containing high silt and sand fractions	Westleigh, Cartref, Longlands, Wasbank, Katspruit
J.	Weakly structured soils, somewhat poorly drained	Oakleaf, Vilafonte

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Sodium

Tentative guideline

Background Information

Introduction Sodium is an alkali metal which reacts with water to form highly soluble positively- charged sodium ions. It is an essential dietary element important for the electrolyte balance and the maintenance of many essential physiological functions. Sodium is present in all food to varying degrees. In minute quantities sodium is beneficial to the growth of some plants. At higher concentrations it is, however, toxic to many plants, especially woody plants. Sodium also has a potentially detrimental effect on soil physical conditions.

Occurrence Sodium is ubiquitous in the environment and usually occurs as sodium chloride, but sometimes as sodium sulphate, bicarbonate or even nitrate. Sodium is found as solid sodium chloride (rock salt) in areas where geological deposits occur. The levels of sodium in surface waters are generally low in areas of high rainfall and high in arid areas with low mean annual precipitation. Sodium is highly soluble in water and does not precipitate when water evaporates, unless saturation occurs. Hence, water in arid areas often contains elevated concentrations of sodium. High concentrations also occur in sea water, at approximately 110 g/R.

Industrial wastes, especially processes that give rise to brines, contain elevated concentrations of sodium. Sodium is also present at high concentrations in domestic waste water. This is in part due to the addition of table salt (sodium chloride) to foods. Furthermore, with re-use or recycling of water, the sodium concentration will tend to increase with each cycle or addition of sodium to the water. Sodium concentrations are mostly elevated in runoffs of leachates from irrigated soils.

Interactions Metabolically, sodium interacts with **potassium**. Sodium and potassium are the most important extracellular and intracellular cations respectively, and vital to all living organisms. Sodium interactions with soil are described in the **SAR** guideline.

Measurement The criteria are given in terms of the dissolved sodium concentration, in units of mg/R. For all practical purposes this is identical to the total sodium concentration, as sodium is always in the dissolved form, except in supersaturated brines.

The reference method for the determination of sodium is flame photometry, with lithium as the internal standard. If other methods for measuring sodium are used, their characteristics relative to the reference method should be known.

Data Interpretation The sodium concentration of irrigation water provides an indication of the levels at which

- ! leaf uptake (i.e. when foliage is wetted by the irrigation method) by crops resulting in the uptake of sodium to plant toxic levels, can be expected to occur. The arithmetic mean concentration during the active growing season (preferably application volume weighted) is used for this purpose.
- ! leaf burn (foliar damage) of crops can be expected to occur when crop foliage is wetted by irrigation water. The maximum concentration during the active growing season is used for this purpose.

- ! Sodium will accumulate in consumable plant parts; a maximum sodium level from a quality perspective has been defined. The arithmetic mean concentration during the active growing season (preferably application volume weighted) is used for this purpose.

Note: The degree to which *root* uptake of sodium affects crop response is dealt with under the SAR guideline.

Treatment Options

It is highly unlikely that sodium can be economically removed from water intended for irrigation purposes. However, should it be required, sodium can be removed from water together with other ions which constitute the TDS by the following desalination processes:

- ! ion-exchange using a mixed-bed ion exchange column, usually where the feed TDS is up to around 2 000 mg/R;
- ! treatment by membrane processes such as reverse osmosis or electrodialysis, where the TDS concentration is in the range of 2 000 to 3 500 mg/R; and
- ! distillation, in cases where the TDS is no less than 10 000 mg/R.

All of the processes are easily fouled by suspended matter, and are prone to scaling with hard waters. All of the processes produce a concentrated waste stream of the salts that may cause disposal difficulties. If used on a large scale, all of the processes require high levels of design, operator and maintenance skills.

The Effects of Sodium

Norms The different norms used in the guideline to assess the effects of sodium on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<ul style="list-style-type: none"> ! Crop yield as affected by crop sensitivity to uptake through foliage ! Crop quality as determined by damage to marketed product or by regulatory limits on concentration in final product
Application to sustain suitability of irrigated soil	! No known effects of sodium on its own (See Sodium Adsorption Ratio)
Maintenance of irrigation equipment	! No known effects

Almost all available information on the effects of sodium in irrigation water are on the effects of crop yield. Sparse information is available with which the sodium concentration of irrigation water can be related to the regulatory limits placed on the sodium concentration in final products.

Effects Sodium is not recognised as an essential plant nutrient, although it does benefit the growth of some plants. Many crops are reported to show sodium toxicity when it accumulates to

elevated levels in plant tissues; sensitivity varies considerably between species. Woody crops are especially sensitive. The effects of sodium toxicity are compounded by indirect effects such as, induced nutritional imbalances and impairment of soil physical conditions. Plants absorb sodium through both their roots and leaves.

Root uptake is determined primarily by sodium concentrations in the soil solution that are determined by a number of factors, of which, the exchangeable sodium percentage (ESP) of the soil and total salt content are the most important. The effects of sodium toxicity through root uptake are dealt with in the SAR guideline.

Crops wetted by water containing sodium are exposed not only to the root zone sodium content but, also to absorption directly through the leaves. Experiments to quantify the additional impact of foliar damage by sprinkler irrigation to crop yield (over and above that caused by root uptake) indicate that the effects may be substantial.

Foliar absorption of sodium is often associated with leaf burn. Leaf burn can be the result of a single exposure to a high sodium concentration. The extreme visual effect on crop/plant reaction will mostly be determined by the maximum sodium concentration. The effect is acute and irreversible over the short term. Provided the damage to the crop was not permanent, the effect can be reversed over the long-term.

Crops vary in foliar absorption rates. The absorption rates of avocado leaves are low while those of citrus, stonefruits and almonds are high. This means that 45 - 70 mg/R sodium can cause damage in crops with a high leaf absorption rate. The relative susceptibility of crops to foliar injury from saline sprinkling is given in Table 2.

Typical symptoms of sodium toxicity are leaf burn, scorch, and dead tissue along the outside edges of leaves. As the severity increases, the symptoms move progressively inward between the veins towards the centre of the leaf. *This contrasts with symptoms of chloride toxicity which occur first at the leaf tip.* Several days or weeks are normally required before sodium accumulates to toxic levels. Symptoms therefore appear first on older leaves.

Crop quality may also be affected by sodium-induced leaf injury in plants of which leaves are the marketed product, or where fruit size and appearance are affected by sodium-induced yield decreases. These aspects of crop quality are covered (to the extent that information is available) by the criteria for yield decreases and foliar damage as a result of sodium absorption through plant leaves; see SAR guideline.

Crop quality is also affected by restrictions by users or regulating authorities on the sodium content of the final product. In South Africa the sodium content of wine is restricted to 100 mg/R.

Mitigation

Common on-farm management practices to cope with increasing sodium content of water affecting crop yield and quality, when the crop is subjected to sprinkler irrigation, are to

- ! switch to an irrigation method that does not wet the leaves; or
- ! accept a reduced crop yield or quality; and/or
- ! switch to crops that are more tolerant to sodium; and/or
- ! switch to crops with a lower foliar adsorption rate; and/or

- ! ameliorate the water and/or soil with plant nutrients such as calcium, magnesium and potassium to overcome plant nutritional imbalances induced by the excess sodium; and/or
- ! reduce the opportunity for foliar absorption of sodium by reducing the number of wetting and drying cycles, (i.e. reduce the irrigation frequency) and/or by irrigating at night when temperature (and thus absorption rate) and evaporation (and thus salt concentration rate) are lower; and/or
- ! rinse the leaves at the end of an irrigation application with low sodium water; and/or
- ! avoid irrigation during periods of high wind (wind is a major factor in the concentration and adsorption of sodium. The downwind drift of sprinklers is more concentrated than the applied sprinkler water and thus more likely to cause foliar damage); and/or
- ! increase sprinkler rotation speed (sprinklers that rotate slowly allow appreciable drying between rotations); and/or
- ! increase application rate (within the limits posed by soil water storage capacity and infiltration rate, thereby reducing the time period available for foliar absorption); and/or
- ! increase droplet size. (This results in less absorption compared to small drops).

Criteria

Table 1: Effects of Sodium on Foliar Crop Yield and Quality

Concentration Range	Crop Yield and Quality
<i>Target Water Quality Range</i> # 70 mg/R	<i>Should prevent the accumulation of sodium to toxic levels in all but the most sensitive plants, even when crop foliage is wet</i>
70 - 115	Crops sensitive to foliar absorption accumulate toxic levels of sodium when crop foliage is wetted. They display symptoms of foliar injury and yield decrease
115 - 230	Crops moderately sensitive to foliar absorption accumulate toxic levels of sodium when crop foliage is wetted. They display symptoms of foliar injury and yield decreases
230 - 460	Crops moderately tolerant to foliar absorption accumulate toxic levels of sodium when crop foliage is wetted. They display symptoms of foliar injury and yield decreases
> 460	Crops tolerant to foliar absorption increasingly accumulate toxic levels of sodium when crop foliage is wetted. They display symptoms of foliar injury and yield decreases

Note:

- ! Crop tolerance to sodium when crop foliage is wetted by the irrigation method (sprinkler irrigation) is not well established, due to limited data. Very little local confirmation of internationally published experiments has taken place.
- ! The indicated concentration ranges apply to daytime sprinkling under conditions that are not too hot or too dry.

Modifications

- ! It should be noted that the effects of sodium absorption by plant roots (see **SAR**) and crop foliage (denoted by sodium concentration) are additive. The most restrictive criteria should thus be used when crop foliage is wetted (sprinkler irrigation).
- ! Environmental or other conditions causing an increased sodium concentration on foliage (e.g. hot, dry conditions) necessitate the use of more conservative criteria.
- ! The relative susceptibility of some crops to foliar injury is presented in Table 2.

Table 2: Relative Susceptibility of Crops to Foliar Injury from Saline Sprinkling

Waters

Sodium Concentration (mg/l) Causing Foliar Injury in Crops Varying Insensitivity to Foliar Absorption			
Sensitive # 115	Moderately sensitive 115 - 230	Moderately tolerant 230 - 460	Tolerant > 460
Almond Apricot Citrus Plum	Grape Pepper Potato Tomato	Barley Maize Cucumber Lucerne Safflower Sesame Sorghum	Cauliflower Cotton Sugar beet Sunflower

Note: The data in this table represent general guidelines for daytime sprinkling under conditions that are not too hot or too dry.

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Suspended Solids

Tentative Guideline

Background Information

Introduction Suspended solids are the particulate matter retained on a glass fibre filter, after filtration of a well-mixed sample and drying of the filter at 103 - 105 °C. The settleable solids fraction is a component of the suspended solids fraction and is that fraction which settles out of solution within a defined period.

Surface water often contains appreciable concentrations of suspended solids. Large quantities of suspended solids can affect irrigation in many ways. Surface deposition may form crusts which inhibit infiltration and seedling emergence; deposition on plant leaves can reduce plant photosynthetic activity, growth and marketability of some crops; dripper outlets may clog; and sprinkler jets may be subject to accelerated wear.

Occurrence Suspended solids in water consist of inorganic and organic matter such as, clay particles or suspended mineral matter and a combination of decay products and living organisms respectively. In clear non-turbid waters, like spring water, the suspended matter is low or absent, while in muddy waters, the amount of suspended matter is high. The amount of suspended matter found in the rivers draining a catchment area usually reflects the degree of soil erosion. Activities which result in accelerated soil erosion will therefore increase the suspended solids load in the draining rivers.

The settleable fraction of the suspended solids accumulates as sediment in lakes, dams and rivers. Scouring action during high flow periods in rivers can resuspend settled matter and finer particles can remain in suspension for long periods.

Interactions Suspended solids give rise to turbidity in water. The relationship between the amount of suspended solids and the turbidity measurement is, however, dependent on the nature and particle size distribution of the suspended matter. Addition of strongly electropositive ions such as ferrous, Fe(II) and aluminium, Al(III) salts to water will neutralise the electrical repulsive charges on the suspended matter and allow coagulation and settling to occur.

Measurement The criteria for the suspended solids concentration are given in units of mg/l. Suspended solids are measured as the mass of material retained on a glass fibre filter after drying at 103 - 105 °C. The settleable solids fraction is determined by difference after a one hour settling period followed by determination of the suspended solids in the supernatant.

Data Interpretation The geometric mean concentration in the applied water (preferably application volume weighted) should be used to compare with the criteria given. The suspended solid content of irrigation water provides an indication of the likelihood that:

- ! drip irrigation systems will become clogged
- ! soil surface crusts will form which may inhibit water infiltration and seedling emergence.
- ! photosynthetic activity reducing films will form on plant leaves when water is applied with sprinkler irrigation.

Treatment Options

Treatment to remove suspended solids is often too costly to be economical for most irrigation applications. Where treatment is required, suspended solid loads are mostly removed by coagulation and flocculation followed by filtration, by one of the following techniques:

- ! Aluminium sulphate and ferric chloride are conventionally used as coagulants. Small doses of polyelectrolytes are often added to assist in flocculation.
- ! Sand and screen filters that can be *backwashed*, as well as centrifugal separators are commonly used in-line to protect drip irrigation systems from clogging.

The Effects of Suspended Solids

Norms

The different norms used in the guidelines to assess the effects of suspended solids on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	<ul style="list-style-type: none"> ! Crop yield as affected by photosynthetic activity reducing films (no numerical criteria given) ! Crop quality as affected by appearance of marketable products as a result of suspended solid deposits (no numerical criteria given)
Application to sustain suitability of irrigated soil	<ul style="list-style-type: none"> ! Reduction in infiltration rate and/or seedling emergence because of a soil surface crust being deposited by suspended solids (no numerical criteria given)
Maintenance of irrigation equipment	<ul style="list-style-type: none"> ! The degree of clogging that can be expected in drip irrigation systems ! Accelerated wear of sprinkler irrigation nozzles and other components in the distribution system (no numerical criteria given)

Effects

Suspended solids are mostly comprised of particulate matter of inorganic origin with no inherent toxic effect for plants or soil and effects are of a physical nature. Because of the particle size distribution found in the suspended solids fraction, and the small size orifices (emitters) used in drip (and to a lesser extent microjet) irrigation systems, partial to complete clogging or plugging of orifices occurs. This leads to a decrease in uniformity of water application and subsequent yield decreases. The abrasive action of particles may also lead to accelerated wear of sprinkler nozzles (decreased uniformity of water application) and other components (pumps, seals and control valves) of the distribution system.

When present in sufficiently high concentrations, deposition of suspended solids on the soil surface can lead to the formation of a *depositional surface crust* which inhibits water infiltration and seedling emergence, and reduces soil aeration. When applied to sandy soils, suspended solids may have a beneficial effect; they may improve the soil texture, consistency and water holding capacity.

Deposition on plant leaves may reduce plant photosynthetic activity and result in reduced yields. Deposition on plant parts may also affect the appearance and marketability of produce.

Mitigation

Common on-farm management practices to mitigate against the negative effects of suspended solids in irrigation water, are to:

- ! Allow suspended solids to settle in temporary storage dams (settling ponds) and extract the supernatant for filtration (if required).
- ! Switch to an application system that will minimise the negative effects (e.g. microjet instead of drip irrigation to overcome clogging or flood irrigation to overcome deposition on foliage).
- ! Reduce the likelihood of clogging by using emitters that are designed to be self-cleaning.
- ! Use regularly flush dripper lines to remove accumulated sediment (suspended solids).
- ! Control the growth of micro-organisms in distribution lines. Suspended particles are often caught by the slime and filament byproducts of bacteria. When these increase in size they cause clogging of emitters. The control of micro-organisms thus helps to alleviate the problem of clogging.

Criteria

Effects of Suspended Solids on the Clogging of Drip Irrigation Systems

Concentration Range (mg/l)	Clogging of Drippers
<i>Target Water Quality Range # 50</i>	<i>Practically no problems with the clogging of drip irrigation emitters</i>
50 - 100	Slight to moderate problems with the clogging of drip irrigation emitters
> 100	Increasingly severe problems with the clogging of drip irrigation emitters

Note:

- ! The above criteria are tentative.
- ! Suspended solids are only one of a number of causes of clogging in drip irrigation systems. See pH, total dissolved solids, manganese, iron and faecal coliforms.

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Total Dissolved Solids

Background Information

Introduction The total dissolved solids (TDS) are a measure of the quantity of various inorganic salts dissolved in water. The TDS concentration is directly proportional to the electrical conductivity (EC) of water. Since EC is much easier to measure than TDS, it is routinely used as an estimate of the TDS concentration.

Electrical conductivity is a measure of the ability of water to conduct an electrical current. This ability is a result of the presence of ions in water such as carbonate, bicarbonate, chloride, sulphate, nitrate, sodium, potassium, calcium and magnesium, all of which carry an electrical charge. Most organic compounds dissolved in water do not dissociate into ions, consequently they do not affect the EC.

Irrigation with water containing salt induces salt into the soil profile. When no or little leaching of salt takes place from the soil profile, salt accumulates and a saline soil is formed. Crops are sensitive to soil salinity; yield is reduced if grown on salt-affected soils. Under conditions of extreme soil salinity, crops cannot be grown successfully.

Occurrence Virtually all natural waters contain varying concentrations of TDS as a consequence of the dissolution of minerals in rocks, soils and decomposing plant material. The TDS of natural waters is therefore often dependent on the characteristics of the geological formations with which the water was, or is, in contact.

Typically, the concentration of the TDS in

- ! rainwater is low, generally less than 1 mg TDS/R;
- ! water in contact with granite, siliceous sand and well-leached soils is generally low, less than 30 mg TDS/R;
- ! water in contact with precambrian shield areas is generally less than 65 mg TDS/R; and
- ! water in contact with palaeozoic and mesozoic sedimentary rock formations is generally in the range of 195 - 1 100 mg TDS/R.

TDS are likely to accumulate in water as water moves downstream because salts are continuously being added through natural and manmade processes whilst very little is removed by precipitation or natural processes. Domestic and industrial effluent discharges and surface runoff from urban, industrial and cultivated areas are examples of the types of return flows that may contribute to increased TDS concentrations.

High TDS concentrations in surface waters are also caused by evaporation in water bodies which are isolated from natural drainage systems. The saline pans in the central parts of South Africa are examples of such water bodies.

Interactions Over the long term (i.e. under equilibrium conditions) the TDS content of irrigation water determines the salt distribution in a soil profile. Since exchange reactions take place on a stoichiometric basis, cation and other exchange reactions in soil have only a limited effect on the TDS of the soil solution. Therefore, the soil salinity profile attains equilibrium conditions more rapidly than do individual cations. Although true equilibrium conditions are seldom attained in practice (due to changes in irrigation management, irrigation water, the TDS concentration and rainfall), quasi-equilibrium soil salinity profiles are mostly attained

within two irrigation seasons.

The salt content in the root zone increases with depth. Close to the surface it is similar to that of the irrigation water. Since plants actively absorb water and leave most of the salt behind (in a reduced volume), the salt concentration throughout the soil profile increases between irrigation applications. During each irrigation the accumulated salt is leached deeper into the soil profile where it is again concentrated and progressively leached down ever deeper by successive irrigation applications, until it is leached from the root zone. Unless salt is leached, salinity within the root zone will accumulate to levels at which plants cannot extract water. The salinity at the bottom of the root zone (i.e. salinity of drainage water, EC_{dw}) is determined by the irrigation water salinity (EC_{iw}) and the degree of leaching that takes place, and is derived from the equation

$$EC_{dw} = EC_{iw}/LF$$

where LF is the leaching fraction, i.e. the fraction of the total water application that is leached to below the root zone, which is derived from the equation

$$LF = D_{dw}/D_{iw}$$

where D_{iw} is the total depth of water applied, and D_{dw} is the depth of drainage water (i.e. D_{iw} is the depth of evapotranspiration).

Therefore, a high leaching fraction results in a lower TDS/EC in the drainage water and in the overlying soil profile compared to a low leaching fraction. A wide range of soil salinities can therefore be induced by varying the leaching fraction.

Measurement

The criteria are given in terms of the TDS concentration in mg/R, as well as the equivalent EC, expressed in milli-Siemens per metre (mS/m), measured at or corrected to a temperature of 25 EC.

The TDS concentration can be measured as

- ! an estimate based on the EC value (see below);
- ! the dry weight of the salts after evaporation of a known volume of filtered water; and
- ! the sum of the concentrations of the constituent cations and anions.

For most natural waters EC is related to the dissolved salt concentration by a conversion factor ranging from 5.5 - 7.5. The average conversion factor for most waters is 6.5. The conversion equation is as follows:

$$EC(\text{mS/m at } 25 \text{ EC}) \times 6.5 = \text{TDS}(\text{mg/R})$$

The exact value of the conversion factor depends on the ionic composition of the water, especially the pH and bicarbonate concentration.

Should very accurate measures of TDS be required the conversion factor should be determined for specific sites and runoff events.

Data Interpretation

The TDS/EC concentration of irrigation water provides an indication of the levels at which

- ! crop yield will be affected. The *arithmetic mean concentration* during the active growing season (preferably application volume weighted) is used.

- ! soil salinity will stabilise under long-term irrigation with water of a particular TDS concentration, under given irrigation water management practices and climatic conditions. The *arithmetic mean concentration* during the active growing season (preferably application volume weighted) is used.

Treatment Options

Although some salts, such as those of calcium, magnesium and certain heavy metals can be removed by chemical precipitation, most of the inorganic salts dissolved in water can only be removed by distillation or by highly sophisticated physical-chemical separation technologies. All these technologies are characterised by their high cost and/or their high energy requirements. *It is highly unlikely that TDS can be economically removed from water intended for irrigation use.* However, should this be required, the technologies available for reducing the concentration of TDS in water are

- ! ion exchange using a mixed ion exchange column, usually where the feed TDS is up to 2 000 mg/R;
- ! treatment by membrane processes such as reverse osmosis or electrodialysis, where the TDS concentration is in the range of 2 000 - 3 500 mg/R; and
- ! distillation in cases where the TDS concentration is approximately 10 000 mg/R.

All of the processes are usually fouled by suspended matter and are prone to scaling with hard waters. All large-scale processes require high levels of design, operator and maintenance skills. Furthermore, all processes produce a concentrated waste stream of the salts that may cause disposal difficulties.

The Effects of Total Dissolved Solids

Norms

The different norms used in the guideline to assess the effects of the TDS on irrigation water use are summarised below:

Irrigation Water Uses	Norms for Measuring Water Quality Effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to irrigation water-induced soil salinity ! Crop quality as affected by soil salinity
Application to sustain suitability of irrigated soil	! Soil salinity that would allow crop production on a sustainable basis
Maintenance of irrigation equipment	! See Total Hardness

A considerable information base is available on the effects of TDS/EC of irrigation water on crop yield and soil salinisation. Much less is known about the effects on crop quality.

Effects

Irrigation with water containing salt introduces salt into the soil profile. When no or little leaching of salt takes place from the soil profile, salt accumulates and a saline soil is formed. Since crops are sensitive to soil salinity, yield is reduced if grown on salt affected soils. Under conditions of extreme soil salinity, crops cannot be grown successfully.

! Saline soils

Irrigation management practices should ensure a stable soil salinity for sustained agricultural practice. Under natural conditions, saline soils are mostly associated with salt accumulation as a result of surface evaporation of salty water. This often occurs in

- low-lying areas (pans) with poor vertical drainage, where salts in the runoff water concentrate and accumulate when the water evaporates; or
- in areas where groundwater seeps to the surface, evaporation takes place and salts accumulate.

Extremely saline soils often display salt efflorescence at the soil surface. Other visual indications of high soil salinity are a powdery, loose appearance at the soil surface. Intermediate salinities need to be determined with field instruments or laboratory analyses. Saline areas within a field can often be identified by the comparatively stunted growth of crops, although stunted growth in itself may be the result of many causes, and does not necessarily indicate soil salinity.

Under irrigation, saline soils are formed primarily when high salinity water is used for irrigation. Soil salinity is determined by interactions between the TDS of irrigation water and leaching. Saline soils can, however, also be formed when salts from an elevated water table (which mostly form under irrigated land as a result of over-irrigation) are concentrated in the soil profile by surface evaporation.

Therefore, provided that soils are adequately drained, soil salinity can be controlled by providing for additional leaching. However, the higher the irrigation water TDS/EC concentration, the higher the leaching fraction, and the greater the soil drainage capacity needed to cope with an additional leaching volume. Increasingly strict screening of soil drainage properties is therefore required to ensure soil sustainability as the TDS/EC concentration of irrigation water increases.

The fact that leaching of salts is required to maintain a stable soil salinity implies that the leached salts have to be disposed of. Their disposal inevitably results in the salinisation of rivers associated with irrigation schemes. For irrigation to be sustainable, the salinisation of rivers as a result of irrigation needs to be minimised as far as possible.

! Crop yield and quality

The magnitude of the yield decrease is determined by both the duration and the level of exposure to *salinity-induced water stress*. The presence of dissolved salts in soil water reduces the physiological availability of water to plants. When the salt content reaches a concentration where the plant is no longer able to extract sufficient water for its requirements, *salinity-induced water stress* develops, the growth rate starts to decline and, if it continues for a significant period of time, crop yield starts to decline.

The soil salinity at which plant growth starts to decline is defined as the *threshold salinity*. It is usually expressed as the TDS/EC of the saturated-soil extract, which is the reference water content for the measurement of soil salinity. Crop yield has been found to decrease approximately linearly with salinity increases above the threshold salinity. Both the threshold salinity and the slope of yield decline above this point are specific to a particular crop or cultivar.

When the time interval between irrigation applications is long, the salt in the soil solution

becomes more concentrated than when applications are applied frequently. The effects that saline irrigation water have on crop growth are therefore more pronounced with low, than with high, frequency irrigation applications.

The symptoms plants display when affected by salinity are similar in appearance to those of drought, namely stunted growth, wilting (even though the soil may not be dry), a darker, bluish-green colour and in some cases thicker, waxier leaves. Symptoms vary with the growth stage. Usually symptoms are more obvious when plants are affected during early growth stages. Mild salinity effects may go unnoticed because the effect may be uniform over a field, with no basis for comparison.

Crop salt tolerance has mostly been determined over a growing season. The available salt tolerance data may therefore reflect the tolerance of the most sensitive growth stage and does not necessarily provide a good indication of salinities that may be tolerated during more resistant growth stages.

Mitigation

Reduced crop yield and quality

Common on-farm management practices to cope with the effects of increasing irrigation water salinity, are to

- ! apply surplus irrigation water (in addition to crop water requirements) in order to leach accumulating salt out of the soil (increase the leaching fraction); and/or
- ! accept a reduced crop yield; and/or
- ! switch to crops which are more salt-tolerant; and/or
- ! plant annual crops at a higher density (a reduced yield on a greater number of plants partially offsets the total yield reduction); and/or
- ! switch to a higher frequency irrigation application.
- ! use irrigation only to supplement rainfall, that is, do not practice full-scale irrigation.

Soil sustainability

Common on-farm practices to cope with the effects of increasing irrigation water salinity, are to

- ! apply surplus irrigation water (in addition to crop water requirements) in order to leach accumulating salt out of the soil by increasing the leaching fraction); and/or
- ! install artificial drainage to supplement or replace the soil's inherent internal drainage, and/or
- ! accept temporary waterlogged conditions and a higher soil salinity; and/or
- ! improve irrigation application efficiency; and/or
- ! switch to a higher frequency irrigation application (thereby reducing the likelihood of temporary waterlogged conditions from developing immediately following a heavy irrigation application).

Criteria

Table 1: Effects of TDS/EC on Crop Yield

EC Range (mS/m)	Crop Yield
<i>Target Water Quality Range # 40</i>	<i>Should ensure that salt-sensitive crops can be grown without yield decreases when using low frequency irrigation systems. A leaching fraction of up to 0.1 may be required and wetting of the foliage of sensitive crops should be avoided</i>
40 - 90	A 95 % relative yield of moderately salt-sensitive crops can be maintained by using a low-frequency irrigation system. A leaching fraction of up to 0.1 may be required and wetting of the foliage of sensitive crops should be avoided
90 - 270	A 90 % relative yield of moderately salt-tolerant crops can be maintained by using a low-frequency application system. A leaching fraction of up to 0.15 may be required and wetting of the foliage of sensitive crops should be avoided
270 - 540	A 80 % relative yield of moderately salt-tolerant crops can be maintained provided that a high-frequency irrigation system is used. A leaching fraction of up to 0.2 may be required and wetting of the foliage of sensitive crops should be avoided
> 540	These waters can still be used for irrigation of selected crops provided sound irrigation management is practised and yield decreases are acceptable. However, the management and soil requirements become increasingly restrictive and the likelihood of sustainable irrigation decreases rapidly

Note:

- ! Since sustainable soil salinity is determined by the soil's ability to sustain crop production, the effects on soil sustainability and crop yield are similar.
- ! Information about the effect of soil salinity on crop quality is too limited to derive general criteria.

Modifications

The limitations of setting criteria for salinity include:

- ! The need to make assumptions about the relationship between saturation extract salinity (for which yield response data is available) and soil water salinity and the deviation of the mean soil profile salinity, to which crops would respond. These were discussed in detail in the first edition of the guidelines.
- ! The fact that most of the available salinity-yield response data was derived from experiments using artificial irrigation waters (consisting of calcium and sodium chloride) and water applications to achieve high leaching fractions. No precipitation of salts can be expected under these conditions. Higher yield could thus be expected if, for example, calcium sulphate rich irrigation water (a portion of which would precipitate

under low leaching conditions) was used.

- ! A lack of information on foliar damage to leaves caused by salinity *per se*; criteria are, however, provided for foliar damage by chloride and sodium.
- ! The criteria for crop salt tolerance do not consider differences in crop tolerance during different growth stages. This needs to be considered for site-specific cases. Table 2 provides some information for the germination period.
- ! A list of commercial crops grouped into salt tolerance classes as used in the criteria is listed in Table 3.
- ! A list of ornamental shrubs, trees and ground cover plants grouped into salt tolerance classes used in the criteria is listed in Table 4.
- ! It may be possible to provide criteria for the effect of salinity on the quality of some specific crops (e.g. the solid content of tomatoes increases with increasing salinity), but the available information is too limited to derive general criteria.
- ! Potted plants usually receive water applications in excess of the assumptions used to derive the criteria. Practically no leaching occurs with the result that salt can accumulate to relatively high concentrations. To control salt accumulation, potted plants should be leached by excessive watering on a regular basis.
- ! Water and plant nutrients are often recirculated in commercial floriculture (e.g. hydroponics and soilless growth media), with the result that salts accumulate. Since water application is mostly controlled to ensure minimal matric potentials, higher salt concentrations can be tolerated. It should, however, still be controlled to within plant tolerance levels.

Table 2: Relative Salt Tolerance of Various Commercial Crops at Germination (after Ayers and Westcott, 1985)

Crop	Fifty Percent Emergence Reduction (EC (mS/m) of Saturated Soil Extract)
Barley	1 600 - 2 400
Cotton	1 550
Sugarbeet	500 - 1 250
Sorghum	1 300
Safflower	1 230
Wheat	1 400 - 1 600
Beet, red	1 380
Lucerne	820 - 1 340
Tomato	760
Rice	1 800
Cabbage	1 300
Muskmelon	1 040
Maize	2 100 - 2 400
Lettuce	1 140
Onion	560 - 750
Bean	800

Table 3 : Commercial Crops classified according to Salt Tolerance Classes (After Maas, 1990 and Ayers and Westcott, 1985)

Table 3a: Fruit and nut crops

Sensitive		Moderately Sensitive	Moderately Tolerant	Tolerant
Almond	Mango	Castorbean	Fig	Date palm
Apple	Orange	Grape	Jujube	Guayule
Apricot	Passion fruit		Olive	Jojoba
Avocado	Peach		Papaya	
Blackberry	Pear		Pineapple	
Boysenberry	Persimmon		Pomegranate	
Cherimoya	Plum/prune			
Cherry, sweet	Pomelo			
Cherry, sand	Raspberry			
Currant	Rose apple			
Gooseberry	Sapote, white			
Grapefruit	Strawberry			
Lemon	Tangerine			
Lime				
Loquat				

Table 3b: Vegetables

Sensitive	Moderately Sensitive	Moderately Tolerant	Tolerant
Bean Carrot Okra Onion Parsnip Pea	Broccoli Brussels sprouts Cabbage Cauliflower Celery Maize, sweet Cucumber Eggplant Kale Kohlrabi Lettuce Muskmelon Pepper Potato Pumpkin Radish Spinach Squash, scallop Sweet potato Tomato Turnip Watermelon	Artichoke Beet, red Squash, zucchini	Asparagus

Table 3c: Fibres, Seed and Sugar

Sensitive	Moderately sensitive	Moderately tolerant	Tolerant
Bean Guayule Rice, paddy Sesame	Broadbean Castorbean Maize Flax Millet, foxtail Groundnut/peanut Sugarcane Sunflower	Cowpea Kenaf Oats Safflower Sorghum Soybean Wheat	Barley Cotton Guar Jojoba Rye Sugarbeet Triticale Wheat, Durum

Table 3d: Grasses and Forage

Sensitive	Moderately Sensitive	Moderately Tolerant	Tolerant
None	Alfalfa (lucerne) Bentgrass Bluestem, Angleton Brome, smooth Buffelgrass Burnet Clover, alsike Clover, Berseem Clover, ladino Clover, red Clover, strawberry Clover, white Dutch Cowpea (forage) Dallis grass Foxtail, meadow Grama, blue Lovegrass Lucerne (alfalfa) Maize (forage) Milkvetch, Cicer Oatgrass, tall Oats (forage) Orchard grass Rye (forage) Sesbania Siratro Sphaerophysa Timothy Trofoil, big Vetch, common	Barley (forage) Brome, mountain Canary grass, reed Clover, Hubam Clover, sweet Fescue, meadow Fescue, tall Harding grass Panic grass, blue Rape Rescue grass Rhodes grass Ryegrass, Italian Ryegrass, perennial Sudan grass Trefoil, narrowleaf birdsfoot Trefoil, broadleaf birdsfoot Wheat (forage) Wheat, Durum (forage) Wheatgrass, standard crested Wheatgrass, inter- mediate Wheatgrass, slender Wheatgrass, western Wildrye, beardless Wildrye, Canadian	Alkali grass, Nuttall Alkali sacation Bermuda grass Kallar grass Saltgrass, desert Wheatgrass, fairway crested Wheatgrass, tall Wildrye, Altai Wildrye, Rus- sian

Table 4: A List of Ornamental Shrubs, Trees and Ground Covers, classified into Salt Tolerance Classes (After Maas, 1990)

Very Sensitive	Sensitive	Moderately sensitive	Moderately Tolerant	Tolerant	Very Tolerant
Star jasmine Pyrenees cotoneaster Oregon grape Photinia	Pineapple guava Chinese holly, cv. Burford Rose, cv. Grenoble Glossy abelia Southern yew Tulip tree Algerian ivy Japanese pittosporum Heavenly bamboo Chinese hibiscus Laurustinus, cv. Robustum Strawberry tree, cv. Compact Crape Myrtle	Glossy privet Yellow sage Orchid tree Southern Magnolia Japanese boxwood Xylosma Japanese black pine Indian hawthorn Dodonaea, cv. atropuruea Oriental arborvitae Thorny elaeagnus Spreading juniper Pyracantha, cv. Gruberi Cherry plum	Weeping bottlebrush Oleander European fan palm Blue dracaena Spindle tree, cv. Grandiflora Rosemary Aleppo pine Sweet gum	Brush cherry Ceniza Natal plum Evergreen Pear Bougainvillea Italian stone pine	White iceplant Rosea iceplant Purple iceplant Croceum iceplant

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Uranium

Tentative Guideline

Background Information

Introduction Uranium has fourteen isotopes, all of which are radioactive. Naturally-occurring uranium consists nominally of 99.27 % U^{238} and 0.72 % U^{235} . Much of the internal heat of the earth is thought to be due to the presence of the naturally-radioactive uranium and thorium. Uranium is chemically quite a reactive element and forms many compounds with other elements, particularly with electronegative elements such as fluorine, phosphorus and arsenic.

Plants respond to the uranium concentration in the soil solution. Similar to most trace elements, uranium is strongly adsorbed by soil. The addition of uranium to the soil in relatively high concentrations over the short-term may not result in reduced crop growth or in its accumulation in plant concentrations detrimental to humans or animals. However, continuous application over extended periods results in its accumulation in the surface soil layer, in practice the cultivated or plough layer.

Occurrence Traces of uranium are found in all soils, typically in the concentration range of 0.7 - 9 mg/kg. Uranium is also found in a variety of uraniferous minerals. For example, uranyl uranate (uraninite, is found in granitic pegmatites together with silver, lead and copper ores and in the yellow mineral carnotite (potassium uranyl vanadate). It also occurs in combination with various phosphate, arsenate and silicate minerals.

The mean concentration of uranium in fresh surface water is approximately 0.4 $\mu\text{g}/\text{R}$ and in sea water, 3.2 $\mu\text{g}/\text{R}$. Considerably higher concentrations can occur in ground water, particularly where concentrations of uranium minerals are found in the rocks.

The U^{235} isotope is used in the nuclear industry, while the U^{238} isotope has various industrial uses, for example the production of yellow glass and glazes.

Interactions Uranium concentrations in the soil solution are largely determined by sorption and desorption reactions with the soil exchange complex. Sorption appears to dominate at the relatively low concentrations that are of concern for water quality criteria for irrigation use.

Soil pH has a major effect on the concentration of uranium in the soil solution and its solubility decreases with increasing pH.

Implications for irrigation with water containing uranium include the following:

- ! Uranium can be expected to be retained in the soil surface layers, because of its strong sorption by the soil exchange complex. In cultivated land it accumulates in the plough layer.
- ! Significant downward movement to below the plough layer and hence contamination of groundwater with uranium is highly unlikely.
- ! The larger the soils cation exchange capacity (determined by clay content and clay mineral type) the more uranium can generally be sorbed.

- ! Soils with a neutral to alkaline pH will be able to accept a greater uranium load than acidic soils before concentrations in the soil solution become phytotoxic.

Measurement A variety of methods can be used to measure uranium. It can be chemically measured, where the concentration is expressed as mg/l uranium, or it can be radiologically measured in terms of the α -particle radiation activity, where the concentration is expressed in units of Bq/l (Becquerel/litre). 1 Bq/l U^{238} activity corresponds to 80 μ g/l uranium.

Data Interpretation Isolated uranium concentrations are difficult to interpret, and should always be evaluated in terms of the natural background concentrations expected in a given area. These can only be determined by extensive surveys.

Because uranium is retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions is established. In order to prevent its accumulation, the total load applied to soil needs to be limited. International guidelines for its concentration in irrigation water have been calculated (using very limited available information) to ensure that it does not accumulate to either phytotoxic levels or levels that are toxic to consumers, within a given time period. The calculations assume that uranium accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The uranium concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that uranium does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for a period exceeding 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The uranium concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *Specialist advice should be sought to remove uranium from water and it is highly unlikely that removal from water intended for irrigation purposes is economically feasible.*

Depending on the degree of removal required, processes such as conventional flocculation with ferric salts, or more sophisticated processes such as ion exchange resins may be used.

The Effects of Uranium

Norms The different norms used in the guideline to assess the effects of uranium on irrigation water use are summarised below:

Irrigation Water Uses	Norms for Measuring Water Quality Effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to uranium uptake through plant roots
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected
Maintenance of irrigation equipment	! No known effects

Effects Uranium is taken up by plants through their roots. Uranium commonly accumulates within the roots of plants. It has been reported that vegetables can concentrate uranium to levels which are a 100 times that of the irrigation water. Reduction of wheat yields by 50 % upon addition of 50 mg/kg uranium, and no effect on yield at 10 mg/kg have been shown.

Mitigation Common on-farm management practices to mitigate against uranium uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline; and/or
- ! switch to a crop that is more tolerant to uranium.

Criteria **Effects of Uranium on Crop Yield and Soil Sustainability**

Concentration Range (mg/R)	Crop Yield
<i>Target Water Quality Range # 0.01</i>	<i>Plant yield remains unaffected at uranium concentrations < 10 mg/kg in soil</i>
0.01 - 0.10	Maximum acceptable concentration for fine-textured neutral to alkaline soils
> 0.10	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soils, and the concentration range for fine-textured neutral to alkaline soils for irrigation periods of up to 20 years, are similar to the few existing international criteria.
- ! The above criteria are based on limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop production.

- Modifications**
- ! The criteria were derived with the assumption that the soil to be irrigated contains only negligible quantities of uranium. Should this not be the case, the period of irrigation needs to be reduced accordingly.
 - ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because the criteria assume that the soil has a capacity to deactivate uranium.
 - ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, the criteria may need adjustment.
 - ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils, can mostly be used.

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Vanadium

Tentative guideline

Background Information

Introduction Vanadium is a white, soft, ductile metal resistant to corrosion. Vanadium occurs in several oxidation states, namely II, III, IV, and V. Soluble vanadium salts are readily taken up by living organisms.

Similar to most trace elements, vanadium is adsorbed by soil and plants respond to the vanadium concentration in the soil solution. The addition of vanadium to soils in relatively high concentrations over the short-term, may not result in reduced crop growth or in its accumulation in plant parts to concentrations detrimental to humans or animals. However, continuous application over extended periods results in its accumulation in the surface soil layer, in practice the cultivated, or the plough layer.

Occurrence Minerals containing vanadium are widespread and include vanadium sulphide and the calcium salt of vanadium. Metallic vanadium does not occur in nature. Vanadium(IV) and vanadium(V) salts are generally soluble in water and tend to remain in solution and are not strongly adsorbed onto soil particles. Compounds of vanadium such as trifluoride, trioxide and trisulphide are insoluble in water and are associated with sediments.

Typically, the concentration of vanadium in

- ! fresh water is less than 1 Fg/R; and
- ! sea water is approximately 3 Fg/R.

Vanadium compounds have various industrial applications and are used as catalysts in the chemical industry, in certain glassware and ceramic products, in the textile industry, and in the manufacture of dyes.

Interactions Vanadium concentrations in the soil solution are influenced by sorption and desorption reactions with the soil exchange complex. Sorption is expected to dominate at the relatively low concentrations that are of concern for water quality criteria for irrigation.

Soil pH also has a major effect on the concentration of vanadium in the soil solution. Its solubility decreases with increasing pH. Because it tends to exist in oxy-anion forms, vanadium is often more mobile in alkaline, oxidised aqueous environments.

Implications for irrigation with water containing vanadium, include the following:

- ! Vanadium can be expected to be retained in the soil surface layers due to sorption of vanadium by the soil exchange complex, and in cultivated land it is expected to accumulate in the plough layer.
- ! Significant downward movement to below the plough layer and contamination of groundwater is unlikely.
- ! The larger the soil's cation exchange capacity (determined by clay content and clay mineral type), the more vanadium can generally be sorbed.

- ! Soils with a neutral to alkaline pH will be able to tolerate a greater vanadium load than acidic soils before concentrations in the soil solution become phytotoxic. On the other hand when vanadium is in the oxyanion form it is commonly mobile in alkaline, oxidised aqueous environments.

Measurement The criteria are given in terms of the total vanadium concentration in units of mg/R. The reference method for the determination of vanadium is by atomic absorption spectrometry, using a nitrous oxide-acetylene flame. If other methods are used, their characteristics relative to the reference method should be known.

Data Interpretation Because vanadium is retained by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions are established. In order to prevent its accumulation, the total load applied to soil needs to be limited. International criteria for the concentration of vanadium in irrigation water have been calculated (using limited available information) to ensure that accumulation to either phytotoxic levels or levels that are toxic to consumers, within a given time period, does not occur. The calculations assume that vanadium accumulates within the surface 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintenance of crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The vanadium concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated such that vanadium does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! For the vanadium concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that vanadium can be economically removed from water intended for irrigation use.* However, should it be required, vanadium is removed by raising the pH and precipitating the insoluble vanadium salts after the addition of lime or iron salts in the pH range of 8.5 - 11.5. Precipitation is followed by settlement and filtration as in conventional water treatment. The precipitation process requires careful monitoring to ensure that removal is complete.

To achieve very low residuals, it may be necessary to pass the stream through an ion exchange column charged with the appropriate ions.

A watery vanadium-rich sludge or concentrate stream is generated in the processes that may present disposal difficulties.

The Effects of Vanadium

Norms The different norms used in the guideline to assess the effects of vanadium on irrigation water use are summarised below:

Irrigation water uses	Norms for measuring water quality effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to vanadium uptake through plant roots.
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where either crop yield or crop quality is affected.
Maintenance of irrigation equipment	! No known effects

Effects Vanadium is not required for plant growth. Vanadium interferes with the uptake of essential plant nutrients such as calcium, copper, iron, manganese and phosphorus. Depending on plant species and soil type, plant growth appears to be inhibited when vanadium concentrations in soil exceed 10 mg/kg. Plant toxicity has also been recorded at concentrations exceeding 0.5 mg/R in nutrient solutions.

Mitigation Common on-farm management practices to mitigate against vanadium uptake by plants on irrigated land, are to

- ! apply lime in order to raise (or maintain) soil pH to neutral to slightly alkaline conditions; and/or
- ! switch to a crop that is more tolerant to vanadium.

Criteria **Effects of Vanadium on Crop Yield and Soil Sustainability**

Concentration Range (mg/R)	Crop Yield and Soil Sustainability
<i>Target Water Quality Range # 0.10</i>	<i>Plant yield appears to be affected at vanadium concentrations exceeding 10 mg/kg in soil</i>
0.10 - 1.0	Maximum acceptable concentration for fine-textured neutral to alkaline soils
> 1.0	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The above criteria are based on relatively limited information and should be viewed as tentative.
- ! The criteria are calculated to ensure soil sustainability for continued crop

production.

- Modifications**
- ! The criteria were derived with the assumption that the soil to be irrigated contained only negligible quantities of vanadium. Should this not be the case the period of irrigation needs to be reduced accordingly.
 - ! The criteria may not protect commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods), because it is assumed that the soil has a capacity to deactivate vanadium.
 - ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, they may need adjustment.
 - ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are, however, grown for only limited periods, the criteria applicable to fine-textured neutral to alkaline soils, can mostly be used.

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Zinc

Tentative Guideline

Background Information

Introduction Zinc is a metallic element. The stable oxidation states of zinc are the metal (0) and the $+II$ oxidation state, which is the form found in nature. The carbonate, hydroxide and oxide forms of zinc are relatively resistant to corrosion, and zinc has many applications.

Zinc is an essential nutritional trace element for plants and animals. Plants respond to the zinc concentration in the soil solution. Similar to most trace elements, zinc is strongly adsorbed by soil and the addition thereof in relatively high concentrations over the short term, may not result in reduced crop growth. However, with continuous applications of zinc over extended periods accumulation occurs in the surface soil layer, the cultivated, or plough layer.

Occurrence The most common mineral form of zinc is the sulphide (sphalerite). Zinc is also found as a carbonate, oxide or silicate and may occur in association with many other metal ores such as copper and arsenic. The chloride, sulphate and nitrate salts of zinc are highly soluble in water, but at neutral and alkaline pH tend to hydrolyse to form relatively insoluble hydroxides which tend to be associated with sediments. On acidification of the water, the insoluble hydroxides are released back into the dissolved phase. If the water is acidic, zinc leaching caused by dissolution of the protective zinc hydroxide layer of galvanised piping can give rise to relatively high concentrations of zinc in solution.

The concentration of zinc in water is usually low, typically around 0.015 mg/R. Elevated zinc concentrations at neutral and alkaline pH arise where zinc occurs largely as a colloidal suspension of zinc hydroxide which imparts a milky white appearance to the water. In sea water the zinc concentration is also very low, typically around 0.005 mg/R.

Zinc and zinc salts are used in many industrial processes. Zinc itself is extensively used in galvanising processes and in alloys. Zinc salts are used in paint pigments, in cosmetics and in the manufacture of pharmaceuticals, dyes and insecticides.

Interactions The soil chemical behaviour of zinc is similar to those of cadmium, lead, copper and nickel. The zinc concentration in the soil solution is largely determined by sorption and desorption reactions with the soil. Sorption dominates at the relatively low concentrations that are of concern for water quality criteria for irrigation. Soil pH has a major effect on the concentration of zinc in the soil solution. Its solubility decreases with increasing pH. Zinc is relatively strongly bound to even coarse-textured soils, and little is known about the factors which affect the release of zinc. Due to the formation of sulphides, zinc has a very low solubility under reducing conditions.

Implications for irrigation with water containing zinc, include the following:

- ! Zinc can be expected to be retained in the soil surface layers due to strong sorption of zinc by soil, and accumulates in the plough layer of cultivated land.
- ! Significant downward movement of zinc to below the plough layer and hence contamination of groundwater is unlikely.

- ! The larger the soil's cation exchange capacity (determined by clay content and clay mineral type) the more zinc can generally be sorbed.
- ! Soils with a neutral to alkaline pH will be able to accept a greater zinc load than acidic soils before concentrations in the soil solution becomes phytotoxic.

Measurement The criteria are given in terms of the total zinc concentration in units of mg/R. Total zinc is measured after acidification of the sample by atomic absorption spectrometry, which is the reference method. If other methods are used, their characteristics relative to the reference method should be known.

Data Interpretation Due to zinc being retained strongly by soils, it is likely to accumulate to phytotoxic concentrations before equilibrium between sorption and desorption reactions is reached. In order to prevent accumulation to phytotoxic concentrations, which would also render the soil unsuitable for continued crop production, the total load of zinc applied to soil needs to be limited. International criteria for the concentration of zinc in irrigation water have been calculated to ensure that accumulation to either phytotoxic concentrations or levels that are toxic to consumers, within a given time period, do not occur. The calculations assume that zinc accumulates within the top 150 mm of soil. As such, the objectives of sustained soil suitability for continued use and maintaining crop yield and quality are accounted for.

The arithmetic mean concentration of the applied water (preferably application volume weighted) is given in the criteria for:

- ! The zinc concentration that can be applied to *any soil on a continuous basis*. This concentration is calculated to ensure that zinc does not accumulate to phytotoxic concentrations in a soil that is irrigated continuously for up to 100 years at an irrigation application rate of 1 000 mm p.a.
- ! The zinc concentration that can be applied to *fine-textured, neutral to alkaline soils for a period of up to 20 years* at an irrigation application rate of 1 000 mm p.a.

Treatment Options *It is highly unlikely that zinc can be economically removed from water intended for irrigation use.* However, should it be required, zinc is removed by raising the pH and precipitating the insoluble zinc hydroxide with lime treatment in the pH range of 9.5 - 10.0. The precipitation is followed by settlement and filtration as in conventional water treatment.

The precipitation process requires careful monitoring to ensure that removal is complete. A watery zinc-rich sludge is generated in the process; this may present disposal difficulties.

The Effects of Zinc

Norms The different norms used in the guideline to assess the effects of zinc on irrigation water use are summarised below:

Irrigation Water Uses	Norms for Measuring Water Quality Effects
Application to commercial crops	! Crop yield as affected by crop sensitivity to zinc uptake through plant roots
Application to sustain suitability of irrigated soil	! Accumulation in soil to concentrations where crop is affected
Maintenance of irrigation equipment	! No known effects

Effects

Zinc is an essential plant nutrient that is required in small amounts. At higher concentrations it causes toxic responses by inducing iron deficiency. Toxicity appears to be induced at concentrations of 0.3 - 10 mg/R (depending on the type of plant) in nutrient solutions. Symptoms of zinc toxicity include iron chlorosis, reduced leaf size, necrosis of tips and distortion of foliage. Since irrigated soils are often alkaline, the low solubility of zinc under these conditions often leads to the development of plant zinc deficiencies.

Mitigation

Common on-farm management practices to mitigate against excessive zinc uptake by plants on irrigated land, are to

- ! apply agricultural lime in order to raise (or maintain) soil pH to neutral to slightly alkaline; and/or
- ! apply huge quantities of organic material; and/or
- ! switch to a crop that is more tolerant to zinc.

Criteria

Effects of Zinc on Crop Yield and Soil Sustainability

Concentration Range (mg/R)	Crop Yield and Soil Sustainability
<i>Target Water Quality Range # 1.0</i>	<i>Toxic to many plants at concentration of 1 mg/R and less in nutrient solutions. The TWQR should protect most plants from absorbing toxic concentrations of zinc, even when grown on acid sandy soils</i>
1.0 - 5.0	Maximum acceptable as concentration for fine-textured neutral to alkaline soils
> 5.0	Acceptable for irrigation only over the short term on a site-specific basis

Note:

- ! The TWQR for relatively unrestricted use on all soil types and the concentration range for fine-textured neutral to alkaline soils for periods of up to 20 years use, are similar to the most conservative of the international criteria. Higher concentrations may apply on a site-specific basis.

! The above criteria are based on relatively limited information and should be viewed as tentative.

! The criteria are calculated to ensure soil sustainability for continued crop production.

- Modifications**
- ! The criteria were derived with the assumption that the soil to be irrigated contains only negligible quantities of zinc. Should this not be the case the period of irrigation needs to be reduced accordingly.
 - ! The criteria may not be protective for commercial floricultural crops grown in greenhouses without soil (hydroponic or similar methods) because it is assumed that the soil has a capacity to deactivate zinc.
 - ! Should the site-specific conditions vary significantly from the assumptions that were used to derive the criteria, they may need adjustment.
 - ! Potted plants normally receive water applications in excess of the assumptions used to derive the criteria. Since potted plants are only grown for limited periods, the criteria applicable to fine-textured neutral to alkaline soils, can mostly be used.

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Chapter 6

Glossaries

Glossary of terminology

<i>aerobic:</i>	of organisms requiring molecular oxygen for respiration <i>or</i> conditions where oxygen is available
<i>adsorption/elution:</i>	the attachment of molecules or ions to, and their removal from, a substrate by manipulation of electrical charge or pH
<i>amphoteric:</i>	the capability of a substance to react as an acid or a base, hence of dissolving under basic or acidic conditions
<i>anaerobic:</i>	conditions lacking oxygen, or organisms not requiring oxygen for respiration
<i>anions:</i>	negatively charged ions
<i>anionic:</i>	characteristic behaviour or property of an ion that has a negative charge. Anions move to the anode in electrolysis
<i>buffering capacity:</i>	a measure of the relative sensitivity of a solution to pH changes on addition of acids or bases
<i>cationic:</i>	characteristic behaviour or property of an ion with a positive charge. Cations move to the cathode in electrolysis
<i>cations:</i>	positively charged ions
<i>chlorophyll:</i>	the green pigment in plants and algae that, during photosynthesis, captures sunlight energy and converts into chemical energy in the form of carbohydrates. Chlorophyll <i>a</i> and <i>b</i> are two forms of chlorophyll which are required in the biochemical reactions of photosynthesis. Chlorophyll <i>a</i> , <i>b</i> and <i>c</i> are forms of chlorophyll. Chlorophyll is used as a measure of the quantity of algae in water
<i>coagulation:</i>	the separation or precipitation of particles in a dispersed state from a suspension resulting from their growth. This may result from the addition of an electrolyte (coagulant), prolonged heating or from a condensation reaction between a solvent and solute
<i>dissolution:</i>	the process of dissolving
<i>electrodialysis:</i>	the process of selective diffusion through a membrane conducted with the aid of an electromotive force applied to electrodes on both sides of the membrane
<i>etiological:</i>	causative, as in causing disease
<i>eutrophic:</i>	refers to water, particularly in lakes and dams, which is high in nutrients and hence has excessive plant and algal growth.
<i>exchangeable sodium percentage (ESP):</i>	Soil particles have the ability to adsorb cations and, through the process of cation exchange maintain a dynamic equilibrium between cations adsorbed onto the particles and those in the soil solution. The equivalent fraction of exchangeable sodium ions, expressed as a percentage of the total cation exchange capacity, is called the ESP

<i>flocculation:</i>	the addition of chemical reagents (flocculants) to bring small particles together in flocs through the process of <i>coagulation</i> , aggregation or biochemical reaction of fine suspended particles
<i>halophytic:</i>	a salt-tolerant plant
<i>hard water:</i>	water that contains high concentrations of calcium, magnesium, and to a lesser extent other alkaline earth metal ions, in solution. Under highly alkaline conditions, the calcium and magnesium of hard waters may precipitate out as scale or as some other insoluble salt of these two metal ions
<i>hardness:</i>	defined as the sum of the calcium and magnesium concentrations, both expressed as calcium carbonate, in milligrams per litre
<i>hygroscopic:</i>	a substance that absorbs water
<i>indole-positive:</i>	means producing a positive reaction in a biochemical test for the production of indole
<i>ion exchange:</i>	the interchange of ions of like charge, usually on a solid medium; used in water treatment, such as water softening
<i>lignin:</i>	an organic polymer providing strengthening and thickening in plant cell walls. The properties of wood are due to the encrustation of plant cell walls with lignin
<i>macrophyte:</i>	any macroscopic form of aquatic vegetation: encompasses certain species of algae, mosses and ferns as well as aquatic vascular plants
<i>mesotrophic:</i>	a term applied to freshwater bodies that contain moderate quantities of plant nutrients and are therefore moderately productive
<i>microbes:</i>	microscopic organisms such as bacteria or viruses
<i>mucilaginous:</i>	the tacky or slimy property of extracellular substances secreted by certain groups of bacteria, such as the slime-producing bacteria
<i>necrosis:</i>	the death of cells or tissues
<i>occlusion:</i>	blockage
<i>osmoregulation:</i>	the regulation of the osmotic pressure of body fluids by controlling the amount of water and/or salts in the body
<i>osmosis:</i>	the diffusion of a solvent, usually water, through a semi-permeable membrane, into a more concentrated solution
<i>pathogenic:</i>	refers to causing disease
<i>permeability:</i>	the condition of allowing the passing of fluid molecules through a particular medium such as soil, etc.
<i>photosynthesis:</i>	the trapping of solar energy and its conversion to chemical energy by plants and algae, which use the energy in manufacturing food molecules from carbon dioxide and water

<i>physico-chemical:</i>	refers to the physical (e.g. pH, temperature, electrical conductivity) and chemical (e.g. concentrations of nitrate, mercury) characteristics of water
<i>point of supply:</i>	that point in an industrial operation where water is obtained for use in various industrial processes
<i>polyvalent metallic ions:</i>	ions of metals having more than one oxidation state e.g. Cr(III) and Cr(VI)
<i>raw water:</i>	source water in its untreated state
<i>redox potential:</i>	an expression of the oxidising or reducing power of a solution relative to a reference potential. This potential is dependent on the nature of the substances dissolved in the water, as well as on the proportion of their oxidised and reduced components
<i>reducing conditions:</i>	conditions prevailing within an aquatic environment in which the redox potential is such that substances become reduced
<i>reverse osmosis:</i>	a technique in the desalination of water in which pressure is applied to the surface of the saline solution, forcing pure water to pass through a semi-permeable membrane which prevents the passage of other ions
<i>salinity:</i>	a measure of the salt content of soil or water
<i>scaling:</i>	the formation of a dense coating of predominantly inorganic material formed from the precipitation of water soluble constituents. The most common substances forming scale are carbonates and sulphates of calcium and magnesium hydroxide
<i>sodicity:</i>	a qualitative term referring to the sodium content of water or soil (refer also to <i>sodium adsorption ratio (SAR) and exchangeable sodium percentage</i>)
<i>sodium adsorption ratio (SAR):</i>	the ratio between soluble sodium and soluble divalent cations in water or soil extracts, which can be used to predict the relative activity of sodium ions in exchange reactions with soil
<i>supersaturation:</i>	refers to a solution containing more solute than equilibrium conditions will allow; unstable to the addition of solute crystals
<i>surficial deposits:</i>	are unconsolidated alluvial, residual or glacial deposits overlying bedrock or occurring on or near the surface of the earth
<i>treatment breakthrough:</i>	the occurrence of contaminants in final water after treatment as a result of failure of a component of the treatment process. This is usually an isolated event with a clearly definable cause and effect, e.g. appearance of bacteria in treated water as a result of failure of chlorination
<i>valency:</i>	the number of electrons required to be gained or lost by an atom to reach a state where the outermost electron shell is full
<i>vascular plants:</i>	plants with woody conducting vessels

Glossary of abbreviations / acronyms

APHA	American Public Health Association
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
BOD	biological oxygen demand
COD	chemical oxygen demand
CSIR	Council for Scientific and Industrial Research
DOC	dissolved organic carbon
EC	electrical conductivity
EC	European Community - in this document, the European Community (EC) is referred to as such when discussing it as an economic/political entity. It is referred to the European Economic Community (EEC) when directly citing a Directive promulgated prior to the change from EEC to EC, formally in 1992.
EEC	European Economic Community
EDTA	ethylenediamine tetra-acetic acid
ESP	exchangeable sodium percentage
GAC	granular activated carbon
HC	hydraulic conductivity
HOCl	hypochlorous acid
HPLC	high performance liquid chromatography
IAWPRC	International Association for Water Pollution Research and Control
IR	infiltration rate
NAS/NAE	National Academy of Sciences/National Academy of Engineering (USA)
PVA	polyvinyl alcohols
SAR	sodium adsorption ratio
TDS	total dissolved solids
TOC	total organic carbon
TWQR	Target Water Quality Range

US EPA United States Environmental Protection Agency

WHO World Health Organisation

Glossary of units of measure

kg/h	kilograms per hectare
µg/l	micrograms per litre
µS/cm	micro-Siemens per centimetre
meq/l	milli-equivalents per litre
mg/l	milligrams per litre
mM/l	millimoles per litre
mS/m	milli-Siemens per metre
ng/l	nanograms per litre
nm	nanometre
EC	degrees centigrade