Colorado Water Quality Control Division

WATER QUALITY PERMITS

Policies & Procedures

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Initiated: Gary Beers
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Implementing Narrative Standards

in Discharge Permits for the Protection of Irrigated Crops

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1.0 INTRODUCTION

1.1 Purpose

The purpose of this policy is to provide additional guidance to the development of effluent limits, under two narrative standards, for permitting discharges to surface waters that subsequently are diverted to crop irrigation. The scope of this guidance is limited to two measures of dissolved salts that can be used to further protect the downstream suitability of state waters for crop irrigation.

Policies provide guidance for Water Quality Control Division (WQCD) practices and vary in degree of expected flexibility during implementation. This policy is a "work in progress." There may be revisions as implementation in permits proceeds and the array of unexpected consequences are evaluated. Intentionally, this policy is not substantially prescriptive or all-inclusive at the outset for reasons such as:

- determination of the suitability of the quality of irrigation water is a complex analysis and dependent upon site-specific interactions of agricultural practices and environmental conditions;
- the proposed salt-based measures of suitability of water for irrigation are properties of water and, thus, dependent on the relative concentrations of several ionic components which are not constant from site to site;
- the ability to translate the quality of a discharge to subsequent impacts on water quality in the root zone of crops irrigated from downstream diversions is limited;
- historic characterization of wastewaters has not included quality measures that are used to assess suitability of irrigation water – thus, currently, there is a limited database for key permitting decisions;
- current practices of wastewater management and treatment have not had to consider control of effluent quality based on the strength and mixture of ionic salts that are important to the production of irrigated crops; and
- water quality protection is provided for a beneficial uses that reside in a terrestrial setting and not in an aquatic setting.

Thus, the policy is broad guidance for permit preparation and recognizes that flexibility must exist, based on highly variable site-specific conditions, to implement options to the policy when there is technical justification, acceptable to the WQCD, that the yield of the most salt-sensitive downstream irrigated crop will not be measurably reduced from 100% and impacts to soil infiltration are not significant due to water quality.

1.2 Relationship to Other Policies and Regulations

During policy development, with the involvement of stakeholders, issues with respect to the following policies were addressed as follows:

- No changes are proposed to the current practices of developing permit limits under the policies for reasonable potential analysis and mixing zone implementation or the policies that guide those practices. As this policy is implemented, revisions to these policies and practices can be considered as appropriate.

- At this time, the provisions of the WQCD antidegradation guidance are not applied in the determination of criteria to implement the narrative standards with respect to irrigated crops. The WQCD will seek clarification from the Water Quality Control Commission (WQCC) on the implementation of antidegradation review for narrative standards before including this step in this policy.
- No changes are proposed to current process for determination of attainment of the narrative standards for "303(d)" purposes.

2.0 BACKGROUND

In 2006, the WQCD and the WQCC were made aware of concerns about the impacts of industrial discharges, containing elevated concentrations of certain salts, on the quality of downstream water and its suitability for use in irrigating crops. The WQCD investigated the concern and decided that further evaluation was needed. The WQCD determined that additional controls to protect this beneficial use should be considered and, working with stakeholders, proceeded to develop a policy for implementing the narrative standards for protection of irrigated crops (i.e., "no harm to plants" and "no harm to the beneficial uses") in discharge permits. The development of this policy does not preclude the WQCD or other stakeholders from proposing changes to the WQCC to add numeric standards to Regulation No. 31. The next WQCC Rulemaking Hearing on this regulation is scheduled for June 2010.

The WQCD completed a four-step process in developing this policy:

- Joint effort with the Colorado Water Quality Forum to start a public, stakeholder process (i.e. Agricultural Diversions Workgroup) to scope the issue, to discuss the prime components of the issue, to provide input to WQCD on preliminary drafts of the policy, and to provide WQCD feedback to stakeholders.
- The WQCD continued to internally discuss how to implement these narrative standards and to further comprehend the consequences of proposed changes in statewide permitting practices to require necessary control of dissolved salt concentrations.
- The WQCD prepared a proposed policy for public review (December 3, 2007), and public comments will be provided to the WQCC (by January 3, 2008) for discussion at the WQCC's Informational Hearing (January 14, 2008)
- The WQCD evaluated the WQCC's feedback and public comments and decided to issue the proposed policy. The WQCD prepared written responses to the public comments and provided these to the WQCC.

3.0 POLICY

3.1 Levels of Protection For Irrigated Crops

The following narrative standards and agricultural beneficial-use definitions from Regulation No. 31 are the starting points for the selection of the appropriate levels of protection that should be provided in permits for discharges to surface waters.

> Section 31.11(1)(a)(iv) State surface waters shall be free from substances attributable to human-caused point source or nonpoint source discharge in amounts, concentrations or combinations which are harmful to the beneficial uses or toxic to humans, animals, plants, or aquatic life
>
> Section 31.13 State Use Classifications. Waters are classified according to the uses for which they are presently suitable or intended to become suitable. In addition to the classifications, one or more of the qualifying designations described in section 31.13(2), may be appended. Classifications may be established for any state surface waters, except that water in ditches and other manmade conveyance structures shall not be classified.
>
> Section 31.13(2) *Agriculture. These surface waters are suitable or intended to become suitable for irrigation of crops usually grown in Colorado and which are not hazardous as drinking water for livestock.*

Given the above narrative standards, two types of protection are required.

- One type of protection is "no harm" to plants (i.e., irrigated crops in this application). Many measures can be employed to assess when a plant is harmed by the quality of irrigated water – such as germination rate, growth rate, crop yield, foliage imperfections, and moisture stress.
- The other type of protection is for "no harm to the beneficial use" which for irrigated agriculture is for "crops usually grown in Colorado."

To implement these aspects of the narrative standards on a statewide basis, no reduction in crop yield and low sodium hazard of water are selected as protective endpoints for use in this policy. These measures relate directly to the protection of the beneficial use, are widely used, apply to all irrigated crops, and have a substantial scientific database that relates crop yield and sodium hazard to quality of irrigation water. Crop protection will be based on the most sensitive, usually grown crop as defined by local agricultural practices. The WQCD will work with agricultural experts at Colorado State University, local county agricultural extension, or local National Resource Conservation Service (NRCS) staff to identify key irrigated crops downstream of specific discharges and which crop is the most sensitive to salts.

The needed levels of protection will be provided on a year-round basis. The rationale for this requirement is that that a water-right holder may exercise a diversion for winter storage with that water and use to irrigate crops in the following growing season. However, the WQCD will evaluate site-specific requests with supporting information for placing seasonal limits in permits and, where the permittee demonstrates there will be no measurable reduction in yield of irrigated crops due to water quality, place these limits in a permit.

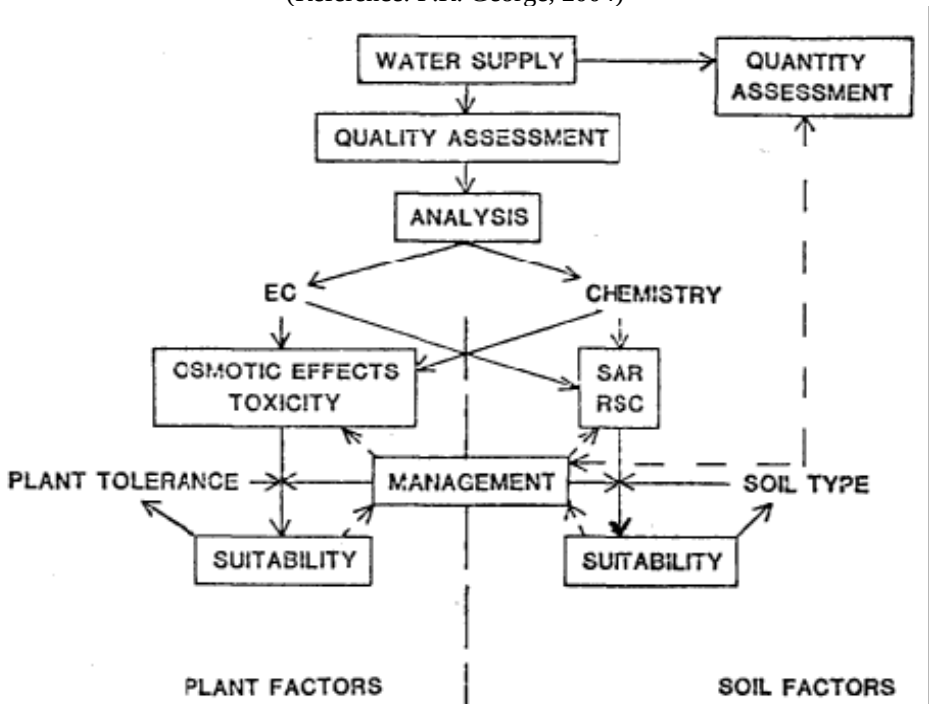
Thus, this policy will implement, at the local level, the narrative standards with goals of causing "no harm" to plants or to "the beneficial use" (i.e. irrigated crops usually grown in Colorado).

3.2 Selection Of Salt Control Parameters

The evaluation of the suitability (i.e., quality) of irrigation water is complex and involves the detailed understanding of the interactions of plant tolerances, soil types, and agricultural management practices (see detailed discussion in P.R. George, 2004). A view of this complexity is provided in Figure 1. Briefly, the salinity, expressed as electrical conductivity, of the water in the root zone (saturation extract or ECe) can have harmful effects on crops as noted on the left side of Figure 1. This harmful effect is based on the ECe level of the water present in the root zone. Concurrently, the sodicity (expressed as a ratio of sodium to calcium and magnesium, or Sodium Absorption Ratio, SAR) of the irrigation water can alter the soil properties with the outcome of reduction in the availability of water in the root zone. The diagram includes Residual Sodium Carbonate (RSC) as another measure of sodicity; however, SAR is the widely preferred measure of sodicity. The import of the diagram is that irrigation water has two properties (i.e., salinity and sodicity) that can have concurrent impacts on the irrigated crop beneficial use. Thus, these two measures, ECe and SAR, are selected for use in determining criteria for implementation in discharge permits to control levels of salts to minimize both the loss of irrigated crop yield and the sodium hazard. The latter is a key determinant in the long-term ability of soils to support crop yields, since the effect is to limit availability of water in the root zone to plants.

Figure 1. Flow Diagram for Evaluation of Irrigation Water Quality

(Reference: P.R. George, 2004)

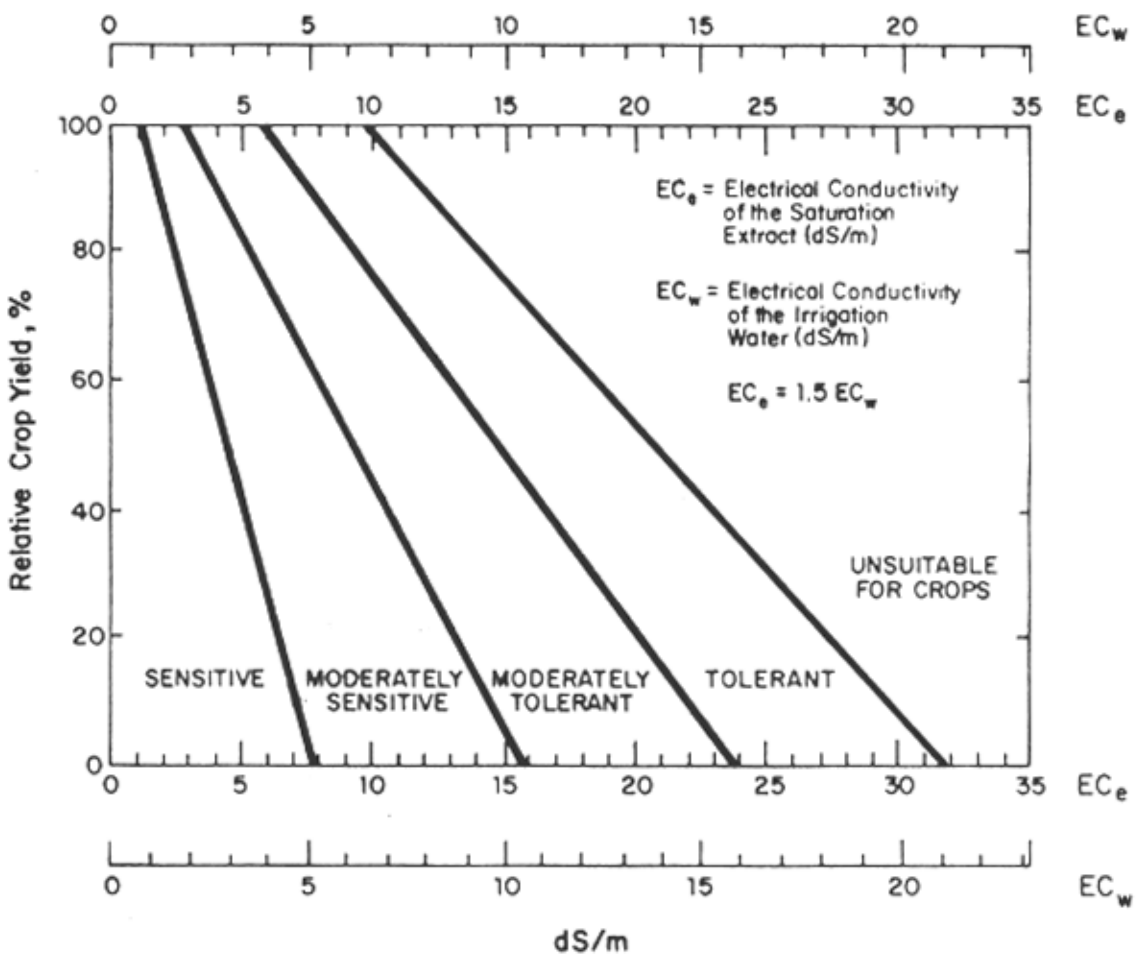


3.2.1 Electrical Conductivity (EC)

The general relationship between ECe levels in soils and yield of crops with various levels of salinity sensitivity is shown in Figure 2. Sensitive crops have a low threshold to ECe and yield quickly decreases with increased ECe. In contrast, tolerant crops have a high threshold to ECe and yield decreases at a slower rate with increased ECe. ECw is a measure of salinity in irrigation water. Figure 2, also, shows the general sensitivity of crop yield to the electrical conductivity of the irrigation water, ECw, which is estimated by dividing the soil ECe values by 1.5.

Figure 2. General Sensitivity of Crop Yield to Soil ECe

(Reference : Ayers and Westcot, Tanji 1990)



To provide examples of the policy's use, selected maximum ECw values, that are not expected to result in a reduction in yield for certain examples of irrigated crops in Colorado, are provided in Table 1. The ECw values listed in Table 1 are consistent with those contained in the salt tolerance database published by the Agricultural Research Service of the U.S. Department of Agriculture, which is included as Appendix B. It should be noted that the values in the salt tolerance database are published as ECe and that those values must be converted to ECw (ECw = Ece/1.5) for use in this policy

Table 1 Maximum ECw That Will Not Reduce The 100% Yield of Selected Irrigated Crops

(Reference : Bauder, Waskom, and Davis 2003)

Selected Crop	Irrigation Water Electrical Conductivity (ECw)
Beans	0.7
Onion	0.8
Corn (grain)	1.1
Potato	1.1
Corn (silage)	1.2
Alfalfa	1.3
Wheat	4.0
Sugarbeet	4.7
Barley	5.3

3.2.2 Sodium Adsorption Ratio (SAR)

The application of irrigation water with a high SAR can impact soil properties and reduce plant yield, especially in clay soils. High SAR water will result in excessive sodium accumulation in the soil, causing soil particles to disperse (deflocculate). This soil dispersion reduces the water movement into and through the soil (i.e., infiltration), thus reducing water availability to crops.

The SAR of irrigation water is calculated by comparing the relative concentration of sodium with those of the calcium and magnesium ions.

The impact of a sodium imbalance in irrigation water can be exacerbated when bicarbonates exceed 150 mg/l (Ayers). For these instances, an adjusted SAR (SAR-adj) must be calculated.

The classic Ayers-Westcot diagram on soil infiltration (Figure 3) incorporates a relationship between SAR (unadjusted) and ECw (irrigation water) which recognizes that as ECw increases, the potential impacts of SAR on soil infiltration decrease. However, based on numerous recent studies on irrigation practices and rainfall patterns (i.e., Saurez, Wood, and Lesch 2006, Hanson, Grattan, and Fulton 1999, US Bureau of Land Management 2002, and others), this relationship is not unbounded because of the potential impact of rainfall on sodic soils. There are several guidelines available for placing boundary on this relationship (i.e., maximum SAR values range from 2 to 16). However, the current guideline used by Colorado State University Extension (Bauder, Waskom, and Davis 2003), as summarized in Table 2, is used in this policy. Specifically, the SAR value that is the upper threshold of the low risk category (i.e., SAR = 9) is applied as a SAR cap in the Ayers-Westcot diagram as shown in Figure 4. The portion of the ECw-SAR line in the Ayers-Westcot diagram for “No Reduction in Infiltration” remains in place for SAR values less than 9.

Figure 3 Relative Rate of Water Infiltration as Affected by ECw and SAR

(Reference: Ayers and Westcot 1985)

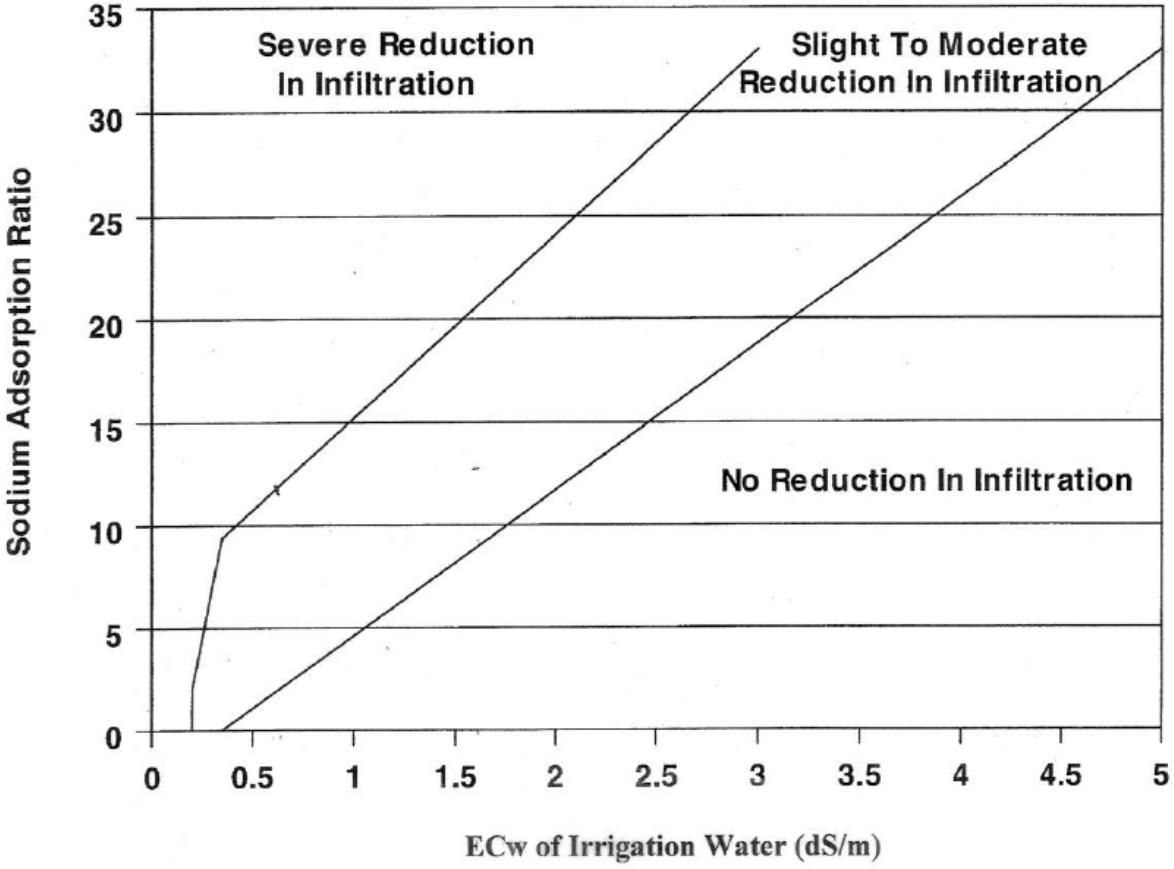
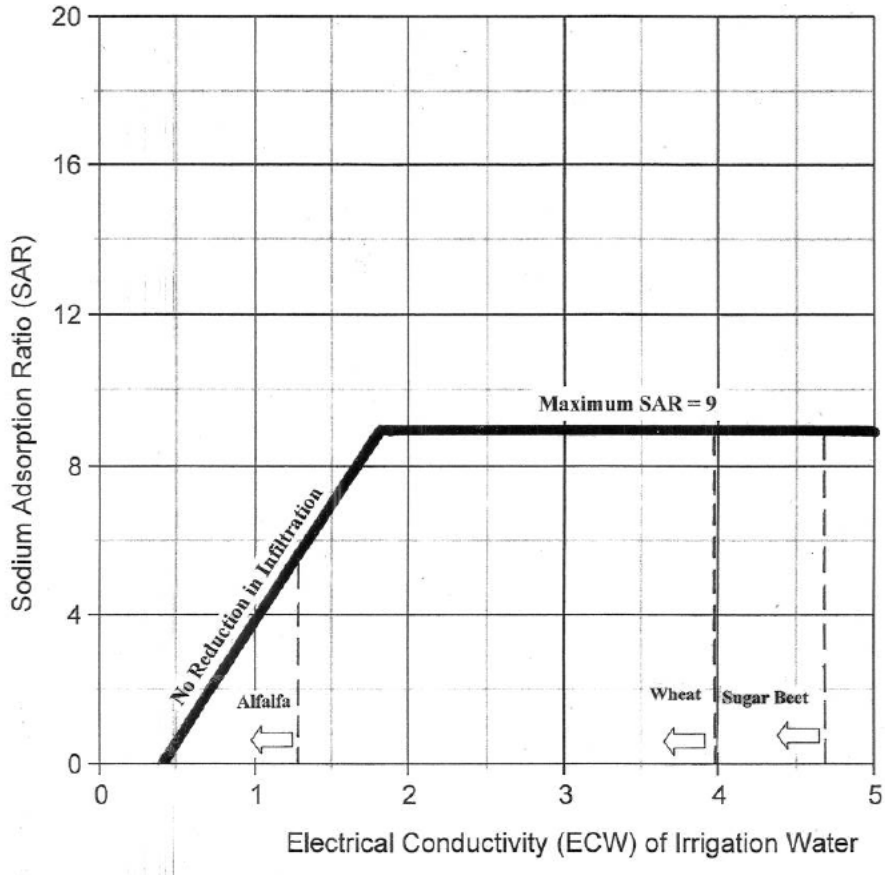


Table 2 General Classification of Water Sodium Hazard Based on SAR Values

(Reference : Bauder, Waskom, and Davis 2003)

SAR Values	Sodium Hazard of Water	Comments
1-9	Low	Use on sodium sensitive crops must be cautioned
10-17	Medium	Amendments (such as gypsum) and leaching needed
18-25	High	Generally unsuitable for continuous use
25 or greater	Very High	Generally unsuitable for use

Figure 4. Relative Rate of Water Infiltration as Affected by ECw and SAR with Modification to Show Upper Limit for SAR = 9



Note: The dashed lines are the ECw values from Table 1 for the three selected crops. The combination of SAR and ECw values to the left of the respective dashed line and below the SAR solid line will not contribute to a reduction in the 100% yield of the named crop.

3.2.3 Protection Based on Consideration of ECw and SAR

Based on the above considerations, the necessary level of protection is based on

- a site-specific selection of the most sensitive crop grown in the area downstream of the discharge, based on ECe tolerance,
- applying the ECw threshold value for no reduction in yield below100% of the expected value, and
- determining the maximum SAR level based on the ECw value with the maximum SAR not to exceed 9.

The resultant maximum ECw and SAR values are established as criteria to implement the narrative standards for protection of irrigated crops in discharge permits. These bounds, for three example crops, are provided in Figure 4. The SAR boundary for a given ECw value is bounded by the Ayers-Westcot relationship when the SAR is less than 9 and is bounded by a SAR equal to 9 in the remaining conditions. Using alfalfa, wheat, sugar beet, and barley as

examples, the ECw criteria are imposed within the area below the above SAR criteria. The area below the SAR criteria and to the left of the ECw criteria contains the SAR and ECw combinations that would not reduce the crop yield below 100% or result in an unacceptable sodium hazard.

Therefore, under this policy, ECw and SAR criteria will be established based simply on the most sensitive crop usually grown in the area downstream of the discharge.

3.3 Application In Discharge Permits

An introduction to how the policy can be applied to permitting discharges to surface waters is discussed and is followed by overview (Table 3).

3.3.1 Segments with Agricultural Diversions

This policy applies only to situations where an agricultural diversion exists for routing water to the use of crop irrigation. Over 90% of the hundreds of waterbody segments in the state are designated for agricultural use which includes livestock watering and crop irrigation. This designation by Regulation No. 31 does not mean that a diversion now physically exists to divert water to an agricultural use.

When preparing specific discharge permits, the WQCD, with the assistance of the Colorado Division of Water Resources (DWR), will determine if downstream waters are being diverted to irrigate crops. DWR does maintain an inventory of water rights which includes point of diversion and use of the water. Further, for many areas of the state, this use is supported by type of crop irrigation. Site-specific efforts will be needed to identify downstream diversions for crop irrigation that are not associated with an adjudicated water right. The latter type of diversion will be considered during the implementation of this policy.

The application of the policy to some instances of actual diversion for a type of agricultural use will have to be determined on a site-specific basis. For example, a water-right holder may periodically divert water to flood irrigate pasture land. The Division will consider factors such as the frequency of diversion and the intended use (i.e., grazing) when determining the application of the policy.

Where water is piped directly to agricultural use for crop irrigation without discharge to surface waters of the state, a CDPS permit is not required and this policy does not apply.

3.3.2 Discharge to Irrigation Ditches

Discharges to irrigation ditches will be required to provide the same levels of protection afforded receiving waters classified for agricultural use (i.e. crop irrigation).
Since all ditches are characterized by zero low flow, there may be circumstances when the management of diverted flow in the ditch supports a discharge with alternate SAR/ECw criteria. This will be a site-specific decision, must be supported by an agreement between the ditch owners and the discharger, and is to be consistent with permitting practices In instances where the ditch water reaches classified water, then the policy will apply without exception.

Table 3. Overview of Policy Application

Site-Specific Conditions				Part A. Application of the Policy
Agricultural Beneficial Use Assigned to Receiving Water Body and Actual Use Is:		Non-agricultural		No
		Agricultural -Livestock		No
		Agricultural-Irrigated Crops	Diversion present	**Yes** (see Part B)
			No diversion present	No
Site-Specific Conditions				**Part B. Application of ECw/SAR Criteria (Figure 4) under the Policy**
Discharge to a natural drainage	Chronic low-flow greater than Zero	Ratio of low-flow to discharge flow is 100:1 or greater		No Due to high immediate dilution, the EC and SAR based effluent limits are not needed.
		Ambient levels (85th percentile) of SAR and/or ECw values upstream of the discharge point are greater than the applicable criteria for the selected, most EC sensitive local crop		No ECw and/or SAR effluent limits are set equal to the 85th percentile values
		Mixing zone can be allowed in accordance with Division policy		**Yes** Effluent limits are based on meeting ECw and SAR criteria at downstream edge of mixing zone.
	Chronic low-flow equal to zero	Discharge (undiluted) does reach diversion point		**Yes** Effluent limits are set equal to ECw and SAR criteria (i.e., end-of-pipe limits)
		Discharge does not reach diversion point		No Since discharge is not diverted for crop irrigation, the EC and SAR based effluent limits are not needed
Discharge to a man-made ditch	Ditch does not return diverted flow to classified surface waters of the state			No Since all ditches are characterized by zero low flow, there may be circumstances when the management of diverted flow in the ditch supports a discharge with alternate SAR/ECw criteria. This will be a site-specific decision, must be supported by an agreement between the ditch owners and the discharger, and is to be consistent with permitting practices.
	Ditch does return diverted flow to classified surface waters of the state			**Yes** Effluent limits are based on meeting ECw and SAR criteria at downstream edge of mixing zone in classified waters of the state. Also, EC and SAR based limits will reflect understandings between ditch owners and discharger.

3.3.3 Point of Compliance

The SAR/ECw based criteria will be applied at the point of discharge and, where the upstream water quality is better than the required water quality, can be adjusted to recognize the availability of a mixing zone. In the latter case, an effluent limit will be calculated based on meeting the required criteria at the downstream edge of the mixing zone.

The WQCD recognizes that additional information is needed to understand the behavior of wastewaters with elevated SAR and EC values in the mixing zone of the discharge. Since these are non-conservative parameters, their behavior is not a linear function of dilution by the receiving water and may quickly be reduced to low levels in the upper reaches of the mixing zone. Site-specific information will be needed to evaluate the actual assimilative capacity of the receiving water to the concentration and mixture of criteria-related ions in the discharge.

3.3.4 Effluent Limits

There will be two criteria employed to control salts in the discharge with the intent of limiting the potential of the discharge to impair of the quality of downstream water used to irrigate crops.

- The ECw limit will be calculated based on protection of 100 % yield for the most sensitive irrigation crop usually grown in the area and will be implemented into the discharge permit as a 30-day (monthly) average limit.
- The SAR limit will be calculated based on the maximum SAR value associated with the most sensitive irrigated crop usually grown in the area and will be implemented into the discharge permit as a 30-day (monthly) average limit.

There can be exemptions to the application of the above criteria if the discharge is a minimal risk to the quality of downstream water at the irrigation use. For example:

- If the discharge flow is diluted by 100 or greater , based on the maximum flow of the discharge and the chronic low flow of the receiving water, then the SAR/ECw criteria will not apply. This ratio is consistent with that used in the WQCD's Antidegradation Review Policy to identify insignificant impacts.
- If the representative upstream SAR-ECw water-quality (i.e., 85th percentile based on historic data) is of a lower quality than the SAR/ECw criteria, and upstream permitted point-source discharges of SAR-ECw water do not significantly contribute to the lower water quality, then the SAR-ECw criteria for use in determining permit conditions will be set equal to the upstream water quality
  The ECw value will be based on the ambient stream data and the SAR value will be the ambient value present with the ambient ECw value and not based on the SAR limit in Table 4 for the ambient ECw value.
- If the undiluted discharge flow does not reach the diversion point due to infiltration into the channel bed under dry weather conditions, then the policy would not apply to this discharge. This permitting practice exists in several permits.

3.3.5 Monitoring Requirements

For determination of compliance with the ECw/SAR limits placed in the permit, the following effluent parameters will be monitored: electrical conductivity, sodium, calcium, magnesium, bicarbonate, carbonate, and pH. If the bicarbonate concentrations do not exceed 150 mg/l, then the permit can be amended to remove the monitoring requirement for these parameters which are needed to calculate the SAR-adj.

4.0 REFERENCES

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2006 Effect of SAR on Water Infiltration under a Sequential Rain-Irrigation Management System. Agricultural Water Management 86:150-164.

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Water Quality Control Commission
Regulation No. 31. The Basic Standards and Methodologies for Surface Water. 5 CCR 1002-31. Amended February 12, 2007. Effective July 1, 2007.

Water Quality Control Division
2001 Antidegradation Significance Determination for New or Increased Water Quality Impacts. Procedural Guidance.
2002 Colorado Mixing Zone Guidance
2003 Reasonable Potential Procedural Guidance

APPENDIX A
KEY DEFINITIONS

30-day (monthly) average
The arithmetic mean of all representative samples of discharged effluent taken in a 30-day period. This value may be based on a single sample or multiple samples.

Chronic Low Flow
Low flow is the flow of water in a stream during prolonged dry weather. Colorado design flow statistics such as the chronic low flow, 30E3, (the lowest 30-day average flow that occurs on average once every 3 years) to define low flow for the purpose of setting chronic effluent limits in discharge permits. There are instances where low flow values are zero, but this does not mean that there may no be flow in the stream during dry periods of the water year.

Conductivity (EC)
Conductivity of water is directly related to the concentration of dissolved, ionized solids in the water. Ions from the dissolved solids in water create the ability for that water to conduct an electrical current, which can be measured using a conventional conductivity meter. The units are deciSiemens per meter at 25°C (dS/m)

Often conversions between EC and TDS are made, but caution is advised because conversion factors depend both on the salinity level and the composition of the water. For example:

TDS (mg/l) = 640 x EC (dS/m) when EC < 5 dS/m
TDS (mg/l) = 800 x EC (dS/m) when EC > 5 dS/m

Sulfate salts do not conduct electricity in the same way as other types of salts. Therefore, if the water contains large quantities of sulfate salts, the conversion factors are invalid and must be adjusted upward.
Also, the conductivity corrected for calcium carbonate ($CaCO_3$)loss is then referred to as the effective conductivity. As salts of low solubility are likely to precipitate out of solution in the soil and not contribute to the salinity of the soil water, some allowance must be made for this. The main salt of concern is calcium carbonate and an estimate is made of the amount of $CaCO_3$ that would precipitate from the water. The conductivity measurement is then corrected accordingly. Correcting the conductivity for loss of these salts allows a wider range of waters to be considered suitable for irrigation use.

<u>ECw</u>
The EC of irrigation water is identified as ECw. In this policy, ECw is applied to effluent flow and ambient surface water flow (i.e., receiving water body, irrigation ditch).

<u>ECe</u>
The EC of water present in the root zone of the crop is identified as ECe.

As a general rule,

ECe = ECw x 1.5.

Effluent Limit and Point of Compliance

Effluent Limit

Any restriction or prohibition established on quantities, rates, and concentrations of chemical, physical, biological, and other constituents which are discharged from point sources into state waters, including, but not limited to, standards of performance for new sources, toxic effluent standards and schedules of compliance.

In instances where there is available dilution in the receiving water body (i.e., mixing zone), the effluent limit may be greater than the applicable water quality standard.

In instances where technology-based standards are applied or there is no available mixing zone, the effluent limit is equal to technology-based standard or the applicable water quality standards. Often, these limits are referred to as "end-of-pipe" limits.

Point of Compliance

Physical point where the discharge constituents do not exceed limits or conditions required by the discharge permit. Typically, the point of release of the discharge flow (i.e., outfall) to the receiving water body is the point of compliance.

Mixing Zone

The mixing zone is where the discharged effluent mixes with the waters of the receiving water body and pollutants are diluted and dispersed at concentrations that can exceed water quality standards. The downstream boundary of the mixing zone exists where complete mixing occurs and is dependent on site-specific characteristics.

A detailed discussion of the Colorado's Mixing Zone Implementation Guidance (April 2002) is available at: http://www.cdphe.state.co.us/wq/PermitsUnit/PolicyandGuidance/MixingZone.PDF

Narrative and Numeric Standards

Water-quality standards can be expressed as qualitative or quantitative. Narrative standards are qualitative and require that certain conditions do not exist or that the discharge of effluent will not cause damage to a beneficial use assigned to the receiving water body. Numeric standards are quantitative and identify specific limit on pollutant concentration or mass. Numeric criteria can serve to implement the narrative standards where additional prescription is needed for development of effluent limits in permits.

Residual Sodium Carbonate (RSC)

Residual sodium carbonate (or residual sodium alkalinity) represents the amount of sodium carbonate and sodium bicarbonate in the water and is said to be present in a water sample if the concentration of carbonate and bicarbonate ions exceed the concentrations of calcium and magnesium ions. RSC is usually expressed as milliequivalents per litre (meq/L) of sodium carbonate, or on some analysis reports as calcium carbonate.

When irrigation water containing RSC is used on clay soils containing exchangeable calcium and magnesium, sodium from the RSC in the water will replace calcium and magnesium in the soil. An increase in clay soils sodium content may cause structure damage

Salinity and Sodicity

Salinity

Salinity refers to level of salts in water and is commonly measured as electrical conductivity (EC).

Sodicity

This is the effect the irrigation water will have on the physical properties of the soil due to an accumulation of sodium. Sodium can affect plants in three ways:(1) by destroying soil structure causing clay particles to disperse rather than cling together as small peds (coarse blocky texture, crust formation after rain or irrigation) and reducing water movement (permeability) and aeration in the soil; (2) by poisoning sodium sensitive plants when absorbed by either their roots or leaves; and (3) Calcium and/or potassium deficiencies may occur if the soil or irrigation water is high in sodium.

Sodium Adsorption Ratio

Unadjusted SAR (SAR)

The sodium adsorption ratio measures the relative proportion of sodium ions in a water sample to those of calcium and magnesium. The SAR is used to predict the sodium hazard of high carbonate waters especially if they contain no residual alkali.

The sodium adsorption ratio is used to predict the potential for sodium to accumulate in the soil, which would result from continued use of a sodic water. Calcium will flocculate (hold together), while sodium disperses (pushes apart) soil particles. This dispersed soil will readily crust and have water infiltration and permeability problems.

SAR is calculated with the following equation

$$SAR = Na^{+1} / [(Ca^{+2} + Mg^{+2})/2]^{0.5}$$

Where,

SAR = sodium adsorption ratio (unitless)
Na = sodium concentration (meq/L; mg/l divided by 23)
Ca = calcium concentration (meq/l; mg/l divided by 20)
Mg = magnesium concentration (meq/l; mg/l divided by 12.2)

The formula for use in Excel is

fx =Na/(SQRT((Ca+Mg)/2))

Adjusted SAR (SAR-adj)

Similarly to conductivity (see definition), SAR can be corrected to allow for calcium carbonate precipitation. It usually raises the reading for SAR because the presence of calcium can cause the calculation for SAR to understate the importance of sodium in a water. An adjusted SAR (SAR-adj) is calculated as detailed in Appendix C.

Sodium Hazard

While EC_w is an assessment of all soluble salts in a sample, sodium hazard is defined separately because of sodium's specific detrimental effects on soil physical properties. The sodium hazard is typically expressed as the sodium adsorption ratio (SAR).

Surface Water

All waters of the state except groundwaters (e.g., streams, ponds, lakes).

Total Dissolved Solids (TDS)

Total dissolved solids is an expression for the combined content of all inorganic and organic substances contained in a liquid which are present in a molecular, ionized or micro-granular (colloidal sol) suspended form. Generally the operational definition is that the solids must be small enough to survive filtration through a sieve size of two micrometers

The two principal methods of measuring total dissolved solids are gravimetry and electrical conductivity. Gravimetric methods involve evaporating the liquid solvent to leave a residue which can subsequently be weighed. In the most common circumstances inorganic salts comprise the great majority of TDS, and gravimetric methods are appropriate.

Water Right and Associated Point of Diversion

Water Right

Under Colorado water law, the right to utilize the waters of the State is based on the priority of a party's appropriation of a specified amount of water, at a specified location, for specified uses (a "water right"). The essence of a water right is its place in the priority system. Colorado's "first in time, first in right" or "prior appropriation" doctrine applies to both surface water and groundwater tributary to a surface stream. In times of water shortage, a senior right may place a "call" on a stream to obtain a full supply. The stream will then come under the administration of the Colorado Division of Water Resources.

Because some projects take a long time to complete, an applicant for a water right who has taken the first steps to appropriate water for beneficial use may obtain a "conditional" water right with a definite priority. In order to maintain a conditional water right, an Applicant must demonstrate to the Water Court reasonable diligence in perfecting the appropriation every six years from the date the decree is awarded. Reasonable diligence is demonstrated by showing continuous efforts and interest in developing the water right. To change the conditional decree to an absolute water right, an Applicant must demonstrate to the Water Court that the water has been put to beneficial use. The water right may then become absolute with the conditionally decreed priority relating back to the originally decreed appropriation date.

Associated Point of Diversion

The Colorado Division of Water Resources (DWR) maintains databases on adjudicated water rights which includes a GIS system that show location of the point of diversion associated with the water rights. This online tool is available at

http://cdss.state.co.us/DNN/MapViewer/tabid/62/Default.aspx

From this tool, additional information can be obtained on the intended use of the water diverted from the stream. While complete statewide coverage is not available, more detailed data on types of irrigated crop are available from DWR databases. Gaps in the coverage are mainly in the southern areas of the state.

Waters of the State.

Waters of the state means any and all surface and subsurface waters which are contained in or flow in or through this state, but does not include waters in sewage systems, waters in treatment works of disposal systems, waters in potable water distribution systems, and all water withdrawn for use until use and treatment have been completed.

APPENDIX B
SALT TOLERANCE OF SELECTED PLANTS

The relative salt tolerance of herbaceous crops in the following categories is provided in this appendix:

Vegetables and Fruit Crops
Fiber, grain, and Special Crops
Grasses and Forage Crops
Woody Crops
Ornamental Shrubs, Trees, and Ground Cover

These databases are available online at
http://www.ars.usda.gov/Services/docs.htm?docid=8908

- Vegetables and Fruit Crops -

Common Name	Botanical Name (b)	Threshold dS/m (c)	Slope % per dS/m	Rating (d)
Artichoke	Cynara scolymus	--	--	MT*
Asparagus	Asparagus officinalis	4.1	2.0	T
Bean	Phaseolus vulgaris	1.0	19.0	S
Bean, mung	Vigna radiata	1.8	20.7	S
Beet, red (h)	Beta Vulgaris	4.0	9.0	MT
Broccoli	Brassica oleracea botrytis	2.8	9.2	MS
Brussel Sprouts	B. oleracea gemmifera	--	--	MS*
Cabbage	B. oleracea capitata	1.8	9.7	MS
Carrot	Daucus carota	1.0	14.0	S
Cauliflower	Brassica oleracea botrytis	--	--	MS*
Celery	Apium graveolens	1.8	6.2	MS
Corn, sweet	Zea mays	1.7	12.0	MS
Cucumber	Cucumis sativus	2.5	13.0	MS
Eggplant	Solanum Melongena esculentum	1.1	6.9	MS
Kale	Brassica oleracea acephala	--	--	MS*
Kohlrabi	B. oleracea gongylode	--	--	MS*
Lettuce	Lactuca sativa	1.3	13.0	MS
Muskmelon	Cucumis Melo	--	--	MS
Okra	Abelmoschus esculentus	--	--	S
Onion	Allium Cepa	1.2	16.0	S
Parsnip	Pastinaca sativa	--	--	S*

Pea	Pisum sativum	--	--	S*
Pepper	Capsicum annuum	1.5	14.0	MS
Potato	Solanum tuberosum	1.7	12.0	MS
Pumpkin	Cucurbita Pepo Pepo	--	--	MS*
Radish	Raphanus sativus	1.2	13.0	MS
Spinach	Spinacia oleracea	2.0	7.6	MS
Squash, scallop	Cucurbita Pepo Melopepo	3.2	16.0	MS
Squash, zucchini	C. Pepo Melopepo	4.7	9.4	MT
Strawberry	Fragaria sp.	1	33	S
Sweet potato	Ipomoea Batatas	1.5	11	MS
Tomato	Lycopersicon Lycopersicum	2.5	9.9	MS
Tomato, cherry	L. esculentum var cerasiforme	1.7	9.1	MS
Turnip	Brassica Rapa	0.9	9	MS
Watermelon	Citrullus lanatus	--	--	MS*

Notes:

(a) These data serve only a guideline to relative tolerances among crops. Absolute tolerances vary, depending upon climate, soil conditions, and cultural practices.
(b) Botanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.
(c) In gypsiferous soils, plants will tolerate ECe about 2 dS/m higher than indicated.
(d) Ratings with a * are estimates.
(e) Less tolerant during seedling stage, ECe at this stage should not exceed 4 or 5 dS/m.
(f) Grain and forage yields of DeKalb XL-75 grown on an organic muck soil decreased about 26% per dS/m above a threshold of 1.9 dS/m.
(g) Paddy rice is grown under flooded conditions, thus electrical conductivity of the soil water refers to the plants while submerged. Less tolerant during seedling stage.
(h) Sensitive during germination and emergence, ECe should not exceed 3 dS/m.
(i) Data from one cultivar, "Probred".
(j) Average of serveral varieties. Suwannee and Coastal are about 20% more tolerant, and common and Greenfield are about 20% less tolerant than the average.
(k) Average for Boer, Wilman, Sand, and Weeping cultivars. Lehmann seems about 50% more tolerant.
(l) Broadleaf birdsfoot trefoil seems less tolerant than narrowleaf.
(m) Sesame cultivars, Sesaco 7 and 8, may be more tolerant than indicated by the S rating.

- Fiber, Grain, and Special Crops -

Common Name	Botanical Name (b)	Threshold dS/m (c)	Slope % per dS/m	Rating (d)
Artichoke,Jerusalem (Tabers)	Helianthus tuberosus	0.4	9.6	MS
Barley (e)	Hordeum vulgare	8.0	5.0	T
Bean	Phaseolus vulgaris	1.0	19.0	S
Broadbean	Vicia Faba	1.6	9.6	MS
Corn (f)	Zea mays	1.7	12.0	MS
Cotton	Gossypium hirsutum	7.7	5.2	T
Cowpea	Vigna unguiculata	4.9	12.0	MT
Flax	Linum usitatissimum	1.7	12.0	MS
Guar	Cyamopsis tetragonoloba	8.8	17.0	T
Kenaf	Hibiscus cannabinus	8.1	--	MT
Millet,foxtail	Setaria italica	--	--	MS
Oats	Avena sativa	--	--	MT*
Peanut	Arachis hypogaea	3.2	29.0	MS
Rice,paddy	Oryza sativa	3.0 (g)	12.0 (g)	S
Rye	Secale cereale	11.4	10.8	T
Safflower	Carthamus tinctorius	--	--	MT
Sesame (m)	Sesamum indicum	--	--	S
Sorghum	Sorghum bicolor	6.8	16.0	MT
Soybean	Glycine max	5.0	20.0	MT
Sugarbeet (h)	Beta vulgaris	7.0	5.9	T

Sugarcane	Saccharum officinarum	1.7	5.9	MS
Sunflower	Helianthus annuus	--	--	MS*
Triticale	X Triticosecale	6.1	2.5	T
Wheat	Triticum aestivum	6.0	7.1	MT
Wheat (semidwarf) (i)	T. aestivum	8.6	3.0	T
Wheat, Durum	T. turgidum	5.9	3.8	T

Notes:

(a) These data serve only a guideline to relative tolerances among crops. Absolute tolerances vary, depending upon climate, soil conditions, and cultural practices.
(b) Botanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.
(c) In gypsiferous soils, plants will tolerate ECe about 2 dS/m higher than indicated.
(d) Ratings with a * are estimates.
(e) Less tolerant during seedling stage, ECe at this stage should not exceed 4 or 5 dS/m.
(f) Grain and forage yields of DeKalb XL-75 grown on an organic muck soil decreased about 26% per dS/m above a threshold of 1.9 dS/m.
(g) Paddy rice is grown under flooded conditions, thus electrical conductivity of the soil water refers to the plants while submerged. Less tolerant during seedling stage.
(h) Sensitive during germination and emergence, ECe should not exceed 3 dS/m.
(i) Data from one cultivar, "Probred".
(j) Average of serveral varieties. Suwannee and Coastal are about 20% more tolerant, and common and Greenfield are about 20% less tolerant than the average.
(k) Average for Boer, Wilman, Sand, and Weeping cultivars. Lehmann seems about 50% more tolerant.
(l) Broadleaf birdsfoot trefoil seems less tolerant than narrowleaf.
(m) Sesame cultivars, Sesaco 7 and 8, may be more tolerant than indicated by the S rating.

- Grasses and Forage Crops -

Common Name	Botanical Name (b)	Threshold dS/m (c)	Slope % per dS/m	Rating (d)
Vetch, common	Vicia angustifolia	3.0	11.0	MS
Rescuegrass	Bromus unioloides	--	--	MT*
Rhodesgrass	Chloris Gayana	--	--	MT
Rye (forage)	Secale cereale	--	--	MS*
Ryegrass, Italian	Lolium italicum multiflorum	--	--	MT*
Ryegrass, perennial	L. perenne	5.6	7.6	MT
Saltgrass, desert	Distichlis stricta	--	--	T*
Sesbania	Sesbania exaltata	2.3	7.0	MS
Sirato	Macroptilium atropurpureum	--	--	MS
Sphaerophysa	Sphaerophysa salsula	2.2	7.0	MS
Sudangrass	Sorghum sudanense	2.8	4.3	MT
Timothy	Phleum pratense	--	--	MS*
Trefoil, big	Lotus uliginosus	2.3	19.0	MS
Wheat (forage) (i)	Triticum aestivum	4.5	2.6	MT
Wheat, Durum (forage)	T. turgidum	2.1	2.5	MT
Wheatgrass, standard crested	Agropyron sibiricum	3.5	4.0	MT
Wheatgrass, fairway crested	A. cristatum	7.5	6.9	T
Wheatgrass, intermediate	A. intermedium	--	--	MT*
Wheatgrass, slender	A. trachycaulum	--	--	MT
Wheatgrass, tall	A. elongatum	7.5	4.2	T

Wheatgrass, western	A. Smithii	--	--	MT*
Wildrye, Altai	Elymus angustus	--	--	T
Wildrye, beardless	E. triticoides	2.7	6.0	MT
Wildrye, Canadian	E. canadensis	--	--	MT*
Wildrye, Russian	E. Junceus	--	--	T
Trefoil, narrowleaf birdsfoot	L. corniculatus tenuifolium	5.0	10.0	MT
Trefoil, broadleaf birdsfoot	L. corniculatus arvenis	--	--	MT
Panicgrass, blue	Panicum antidotale	--	--	MT*
Rape	Brassica napus	--	--	MT*
Alfalfa	Medicago sativa	2.0	7.3	MS
Alkaligrass,Nuttall	Puccinellia airoides	--	--	T*
Alkali sacaton	Sporobolus airoides	--	--	T*
Barley (forage) (e)	Hordeum vulgare	6.0	7.1	MT
Bentgrass	Agrostis stolonifera palustris	--	--	MS
Bermudagrass (j)	Cynodon Dactylon	6.9	6.4	T
Bluestem, Angleton	Dichanthium aristatum	--	--	MS*
Brome,mountain	Bromus marginatus	--	--	MT*
Brome,smooth	B.inermis	--	--	MS
Buffelgrass	Cenchrus ciliaris	--	--	MS*
Burnet	Poterium Sanguisorba	--	--	MS*
Canarygrass,reed	Phalaris arundinacea	--	--	MT
Clover, alsike	Trifolium hybridum	1.5	12.0	MS
Clover, Berseem	T. alexandrinum	1.5	5.7	MS
Clover, Hubam	Melilotus alba	--	--	MT*
Clover, ladino	Trifolium repens	1.5	12.0	MS
Clover, red	T. pratense	1.5	12.0	MS
Clover, strawberry	T. fragiferum	1.5	12.0	MS
Clover, sweet	Melilotus	--	--	MT*
Clover, white Dutch	Trifolium repens	--	--	MS*
Corn (forage) (f)	Zea mays	1.8	7.4	MS

Cowpea (forage)	Vigna unguiculata	2.5	11.0	MS
Dallisgrass	Paspalum dilatatum	--	--	MS*
Fescue, tall	Festuca elatior	3.9	5.3	MT
Fescue, meadow	F. pratensis	--	--	MT*
Foxtail, meadow	Alopecurus pratensis	1.5	9.6	MS
Grama, blue	Bouteloua gracilis	--	--	MS*
Hardinggrass	Phalaris tuberosa	4.6	7.6	MT
Kallargrass	Diplachne fusca	--	--	T*
Lovegrass (k)	Eragrostis sp.	2.0	8.4	MS
Milkvetch,Cicer	Astragalus cicer	--	--	MS*
Oatgrass, tall	Arrhenatherum, Danthonia	--	--	MS*
Oats (forage)	Avena sativa	--		MS*
Orchardgrass	Dactylis glomerata	1.5	6.2	MS

Notes:

(a) These data serve only a guideline to relative tolerances among crops. Absolute tolerances vary, depending upon climate, soil conditions, and cultural practices.
(b) Botanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.
(c) In gypsiferous soils, plants will tolerate ECe about 2 dS/m higher than indicated.
(d) Ratings with a * are estimates.
(e) Less tolerant during seedling stage, ECe at this stage should not exceed 4 or 5 dS/m.
(f) Grain and forage yields of DeKalb XL-75 grown on an organic muck soil decreased about 26% per dS/m above a threshold of 1.9 dS/m.
(g) Paddy rice is grown under flooded conditions, thus electrical conductivity of the soil water refers to the plants while submerged. Less tolerant during seedling stage.
(h) Sensitive during germination and emergence, ECe should not exceed 3 dS/m.
(i) Data from one cultivar, "Probred".
(j) Average of serveral varieties. Suwannee and Coastal are about 20% more tolerant, and common and Greenfield are about 20% less tolerant than the average.
(k) Average for Boer, Wilman, Sand, and Weeping cultivars. Lehmann seems about 50% more tolerant.
(l) Broadleaf birdsfoot trefoil seems less tolerant than narrowleaf.
(m) Sesame cultivars, Sesaco 7 and 8, may be more tolerant than indicated by the S rating.

- Woody Crops -

Common Name	Botanical Name (b)	Threshold dS/m (c)	Slope % per dS/m	Rating (d)
Almond (e)	Prunus Duclis	1.5	19.0	S
Apple	Malus sylvestris	--	--	S
Apricot (e)	Prunus armeniaca	1.6	24.0	S
Avocado (e)	Persea americana	--	--	S
Blackberry	Rubus sp	1.5	22.0	S
Boysenberry	Rubus ursinus	1.5	22.0	S
Castorbean	Ricinus communis	--	--	MS*
Cherimoya	Annona Cherimola	--	--	S*
Cherry, sweet	Prunus avium	--	--	S*
Cherry, sand	P. Besseyi	--	--	S*
Currant	Ribes sp.	--	--	S*
Date palm	Phoenix dactylifera	4.0	3.6	T
Fig	Ficus carica	--	--	MT*
Gooseberry	Ribes sp.	--	--	S*
Grape (e)	Vitis sp.	1.5	9.6	MS
Grapefruit (e)	Citrus paradisi	1.8	16.0	S
Guayule	Parthenium argentatum	15.0	13.0	T
Jojoba (e)	Simmondsia chinensis	--	--	T
Jujube	Ziziphus Jujuba	--	--	MT*
Lemon (e)	Citrus limon	--	--	S
Lime	C. aurantiifolia	--	--	S*
Loquat	Eriobotrya japonica	--	--	S*

Mango	Mangifera indica	--	--	S*
Olive	Olea europaea	--	--	MT
Orange	Citrus sinensis	1.7	16.0	S
Papaya (e)	Carica papaya	--	--	MT
Passion fruit	Passiflora edulis	--	--	S*
Peach	Prunus Persica	1.7	21.0	S
Pear	Pyrus communis	--	--	S*
Persimmon	Diospyros virginiana	--	--	S*
Pineapple	Ananas comosus	--	--	MT*
Plum; Prune (e)	Prunus domestica	1.5	18.0	S
Pomegranate	Punica granatum	--	--	MT*
Pummelo	Citrus maxima	--	--	S*
Raspberry	Rubus idaeus	--	--	S
Rose apple	Syzygium jambos	--	--	S*
Sapote, white	Casimiroa edulis	--	--	S*
Tangerine	Citrus reticulata	--	--	S*

Notes:

(a) These data are applicable when rootstocks are used that do not accumulate Na+ or Cl- rapidly or when these ions do not predominate in the soil.
(b) Botanical and common names follow the convention of Hortus Third (Liberty Hyde Bailey Hortorium Staff, 1976) where possible.
(c) In gypsiferous soils, plants will tolerate ECe about 2 dS/m higher than indicated.
(d) Ratings with a * are estimates.
(e) Tolerance is based on growth rather than yield.

Salt Tolerance of Ornamental Shrubs, Trees, and Ground Cover

Maas (1990) (a)

- Very Sensitive -

Common Name	Botanical Name	Max permissible (b) ECe; dS/m
Star jasmine	Trachelospermum jasminoides	1-2
Pyrenees cotoneaster	Cotoneaster congestus	1-2
Oregon grape	Mahonia Aquifolium	1-2
Photinia	Photinia x Fraseri	1-2

- Sensitive -

Common Name	Botanical Name	Max permissible (b) ECe; dS/m
Pineapple guava	Feijoa Sellowiana	2-3
Chinese holly,cv. Burford	Ilex cornuta	2-3
Rose, cv. Grenoble	Rosa sp.	2-3
Glossy abelia	Abelia x grandiflora	2-3
Southern yew	Podocarpus macrophyllus	2-3
Tulip tree	Liriodendron Tulipifera	2-3
Algerian ivy	Hedera canariensis	3-4
Japanese pittosporum	Pittosporum Tobira	3-4
Heavenly bamboo	Nandina domestica	3-4
Chinese hibiscus	Hibiscus Rosa-sinensis	3-4
Laurustinus, cv. Robustum	Viburnum Tinusm	3-4
Strawberry tree, cv. Compact	Arbutus Unedo	3-4
Crape Myrtle	Lagerstroemia indica	3-4

- Moderately Sensitive -

Common Name	Botanical Name	Max permissible (b) ECe; dS/m
Glossy privet	Ligustrum lucidum	4-6
Yellow sage	Lantana Camara	4-6
Orchid tree	Bauhinia purpurea	4-6
Southern Magnolia	Magnolia grandiflora	4-6
Japanese boxwood	Buxus microphylla var. japonica	4-6
Xylosma	Xylosma congestum	4-6
Japanese black pine	Pinus Thunbergiana	4-6
Indian hawthorn	Raphiolepis indica	4-6
Dodonaea, cv. atropurpurea	Dodonaea viscosa	4-6
Oriental arborvitae	Platycladus orientalis	4-6
Thorny elaeagnus	Elaeagnus pungens	4-6
Spreading juniper	Juniperus chinensis	4-6
Pyracantha, cv. Graberi	Pyracantha Fortuneana	4-6
Cherry plum	Prunus cerasifera	4-6

- Moderately Tolerant -

Common Name	Botanical Name	Max permissible (b) ECe; dS/m
Weeping bottlebrush	Callistemon viminalis	6-8
Oleander	Nerium oleander	6-8
European fan palm	Chamaerops humilis	6-8
Blue dracaena	Cordyline indivisa	6-8
Rosemary	Rosmarinus officinalis	6-8
Aleppo pine	Pinus halepensis	6-8
Sweet gum	Liquidamabar Styraciflua	6-8

- Tolerant -

Common Name	Botanical Name	Max permissible (b) ECe; dS/m
Brush cherry	Syzygium paniculatum	>8 (c)
Ceniza	Leucophyllum frutescens	>8 (c)
Natal plum	Carissa grandiflora	>8 (c)
Evergreen Pear	Pyrus Kawakamii	>8 (c)
Bougainvillea	Bougainvillea spectabilis	>8 (c)
Italian stone pine	Pinus pinea	>8 (c)

- Very Tolerant -

Common Name	Botanical Name	Max permissible (b) ECe; dS/m
White iceplant	Delosperma alba	>10 (c)
Rosea iceplant	Drosanthemum hispidum	>10 (c)
Purple iceplant	Lampranthus productus	>10 (c)
Croceum iceplant	Hymenocyclus croceus	>10 (c)

Notes:

(a) Species are listed in order of increasing tolerance based on appearance as well as growth reduction.
(b) Salinities exceeding the maximum permissible ECe may cause leaf burn, loss of leaves, and/or excessive stunting.
(c) Maximum permissible ECe is unknown. No injury symptoms or growth reduction was apparent at 7 dS/m. The growth of all iceplant was increased by soil salinity of 7 dS/m.

APPENDIX C
CALCULATION OF ADJUSTED SAR

Unadjusted Sodium Adsorption Ratio Reference

I. Basic Calcium Carbonate-Carbon Dioxide Equilibrium

(a)

$$CO_2 + H_2O + CaCO_3 \Leftrightarrow Ca^{2+} + 2HCO_3^-$$

(b)

$$(CO_2)_g \Leftrightarrow (CO_2)_{aq}$$

(c)

$$(CO_2)_{aq} + H_2O \Leftrightarrow (H_2CO_3)_{aq} \quad \text{(i)}$$

$$(H_2CO_3)_{aq} \Leftrightarrow (H^+)_{aq} + (HCO_3^-)_{aq} \quad \text{(ii)}$$

$$(HCO_3-)_{aq} \Leftrightarrow (H^+)_{aq} + (CO_3^{2-})_{aq} \quad \text{(iii)}$$

$$(CO_3^{2-})_{aq} + (Ca^{2+})_{aq} \Leftrightarrow (CaCO_3)_s \quad \text{(iv)}$$

(d)

$$\text{(i) } KCO_2 = \frac{(H_2CO_3)}{P_{CO2}(H_2O)} \quad \text{(ii) } K_1 = \frac{(H^+)(HCO_3^-)}{(H_2CO_3)} \quad \text{(iii) } K_2 = \frac{(H^+)(CO_3^{2-})}{(HCO_3-)} \quad \text{(iv) } K_{sp} = (CO_3^{2-})_{aq}(Ca^{2+})_{aq}$$

TABLE 1.1a. Selected values of equilibrium constants at 25°C at ionic strength equal to zero (Suarez, Robbins and Adams).

Equilibrium Constant		Suarez		Robbins & Adams	
		- log X_1	X_1	- log X_2	X_2
$CaCO_3$ Sol. Product (ion-pair uncorrected)	K_{sp}	8.470	3.39E-09	8.352	4.45E-09
$CaCO_3$ Sol. Product (ion-pair corrected)	K_c				
Sol. Constant of H_2CO_3 (Henry's Law)	KCO_2, K_H	1.460	3.47E-02	1.471	3.38E-02
1st Dissociation Constant of H_2CO_3	K_1	6.360	4.37E-07	6.352	4.45E-07
2nd Dissociation Constant of H_2CO_3	K_2	10.330	4.68E-11	10.331	4.67E-11

TABLE 1.1b. Selected values of equilibrium constants at 25°C at ionic strength equal to zero (Stumm and Morgan).

Equilibrium Constant		Stumm & Morgan			
		- log X_3	X_3		
$CaCO_3$ Sol. Product (ion-pair uncorrected)	K_c	8.340	4.57E-09		
$CaCO_3$ Sol. Product (ion-pair corrected)	K_{sp}	8.520	3.02E-09		
Sol. Constant of H_2CO_3 (Henry's Law)	KCO_2, K_H	1.470	3.39E-02		
1st Dissociation Constant of H_2CO_3	K_1	6.352	4.45E-07		
2nd Dissociation Constant of H_2CO_3	K_2	10.329	4.69E-11		

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II. Unadjusted SAR Derivations

A. Method #1 "Old Method"

$$adj_1 R_{Na} = \left(\frac{1}{\sqrt{LF}}\right) SAR_w [1+(8.4-pH_c)]$$

Bower, *et al.* (1968b)

$$adj_1 R_{Na} = \left(\frac{y^{(1+2LF)}}{\sqrt{LF}}\right) SAR_w [1+(8.4-pH_c)]$$

Rhoades (1968a, 1968b)

Leaching Fraction (LF) terms within brackets equal to unity at near soil-surface

B. Method #2 "Revised Method or Table Method"

$$adj_2 R_{Na} = \frac{Na/LF}{\sqrt{\frac{Ca_{eq} + (Mg/LF)}{2}}}$$

Rhoades (1982); Suarez (1981)

III. Computational Procedures-pH

(a) Theoretical pH (pH_c) in equilibrium (saturated) with calcite ($CaCO_3$)

$$pH_C = (pK_2' - pK_c') + p(Ca + Mg) + pAlk$$

Bower, *et al.* (1968)

$$pH_C^{\delta} = (pK_2' - pK_c') + pCa + pAlk$$

Bower and Wilcox (1965)

$$(pK_2' - pK_c') = 2.0269 + 0.5092 \frac{4(\mu)^{0.5}}{1+2(\mu)^{0.5}} + \frac{(\mu)^{0.5}}{1+1.45(\mu)^{0.5}}$$

$$1000\ \mu = 1.3477\ C + 0.5355$$

Bower, *et al.* (1965)

$$(pK_2' - pK_c') = 2.0269 + 0.059 \left(\frac{4(\mu)^{0.5}}{1+2(\mu)^{0.5}} + \frac{(\mu)^{0.5}}{1+1.45(\mu)^{0.5}}\right)$$

$$1000\ \mu = 1.3477\ C + 0.5355$$

Suarez (1981)

μ = ionic strength
C = total salt concentration expressed as $mmol_c/l$ (meq/l)

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(b) Fixed pH (pH_i); pH required in equilibrium (saturated) with calcite ($CaCO_3$)

$$pH_i = pK_2 - pK_{sp} + p\frac{Ca}{LF} + p\frac{Alk}{LF}$$

Suarez (1981)

(c) Actual pH (pH_{eq}) in equilibrium (saturated) with calcite ($CaCO_3$)

$$pH_{eq} = 10\exp - \left(\frac{K^2 CO_2 K^2{}_1 P^2 CO_2 K_2}{(HCO_3/Ca) K_{sp}} \right)^{0.33}$$

Suarez (1981)

<u>III. Computational Procedures-Comparable Derivations of Adjusted SAR (adj_2R_{Na})</u>

A. Alternative #1 ("Table Method"):

$$adj_2R_{Na} = \frac{\frac{(Na)}{LF}}{\sqrt{Ca_{eq} + \frac{(Mg)}{LF}}}$$

(1a) $Ca_{eq} = (P_{CO_2})^{0.33} (\nabla_X) \bullet 10^3$ (1b) $\nabla_X = \left(\frac{K_1 K_{sp} K_{CO_2}}{K_2 (HCO_3/Ca)^2 \bullet \gamma_{Ca} \gamma^2{}_{HCO_3}} \right)^{0.33}$

B. Alternative #2:

$$adj_2R_{Na} = \frac{\frac{(Na)}{LF}}{\sqrt{Ca_X + \frac{(Mg)}{LF}}}$$

(1) $$Ca_X = \frac{(Ca)}{LF \bullet 10^{-(pH_i - pH_{eq})/2}}$$

(2) $$Ca_X = \frac{(Ca)}{LF \bullet 10^{-(pH_c^{\delta} - pH_{eq})/2}}$$

C. Alternative #3:

$$adj_2R_{Na} = \frac{\frac{(Na)}{LF}}{\sqrt{9.33(P_{CO_2}) + \frac{(Mg)}{LF}}}$$

( ) parenthesis represents concentrations on a molar basis expressed as millimoles per liter

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D. Adjusted calcium concentration (Ca_{eq}) expressed as meq/l substituted for calcium concentration in Equation in II(B) with Adjusted SAR "Table Method" calculated using Alternative #1-III(A) with a near soil-surface partial pressure of CO_2 equal to 0.0007 atmospheres and no precipitation of magnesium:

				Ionic Strength											
				0.0013	**0.0025**	**0.0038**	**0.0064**	**0.0089**	**0.0127**	**0.0191**	**0.0254**	**0.0381**	**0.0508**	**0.0762**	**0.1016**
				Salinity of Applied Water, dS/m											
				0.10	**0.20**	**0.30**	**0.50**	**0.70**	**1.00**	**1.50**	**2.00**	**3.00**	**4.00**	**6.00**	**8.00**
Total Alkalinity/Ca Ratio (mmole/l)	**0.10**	**Total Alkalinity/Ca Ratio (meq/l)**	**0.05**	13.20	13.61	13.92	14.40	14.79	15.26	15.91	16.43	17.28	17.97	19.07	19.94
	0.20		**0.10**	8.31	8.57	8.77	9.07	9.31	9.62	10.02	10.35	10.89	11.32	12.01	12.56
	0.30		**0.15**	6.34	6.54	6.69	6.92	7.11	7.34	7.65	7.90	8.31	8.64	9.17	9.58
	0.40		**0.20**	5.24	5.40	5.52	5.71	5.87	6.06	6.31	6.52	6.86	7.13	7.57	7.91
	0.50		**0.25**	4.51	4.65	4.76	4.92	5.06	5.22	5.44	5.62	5.91	6.15	6.52	6.82
	0.60		**0.30**	4.00	4.12	4.21	4.36	4.48	4.62	4.82	4.98	5.24	5.44	5.77	6.04
	0.70		**0.35**	3.61	3.72	3.80	3.94	4.04	4.17	4.35	4.49	4.72	4.91	5.21	5.45
	0.80		**0.40**	3.30	3.40	3.48	3.60	3.70	3.82	3.98	4.11	4.32	4.49	4.77	4.98
	0.90		**0.45**	3.05	3.14	3.22	3.33	3.42	3.53	3.68	3.80	4.00	4.15	4.41	4.61
	1.00		**0.50**	2.84	2.93	3.00	3.10	3.19	3.29	3.43	3.54	3.72	3.87	4.11	4.30
	1.50		**0.75**	2.17	2.24	2.29	2.37	2.43	2.51	2.62	2.70	2.84	2.95	3.14	3.28
	2.00		**1.00**	1.79	1.85	1.89	1.96	2.01	2.09	2.16	2.23	2.35	2.44	2.59	2.71
	2.50		**1.25**	1.54	1.59	1.63	1.68	1.73	1.78	1.86	1.92	2.02	2.10	2.23	2.33
	3.00		**1.50**	1.37	1.41	1.44	1.49	1.53	1.58	1.65	1.70	1.79	1.86	1.97	2.07
	3.50		**1.75**	1.23	1.27	1.30	1.35	1.38	1.43	1.49	1.54	1.62	1.68	1.78	1.86
	4.00		**2.00**	1.13	1.16	1.19	1.23	1.26	1.31	1.36	1.40	1.48	1.54	1.63	1.70
	4.50		**2.25**	1.04	1.08	1.10	1.14	1.17	1.21	1.26	1.30	1.37	1.42	1.52	1.58
	5.00		**2.50**	0.97	1.00	1.02	1.06	1.09	1.12	1.17	1.21	1.27	1.32	1.40	1.47
	6.00		**3.00**	0.85	0.89	0.91	0.94	0.96	1.00	1.04	1.07	1.13	1.17	1.24	1.30
	7.00		**3.50**	0.78	0.80	0.82	0.85	0.87	0.90	0.94	0.97	1.02	1.06	1.12	1.17
	8.00		**4.00**	0.71	0.73	0.75	0.78	0.80	0.82	0.86	0.88	0.93	0.97	1.03	1.07
	9.00		**4.50**	0.66	0.68	0.69	0.72	0.74	0.76	0.79	0.82	0.86	0.90	0.95	0.99
	10.0		**5.00**	0.61	0.63	0.65	0.67	0.69	0.71	0.74	0.76	0.80	0.83	0.88	0.93
	14.0		**7.00**	0.49	0.50	0.52	0.53	0.55	0.57	0.59	0.61	0.64	0.67	0.71	0.74
	20.0		**10.00**	0.39	0.40	0.41	0.42	0.43	0.45	0.47	0.48	0.51	0.53	0.56	0.58
	40.0		**20.00**	0.24	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.32	0.33	0.35	0.37
	60.0		**30.00**	0.18	0.19	0.20	0.20	0.21	0.21	0.22	0.23	0.24	0.25	0.27	0.28

Adapted from: Ayers and Wescot (1985); Hanson, et al. (2006)

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