Lower Colorado River Multi-Species Conservation Program

Balancing Resource Use and Conservation

REVIEW OF SALINITY AND SODICITY, MONITORING, AND REMEDIATION FOR RIPARIAN RESTORATION AREAS

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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Lower Colorado River
Multi-Species Conservation Program

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EXECUTIVE SUMMARY

Nearly 6,000 acres of riparian restoration are proposed under the Lower Colorado River (LCR) Multi-species Conservation Program (MSCP). Fremont cottonwood (*Populus fremontii*) and willow species (*Salix* spp.) are obligate phreatophytes with low salinity tolerance. Existing data shows soil and groundwater salinity in excess of reported phreatophyte tolerance at some MSCP restoration areas. Remediation of these saline soils and groundwater might be necessary for successful re-vegetation with these species.

Soil and groundwater salinity conditions on the LCR are driven by a combination of altered hydrologic regimes, irrigation practices, and the groundwater depth. At MSCP restoration areas, the primary causes of potential salinity and/or sodicity are likely to be shallow groundwater, poor drainage of irrigation water, inadequate groundwater flow, and/or inadequate flushing of salts.

Saline soil remediation techniques include leaching and water table lowering through pumping or drainage. In the MSCP restoration areas, care must be used in leaching salts from the soil because the salts do not disappear from the soil; they are either relocated deeper in the soil or deposited into the aquifer. Good quality groundwater is critical to support native phreatophyte (i.e. riparian) vegetation.

Unconfined saline aquifer remediation options include creation of a freshwater mound with flooding (irrigation), freshwater injection, or by induction of river recharge. These techniques have been used successfully in conjunction with water table lowering. Groundwater remediation modeling and field trials are needed to determine the feasibility and long-term success of these options at MSCP sites.

In general, current salinity monitoring and management practices at MSCP sites include soil sampling prior to revegetation and flooding and phytoremediation if soil salinity is above plant tolerance. Groundwater salinity has generally not been monitored at MSCP restoration sites. Development of a standard protocol for site characterization including sampling and monitoring soil and groundwater salinity, soil type, and groundwater depth and modeling long-term salinity trends could improve efficiency and success of restoration projects at MSCP restoration sites.

Irrigation management could maintain or reduce soil salinity through leaching, particularly if developed in conjunction with a water budget analysis for the active MSCP restoration sites.

If active salinity remediation is required, remediation will be site-specific and dependent on salinity levels, soil physical and hydraulic characteristics, groundwater depth and gradients, and aquifer hydraulic characteristics and may include leaching, drainage, flooding, groundwater freshening, or some combination of the above.

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ACRONYMS AND ABBREVIATIONS

AEM	airborne electromagnetic
CED	cation exchange capacity
EC	electrical conductivity
EM	electromagnetic induction
ESP	exchangeable sodium percentage
ET	evapotranspiration
ET_0	reference evapotranspiration
GIS	geographic information systems
GPS	global positioning systems
LCR	lower Colorado River
LF	leaching fraction
LR	leaching requirement
MSCP	Multi-species Conservation Program
NWR	National Wildlife Refuge
RS	remote sensing
SAR	sodium adsorption rate
SWFL	Southwestern willow flycatcher
T	transpiration
TDR	time-domain reflectometry
USDA	US Department of Agriculture

1.0 INTRODUCTION

At least 7200 acres of riparian and mesquite habitat restoration and 870 acres of marsh and backwater habitat creation are proposed under the Lower Colorado River (LCR) Multi-species Conservation Program (MSCP) (USBR 2010). Restoration and long-term management of these riparian areas will rely on irrigation water from the Colorado River. Because Fremont cottonwood (*Populus fremontii*) and willow species (*Salix* spp.) are obligate phreatophytes with low salinity tolerance, successful restoration and long-term vegetative success will require both shallow and low salinity groundwater conditions. Moreover, recent research suggests that optimum Southwestern willow flycatcher (*Empidonax traillii extimus*, SWFL) habitat includes some amount of standing water or saturated soils within or adjacent to riparian vegetation during at least a portion of the year (Soggee & Marshall 2000; Hinojosa-Huerta 2006; Ahlers & Moore 2009; Soggee & Sferra 2010;). However, irrigation in arid regions with shallow water tables can result in salt accumulation (salinization) of both soils and groundwater without rigorous irrigation management. There is also evidence of existing soil and groundwater salinity in excess of phreatophyte tolerance at several MSCP restoration areas (Raulston 2003; USFWS 2007).

Saline and sodic soils are the two types of salt-affected soils, which differ not only in their chemical characteristics, but also in their physical properties and biological effects, and consequently, successful reclamation approaches. In arid and semiarid regions, soil salinity, groundwater salinity and soil sodicity are often inherent problems due to climatic conditions and can be exacerbated by changing land use, using irrigation, and altering hydrological conditions. Salt is naturally found in soil and water; soil salinization is the concentration of salts in the surface or near-surface zones of soils (Thomas and Middleton 1993). Secondary salinization is the term used to distinguish human-induced salinization from naturally salt-affected soils.

Soil salinization typically occurs in one of the two following scenarios:

1) Where shallow groundwater is raised by capillary action to the near-surface soil, it evaporates or is transpired while the salts are left behind to accumulate in the soil. Natural

salinization may occur in dry lakes or playas, where natural groundwater flow discharges to the atmosphere via the lakes/playas;

2) In irrigated areas, the absence of adequate salt leaching or drainage allows evapo-concentration to increase soil salinity over time.

Salts can also accumulate in areas with shallow water tables by leaching from the surface soils into the underlying aquifer. This process can be exacerbated with irrigation or if groundwater flow into and away from the area is limited.

This review identifies the causes, problems, monitoring methods, and potential remediation techniques for salt-affected soils and groundwater that are applicable to the MSCP restoration areas. Soil salinity and sodicity are discussed in Section 2.0. The effects of salinity and sodicity on riparian vegetation are discussed in Section 3.0. Techniques for measuring and mapping soil salinity are described in Section 4.0. Causes and contributing factors to soil and groundwater salinity and sodicity are discussed in Section 5.0. Techniques for reclaiming saline and sodic soil and saline groundwater and irrigation management are discussed in Sections 6.0 and 7.0, respectively. Finally, conclusions and recommendations are given in Section 8.0.

2.0 DEFINTIONS OF SOIL SALINITY AND SODICITY

2.1 Salinity Definition

Salinity describes the dissolved salt content of water; soil salinity describes the soluble salt content of soil. Saline soils contain large concentrations of soluble salts, usually the chlorides (Cl^-) and sulfates (SO_4^{2-}) of sodium (Na^+), calcium (Ca^{2+}), potassium (K^+), and magnesium (Mg^{2+}) salts. Only rarely are nitrates present in appreciable quantities (Abrol et al. 1988). Water salinity is measured as the total dissolved solids (TDS) expressed in milligrams of solid per liter of water (mg/L). Pure water is a poor conductor of electricity, but the electrical conductivity (EC) of water increases as dissolved salts increase. Therefore, the EC, or specific conductance of a solution provides an indirect measurement of the salt content. Different dissolved salts have varying abilities to conduct electricity due to the differences in ionic charge, size, weight, and mobility, therefore, EC can vary in relationship to the TDS. Although it is possible to calculate the conductivity for any electrolyte at any temperature and concentration, the exact contribution of individual ions is difficult to determine. In a review of natural waters, Hem (1986) concluded that the majority showed an approximate ratio of EC (in μmhos/cm) to TDS (in mg/l) of 0.55 to 0.75, with the lower values generally being associated with dissolved sodium chloride and higher values generally being associated with dissolved sulfate. For general estimation purposes, each 1000 μmhos/cm EC can be assumed to be equivalent to 650 mg/l TDS (Hem, 1986).

Soil salinity is typically measured via a water extract equivalent to a 1:1 solution to volume ratio or a soil saturated paste extract, which is generally estimated as twice the 1:1 extract concentration. It is typically expressed in EC units of μmhos (or microsiemens, μS) per centimeter or decisiemens per meter (dS/m), equivalent to μS/cm divided by 1000. Saline soils are generally defined as having an EC of the soil paste extract (EC_e) greater than 4 dS/m (Brady and Weil 2002). When the EC_e is between 4 to 8 dS/m, the soil is considered moderately saline; between 8 and 16 dS/m, it is saline; and when it is greater than 16 dS/m, it is defined as severely saline.

2.2 Sodicity Definition

Sodic soils are formed by the adsorption of sodium ions to the negatively charged sites on soil particles, typically soil clays, from soil solutions containing free salts (Rengasamy 2006). Sodic

soils contain disproportionately high concentrations of sodium salts and lack appreciable quantities of neutral (neither acidic nor basic) soluble salts such as $CaCl_2$, KCl (Abrol et al. 1988). Therefore, sodic soils are typically rich in clay and contain high amounts of Na^+ and low amounts of Ca^{2+} and Mg^{2+}. Sodic soils are defined as having a sodium adsorption rate (SAR) value greater than or equal to 13 or an Exchangeable Sodium Percentage (ESP) greater than 15%. SAR is a ratio of sodium ions to calcium and magnesium ions. It is expressed as follows:

$$SAR = \frac{[NA^+]}{\sqrt{\frac{1}{2}([Ca^{2+}]+[Mg^{2+}])}} \qquad \textit{Equation 1}$$

where the cation concentrations are in millimoles of charge per liter ($mmol_c/L$). ESP is the extent to which the adsorption complex of a soil is occupied by sodium. It is expressed as follows:

$$ESP = \frac{echangeabl\,e_sodium}{CEC} \qquad \textit{Equation 2}$$

where the exchangeable sodium is expressed in centimoles of charge per kilogram of soil ($cmol_c/kg$), and CEC is the cation exchange capacity expressed in centimoles of charge per kilogram of soil ($cmol_c/kg$). SAR is more easily measured and takes into consideration that the adverse effect of sodium is moderated by the presence of calcium and magnesium ions (Brady and Weil 2002).

3.0 SALINITY AND SODICITY EFFECTS ON SOIL AND RIPARIAN VEGETATION

3.1 Salinity Effects

3.1.1 Soil Salinity

Saline soils are problematic because they decrease plant productivity and can inhibit the growth of salt-intolerant vegetation. Slightly saline soils typically have favorable soil structure, because the presence of salts keeps clay particles in a flocculated state; air and water permeability and soil stability are similar to and sometimes greater than, non-saline soils (Abrol et al. 1988). However, excessive salt concentrations can reduce pore space and increase aggregation, which can lead to soil sealing.

Saline soils negatively affect plant growth at the cellular level primarily through increasing the osmotic pressure of the soil solution. Osmotic pressure prevents the inward flow of water across a semipermeable membrane (e.g. plant roots) dehydrating the plant (Voet et al. 2001). Increasing osmotic pressure (osmotic stress) inhibits growth by reducing the soil water availability and increasing the energy required to extract moisture from the saline soil, which would otherwise contribute to growth (Rhoades 1991). Additionally, excess absorption of salt ions, e.g. Na^+, Cl^-, B^-, by plants can be phytotoxic and/or may retard the absorption of other essential nutrients (Abrol et al. 1988).

The precise mechanisms by which salinity inhibits growth and germination are complex and controversial. A reduction in seed germination under saline conditions may be caused by only osmotic stress or by both salt toxicity and osmotic stress and varies for different species (Prisco & O'Learv 1970; Macke & Ungar 1971; Redmann 1974; Romo & Haferkamp 1987; Myers & Couper 1989). In addition, ion-specific effects result in different degrees of toxicity. For example, Redmann (1974) found that Na_2SO_4 and $MgCl_2$ were more toxic than iso-osmotic solutions of NaCl. No research was found on the causes of reduced germination and growth for the priority species for the MSCP under saline conditions. Germination and growth of two other species of *Atriplex* in different concentrations of NaCl were found to be reduced due to both osmotic stress and an ion-specific effect (Katembe et al. 1998). The cause(s) of salinity effects

are important because they can guide the salinity remediation and management strategies used at a site (See Section 6.1).

3.1.2 Riparian Vegetation Salinity Tolerance

Salinity tolerance of crop plants has been widely studied, but much less is known about the salinity responses of native species (Shafroth et al. 2008). The USDA National Resources Conservation Service characterizes plant salinity tolerance as "None" (0-2 dS/m), "Low" (2.1-4.0 dS/m), "Medium" (4.1-8.0 dS/m), and "High" (greater than 8.0 dS/m) when growth is reduced by no more than 10% when grown in soil of the indicated soil salinity range. Plants are also characterized into the following categories (Goodin et al. 1999; See Figure 1):

- Salt sensitive: Plant growth decreases as soil or water salinity increases;
- Salt tolerant: Plant growth is unaffected by salinity up to a plant-specific threshold, and then decreases as salinity increases; and
- Halophytic: Plant growth increases as salinity increases until a salinity threshold, beyond which plant growth decreases.

Salinity can differentially affect germination, growth, and survival. Beauchamp et al. (2009) studied the salinity tolerance of numerous native riparian plants in the semi-arid western United States and found that survival and growth was correlated with salinity for many species. Conversely, germination was not well correlated with salinity, growth, and survival. Under saline conditions, some species experienced reduced growth and lower survival rates; however, growth and survival of other species was not affected by saline conditions although low germination rates were observed. This suggests that different factors may be responsible for salinity tolerance during the germination and seedling stages (Norlyn 1980).

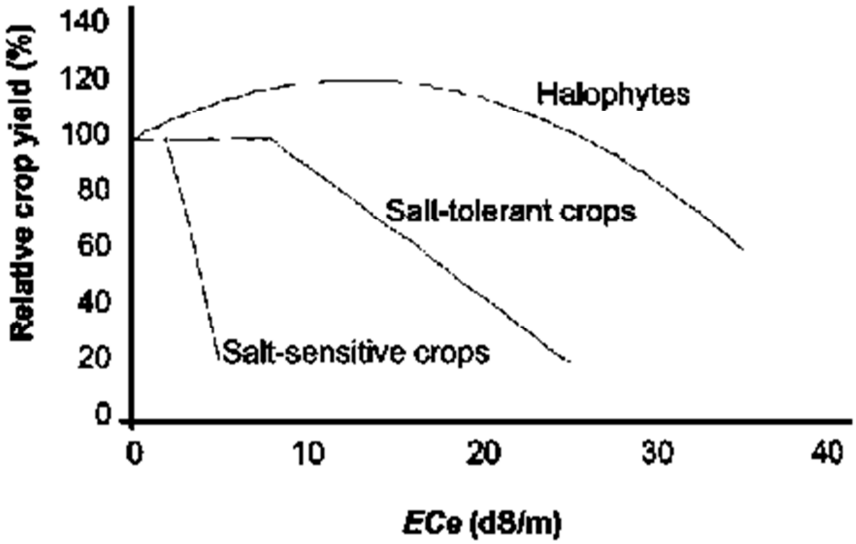

Figure 1. Relative plant growth response to varying levels of salinity (EC_e = paste saturation EC). (From Goodin et al. 1999)

One of the challenges in determining salinity tolerance is that both inter- and intra-species variation occurs (Glenn et al. 1996; Hester et al. 1998). Seed from plants at high-salinity sites may exhibit superior establishment and performance under saline conditions than seed from lower-salinity origins or of unknown origin from commercial suppliers (Glenn et al. 1996; Sanderson and McArthur 2004; Beauchamp 2009). Table 1 summarizes published literature on the salinity tolerance of priority species for the MSCP. These results were observed primarily in controlled growth experiments (e.g. greenhouse, petri dish germination), except for the planting requirements, which were from Bosque del Apache NWR (USFWS 2007). Cottonwood and willow trees have been observed in MSCP areas in soils with higher salinities than published plant salinity tolerances (GSA, 2008b). Where soil salinity is elevated above riparian tree tolerance, trees might survive due to the availability of better quality groundwater. Since groundwater salinity is generally not monitored, more information needs to be collected to validate this theory. Table 1 only serves as a general guide to predict plant performance in the field because intra-specific variations in salinity tolerance, the heterogeneity of soil profiles, and differences between conditions in controlled growth experiments and the field preclude reliable generalizations.

The upper level of salinity tolerance (i.e. death of mature trees) for Fremont cottonwood (*Populus fremontii*) and Goodding's willow (*Salix gooddingii*), is estimated to be 8 dS/m (5,000 mg/l TDS) in the soil solution or groundwater based on field and controlled growth experiment data (Glenn and Nagler 2005; Zamora-Arroyo et al. 2001; Busch and Smith 1995). In prior studies, growth of cottonwood and willow was reduced 7-9% per gram per liter increase in sodium chloride until death occurred (Glenn et al. 1998). Germination salinity tolerance for riparian tree species is reported within the same range, between 3 and 12 dS/m; however may be as low as 5 dS/m for cottonwood and willow (GSA 2007). Salinity tolerance for coyote willow (*S. exigua*) is also estimated to be around 5 dS/m (GSA 2007). The upper level of salinity tolerance for the mesquite bosque tree species, honey mesquite (*Prosopis glandulosa*), screwbean mesquite (*P. pubescens*), and desert willow (*Chilopsis linearis*), is unknown, but greater than 15 dS/m for the mesquite and 8 dS/m for desert willow (Glenn 1998; Beauchamp 2009). Germination of screwbean mesquite seeds has been observed in soils with salinity greater than 90 dS/m at Beal Lake restoration site after it was cleared of vegetation (Ashlee Rudolph, LCR MSCP, personal communication). Salinity tolerance is above 8 dS/m for all of the MSCP shrub species (mule's fat (*Baccharis salicifolia*), Emory's baccharis (*B. emoryi*), quailbush (*Atriplex lentiformis*), fourwing saltbush (*A. canescens*), cattle saltbush (*A. polycarpa*), and wolfberry (*Lycium* spp.)) based on available data (refer to Table 1).

Table 1. Summary of sensitivity ratings of priority species for the Multi-Species Conservation Program (MSCP).

Common Name	Scientific Name	USDA Classification	Salinity Tolerance Acceptable Upper Limit (unless otherwise noted dS/m)	Germination/ Planting Salinity Tolerance (dS/m)	Reference(s)
Riparian Tree Species					
Fremont cottonwood	*Populus fremontii*	POFR	Low-Medium 3-12 dS/m; Growth reduced by 7-9% per g/L NaCl	3-8 dS/m: germination <1.0-2.5: planting in sandy loam soil	Jackson (1990) Shafroth (1995) Siegel (1990) Glenn (1998) Glenn (2005) GSA (2007) USFWS (2007)
Goodding's willow	*Salix gooddingii*	SAGO	Low-Medium 3-12 dS/m; Growth reduced by 7-9% per g/L NaCl	3 dS/m	Jackson (1990) Glenn (1998) Glenn (2005) GSA (2007)
coyote willow	*S. exigua*	SAEX	5 dS/m	5 dS/m	GSA (2007)
Mesquite Bosque Tree Species					
honey mesquite	*Prosopis glandulosa*	PRGL	High 15 dS/m	10.8+ dS/m	Glenn (2005) Beauchamp (2009)
screwbean mesquite	*P. pubescens*	PRPU	High Growth reduced between 15 and 90 dS/m	90 dS/m: germination 3.0-7.99: planting in clayey soil	Glenn (1998) Glenn (2005) Beauchamp (2009) USFWS (2007)
desert willow	*Chilopsis linearis*	CHLI	Medium Growth reduced at 10.8 dS/m	Germination decreased at 6.7 and 10.8 dS/m	Beauchamp (2009)
Shrub Species					
mule's fat	*Baccharis salicifolia*.	BASAL	High 12 dS/m; Growth reduced by 7-9% per g/L NaCl	Germination decreased at 6.7 and 10.8 dS/m	Glenn (1998) Beauchamp (2009)
Emory's baccharis	*B. emoryi*	BAEM	High	NR	Nevada Division of Forestry (2010)
desertbroom	*B. sarothroides*	BASAR	NR	NR	
quailbush	*Atriplex lentiformis*	ATLE	High; Halophyte Growth reduced between 65-100 dS/m	100+ dS/m NaCl	Jackson (1990)
fourwing saltbush	*A. canescens*	ATCA	High; Halophyte Growth reduced at 10.8 dS/m; Growth decreased by 50% when EC ranged from 50-110 dS/m for different accessions	8.0-13.99: planting	Beauchamp (2009) Glenn (1996) USFWS (2004)
Cattle saltbush	*A. polycarpa*	ATPO	High; Halophyte Unaffected at 10.8 dS/m	NR	Beauchamp (2009)
Wolfberry	*Lycium* spp.		High; some halophytic species Growth reduced above 8 dS/m	Unaffected germination at 10.8 dS/m; 3.0-7.99: planting	Beauchamp (2009) USFWS (2007)
Desert globemallow	*Sphaeralcea ambigua*	SPAM	NR	NR	

Note: NR: none reported; TDS and ppm converted to dS/m using a ratio of EC to TDS of 0.55 for NaCl and 0.65 for all other salt solutions.

3.2 Sodicity Effects

3.2.1 Soil Sodicity

Soil sodicity often leads to soil structural degradation; drainage, runoff, and erosion problems; and indirectly, to poor plant growth and productivity (Shainberg and Letey 1984). Sodic (high sodium) soils are characterized as unstable, exhibiting poor physical and chemical properties that impede water availability and water infiltration. Sodicity can cause soil dispersal because of the relatively large size, single electrical charge, and hydration status of the sodium ion. Soils with high clay contents are especially susceptible to soil dispersion. Sodium-induced dispersion can cause loss of soil structure, plug soil pores, and create surface crusting, which subsequently reduces hydraulic conductivity and water infiltration, and increases water runoff (Agassi et al. 1981; Brady and Weil 2002).

3.2.2 Effects of Sodicity on Vegetation

Sodic soils negatively affect vegetation due to:

- toxic effects of sodium and typically-associated high pH values (Abrol et al. 1988);
- plant nutrient deficiencies due to imbalances in soil cations (Qadir et al. 2001);
- negative impacts on germination, growth, and survival from changes in soil structure (Abrol et al. 1998), and;
- anaerobic conditions created by waterlogged soils.

Sodic soil conditions make it difficult or impossible for plants to germinate, roots to penetrate the soil; seedlings to emerge; and plants to obtain adequate water and nutrients (Qadir et al. 2001; Hanson et al. 1999; Shainberg and Letey 1984; Ayers and Westcot 1994).

Decreased drainage from sodium-induced soil dispersal can also increase sodicity in the root zone via increased salt concentration as evapotranspiration (ET) occurs. Sodium-induced dispersal can make it difficult for plant roots to get the water and nutrients they need to survive because sodic soils can become and remain waterlogged, resulting in anaerobic conditions. If anaerobic conditions persist for more than a few days, roots fail to obtain sufficient oxygen,

which reduces plant growth and can cause plant injury and eventually death. Figure 2 shows soils classification based on EC, SAR, and pH and plant effects.

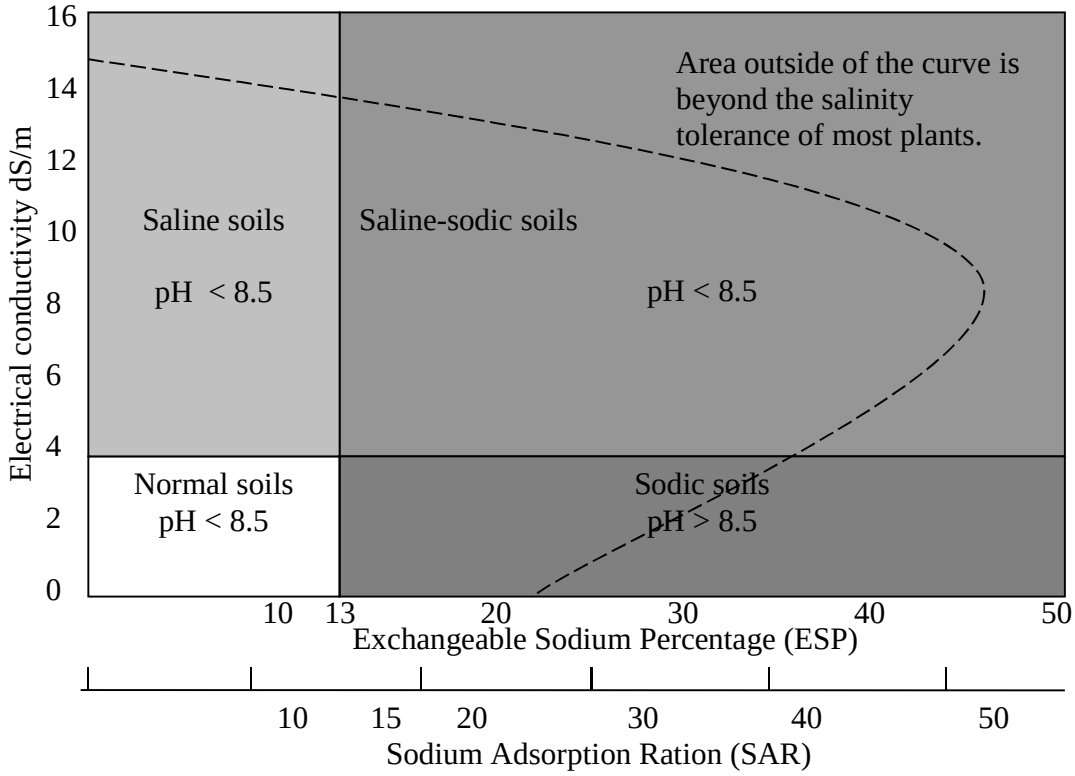

Figure 2. Diagram illustrating the classification of normal, saline, saline-sodic, and sodic soils in relation to soil pH, electrical conductivity, sodium adsorption ratio, and exchangeable sodium percentage and the effect on plants. (From Brady and Weil 2002)

4.0 MEASURING AND MAPPING SOIL AND GROUNDWATER SALINITY

Characterization of soil salinity and sodicity is necessary to manage salt-affected soils. No single approach for mapping and assessing salinity risk exists; there are numerous satellite, airborne and ground mapping techniques available. Spies and Woodgate (2005) provide detailed descriptions of various mapping techniques. Traditionally, soil salinity is assessed by collecting soil samples and analyzing them in the laboratory. Salinity can also be measured indirectly with electromagnetic induction (EM) and time-domain reflectometry (TDR). Satellite and airborne remote sensing (RS) techniques can map existing surface salinity and track changes over time. However, any of these methods should be combined with at least some soil sampling and laboratory testing of EC_e to correct for confounding influences of soil moisture and texture.

4.1 Soil Salinity Monitoring

4.1.1 Soil Sampling and Laboratory Testing

The most common method of determining soil salinity is through laboratory analysis of grab samples for "saturated paste EC" (e.g. Rhoades 1986). Under this method, soil samples are brought to saturation by slowly adding de-ionized water. Once saturated, soil water is extracted using a vacuum, and the EC of extract water (soil-water extract EC or EC_e) is determined using laboratory instruments. Alternatively, soil samples can be dried in an oven, and then combined with an equal weight of de-ionized water. The decant water is then tested for EC to determine "1:1 paste EC." Typically, laboratories determine 1:1 EC and then double the value to estimate saturated paste EC, which is the standard value presented (GSA 2008b).

4.1.2 Electromagnetic Induction (EM)

Rapid, continuous field measurement of bulk soil conductivity, which is related to soil salinity and soil physical properties, is possible with electromagnetic induction (EM). Electrode sensors are inserted into the soil, placed on the soil surface, or mounted on a vehicle (Figure 3) to generate continuous apparent EC (EC_a) measurements (Fitzpatrick et al. 2003). Airborne electromagnetic (AEM) methods have been used extensively in Australia to understand salinity and hydrology at depth (e.g. Creswell et al. 2007; Lawrie 2008). A pulse of EM radiation is emitted from a transmitter, which interacts with conductive material in the ground. A modified,

secondary signal 'bounces' back to a receiver that collects data in either time or frequency domains. The data can then be modeled to define the three-dimensional conductivity structure of the survey area.

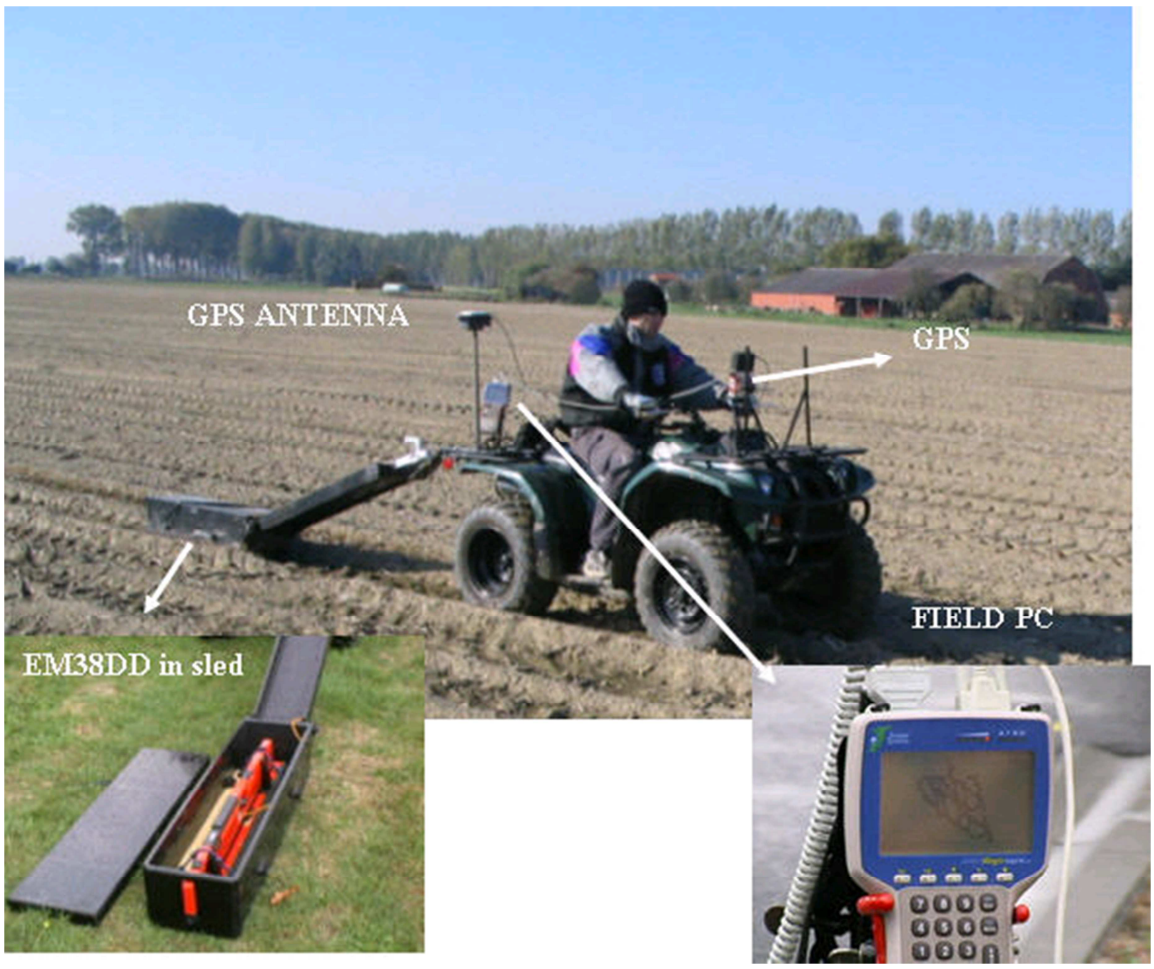

Figure 3. EM38 pulled across a field and used with GPS to map salinity across a field.

EM can be used to describe the relative composition of salts, water, and soil in the profile; to identify high and low salinity groundwater and zones of high and low salt load; and to indicate subsurface soil variability, specifically the ratio of clay, silt, and sand. Advantages of EM include the ability to measure EC non-invasively to considerable depths, instantaneous readings, and the ease of use (Nogués et al. 2006; Doolittle et al. 2001; McKenzie 2000). The EM-38 is the most widely used soil salinity instrument and measures apparent conductivity of the ground to a depth of up to 1.5 m (Chesworth 2008). Airborne electromagnetic induction (AEM) measures apparent conductivity of the ground to depths of 200 m or more (Paine & Collins

2003). Disadvantages are that readings are influenced by the same factors: bulk soil conductivity, soil temperature, moisture, and texture (Cassel et al. 2009) such that soil EC may not be easily quantified by EM in highly heterogeneous soils. Consequently, soil sampling is necessary to calibrate salinity estimates for these factors. Previous work indicates that for sites on the LCR, calibration of EM readings was quite poor (GSA 2008b). With AEM, vertical resolution and accuracy are strongly dependent on the modeling techniques used to convert the raw data into depth images. This is highly constrained by the interpretation of site-specific data and the conceptual models of the landscape and nature of the subsurface; therefore interpreted data must be treated with extreme care (Creswell and Gibson 2004).

4.1.3 In-situ Instrumentation

In-situ measurements of soil salinity can be made using time-domain reflectometry (TDR) probes or an array of recently-developed electronic sensors. TDR rapidly assesses salinity (Cassel et al. 2009) and can be installed and connected to a data logger to measure salinity changes in real-time (Schroder et al. 2008). However, the stationary nature of the device limits its use in mapping large areas. Alternatively, handheld TDR or other salinity monitoring instruments can be used to make point measurements during field campaigns. Similar to EM methods, TDR readings are also affected by soil moisture; however, this method can potentially be used to make simultaneous point measurements of both soil salinity and soil moisture.

Other instruments for measuring soil EC include capacitance type instruments. Like TDRs, these devices can be attached to a data logger and used to measure real-time soil salinity and changes over time, and also estimate soil water content and temperature. Handheld logging units are also either commercially available or easily constructed. These sensors are generally limited to a soil EC of less than five to 25 dS/m. At higher ends of the salinity range, the sensors lose the ability to estimate soil water content. However, the range of acceptable EC operating conditions is generally within the levels appropriate for riparian vegetation because they are lower than threshold values presented in Table 1.

4.1.4 Remote Sensing (RS)

Remote sensing (RS) has been used to map salt-affected areas (e.g. Abdelfattah et al. 2009; Khan et al. 2001; Peng 1998; Metternicht and Zinck; Verma et al. 1994; Rao et al. 1991). Most studies

that use RS, map severely saline areas or differentiate between saline and non-saline soils; it is difficult to differentiate between low-saline and non-saline soils. No unique remote sensing signature currently exists for detecting sodium chloride in the soil (personal communication, Ed Glenn, professor, University of Arizona Department of Soil, Water, and Environmental Science). Salinity can be mapped directly from broadband spectral images if salt crusts are present and indirectly by the amount of crop damage or the presence of halophytes. Sulfate and carbonate salts or other cations can be mapped with hyperspectral imagery because they have features in narrow wavelength bands (personal communication, Susan Ustin, professor, University of California at Davis Department of Environmental and Resource Sciences); in general, such detailed spectral features are lost when the bandwidths are wide, as with multispectral remote sensing data (Weng et al. 2008). Advantages of RS are the ability to map soil salinity of large areas with minimal field data and track changes over time. Disadvantages are that RS only maps surface salinity and generally, is best used to differentiate saline and non-saline soils. Due to the current constraints in RS mapping, the low salinity tolerance of riparian vegetation, and the dependence of some native riparian vegetation on groundwater, RS may not be practical for mapping active MSCP restoration areas. However, this method may be useful for identification of areas that are not favorable for riparian revegetation. Areas that are identified as potentially having suitably low salinity should be further analyzed via laboratory analysis of soil samples.

4.2 Groundwater Salinity Monitoring

Because most target MSCP plant species are obligate or facultative phreatophytes, high groundwater salinity can limit the success of revegetation efforts even if soil salinity appears favorable. Groundwater salinity is monitored by sampling groundwater from monitoring wells or piezometers. Various well installation methods can be used depending on the soil type and depth to groundwater. In areas with shallow groundwater and free of rocky material in the near-surface, piezometers can generally be driven or placed within hand-augered holes, as has been accomplished at Beal Lake Restoration Site and Cibola National Wildlife Refuge (GSA 2008b; GSA 2011a). Where the depth to groundwater is greater than 10 feet, mechanical drilling is advisable. Hollow-stem auger drilling was used successfully at Palo Verde Ecological Reserve, where the depth to groundwater is between 12 and 20 feet (GSA 2011a). Once the wells are installed, groundwater can be manually sampled using bailers or monitored electronically using a

salinity probe. Bailing and sampling generally provides a more accurate estimate of aquifer salinity, because bailing purges the well to ensure groundwater is sampled from the aquifer (and not just the well), and a full suite of water quality parameters can be determined.

The location of the well screened interval (the portion of the well open to the aquifer), is important. Tree roots will generally access shallow water; therefore, determining salinity at the top of the aquifer (the phreatic surface) is critical. Additionally, monitoring of this groundwater might allow for documentation of freshwater lenses created by irrigation and recharge. Consequently, monitoring wells used to determine water quality for riparian habitat restoration should be screened to depths no greater than 2 to 3 meters below the phreatic surface. Conversely, to determine the water quality of the underlying aquifer, it is useful for the screened interval to be entirely beneath the phreatic surface. Multiple completion wells, where two or more screened piezometers are placed within one borehole, can allow for observation of both near-surface and deeper aquifer water quality to allow direct comparison of multiple depths at a given location.

5.0 CONTROLLING FACTORS FOR SALINITY AND SODICITY IN THE MSCP RESTORATION AREAS

Soil and groundwater salinity conditions on the LCR are driven by a combination of altered hydrologic regimes, irrigation practices, and the groundwater depth. At MSCP restoration areas, the primary causes of potential salinity and/or sodicity are likely to be poor drainage of irrigation water, inadequate groundwater flow and/or inadequate flushing of salts.

5.1 Altered hydrology

Dams and river diversions can result in salinization due to changes in the historic hydrological patterns. Because of generally low natural recharge rates, semi-arid floodplains tend to accumulate salts and require periodic flushing to prevent the development of saline soil and groundwater (Jolly 1996). River regulation impairs the natural flushing cycle of floodplains by decreasing the frequency and duration of floods (Poff et al. 1997), which can result in floodplain salinization (Jolly 1996).

The historic Lower Colorado River (LCR) hydrologic regime consisted of annual flooding of the floodplain alluvium during the spring and early summer, with a concomitant increase in groundwater elevations and subsequent release of groundwater back into the LCR over the fall and winter. This regime supported shallow groundwater conditions in the floodplain alluvium and annual flushing of evapo-concentrated salts resulting from shallow water table evaporation and groundwater use by phreatophyte vegetation. The introduction of dams and irrigated agriculture in the 20th century has reduced the flushing of salts from the floodplain and there is evidence of increased groundwater salinity throughout much of the LCR (Busch and Smith 2005; Nagler 2005). The seasonal flow pattern of the Colorado River currently is that flow is lowest in the winter, steadily increases through the spring, peaks in the summer, and then steadily decreases until the winter (USGS 2010). Proximity to the mainstem is likely one of the main factors determining if river flow or ET demand is the dominant factor for groundwater elevation changes, i.e. groundwater elevations for sites closer to the river will be more readily affected by changes in river flow.

As a result of this altered hydrologic regime, salinity effects vary throughout the LCR. Salt crusts are present at highly salt-affected areas at Cibola National Wildlife Refuge. In addition,

salt stress can be observed in the plants by dead trees and reduced foliage at both irrigated restoration sites (e.g. Cibola NWR Farm Unit 1) and un-irrigated areas on the LCR (e.g. Havasu NWR, Cibola NWR, Imperial NWR). Depending on the local hydrologic regime, salinization has occurred to the extent to stress even halophytic vegetation, which was observed under pre-restoration conditions at Hart Mine Marsh (Figure 4). Similar conditions have been observed within the historic floodplain at the Imperial and Havasu National Wildlife Refuges (Matt Grabau, personal observations).

Figure 4. Soil surface salt crusting and poor growth of saltcedar (*Tamarix ramosissima*) due to excessive soil salinity at Hart Mine Marsh. Photo by Matt Grabau.

5.2 Irrigation Management

Irrigation can cause soil salinization as a result of water leakage from supply canals, over-application of water with poor soil drainage, or insufficient water application to leach salts. However, proper irrigation management can assist in maintenance or mitigation of soil salinity (Section 7.0). The time required for salinization to occur is correlated with the concentration of dissolved salts in irrigation water; irrigating with poor-quality water accelerates soil salinity and sodicity problems. Plants with low salinity tolerance, such as cottonwood and willows, are

susceptible to the effects of salinization even when "good quality" irrigation water is applied. For example, if irrigation water with an EC of 1 dS/m is applied (approximate value for Cibola NWR Farm Unit 1 water, GSA 2010) and 75% of the water is evapotranspired (i.e. 25% is leached), soil water EC would approach thresholds of native phreatophytes:

$$\frac{EC_{iw}}{LF} = \frac{1dS/m}{0.25} = 4dS/m \qquad \textit{Equation 3}$$

where EC_{iw} is the specific conductivity of the irrigation water and LF is the leaching fraction. Irrigation efficiency, the fraction of applied water used beneficially by plants, ranges from 40% to 70% for flood irrigation (Howell 2003), the method used at the MSCP restoration areas. Water not used by plants is lost through evaporation, percolation below the root zone, and irrigation tailwater (Howell 2003).

5.3 Groundwater Depth

A shallow water table can contribute to soil salinity through the upward movement of groundwater through capillary rise and subsequent ET and accumulation of residual salts in the surface soil. Shallow water tables naturally occur in a number of LCR restoration areas due to shallow topographic and hydraulic gradients between the restoration area and the Colorado River. Elevated water tables may also occur from insufficient subsurface drainage caused by low aquifer transmissivity or because water cannot exit the aquifer, for instance, in a topographical depression (i.e. a playa system). Irrigation can also contribute to an elevated water table. During experimental irrigation management on the Cibola National Wildlife Refuge (NWR), mounding of irrigation water has been observed during the irrigation season (GSA 2008b). Extended periods of groundwater mounding are also observed during flooding of adjacent fields for wintering waterfowl (GSA 2008b). Elevation of water tables may occur in some areas when basin-wide evapotranspiration demand is reduced during winter months. Since this corresponds to a period of low or no irrigation, salt flushing through the rooting zone is likely to be minimal. Proximity to the mainstem Colorado can also affect winter groundwater elevation as described in Section 5.1.

Maintenance of lower water tables can reduce the prevalence of evapo-concentrated groundwater in near-surface soils and allow for enhanced leaching of soil salts. This management action is

discussed in further detail in Section 6.1. Additionally, lowered water tables can potentially allow for the freshening of groundwater as discussed in Section 6.2.

6.0 SALINE AND SODIC SOIL REMEDIATION

Remediation is the act of remedying past actions that have created an adversely impacted system. In the case of the MSCP restoration areas, hydrological and land use changes have increased soil and/or groundwater salinity, which could negatively affect MSCP restoration efforts. Within salt-affected MSCP areas, soil remediation may be necessary to enhance the potential for plant survival. Any soil remediation must be done in conjunction with groundwater remediation, or if the groundwater is not saline, then with care so as not to increase salinization of the groundwater, since native phreatophytes access water from both sources. If soil and groundwater salinity have not yet been adversely affected, then soil and groundwater management to prevent salinization should be implemented.

6.1 Saline Soil Remediation

The most common saline soil remediation techniques include physical removal, leaching, and/or subsurface drainage to reduce groundwater elevations. Soil profiles are naturally heterogeneous; it may not be necessary to remediate all of soil in a site in order to support plant growth. If salts are not inherently phytotoxic to the target species, plant germination or growth may be improved by maintaining higher water content (reducing osmotic stress) or providing access to non-saline water in a segment of the soil profile.

6.1.1 Physical Removal

Physical removal, the scraping of the soil surface to remove the accumulated salts, and flushing water over the surface to remove salt crusts have limited uses. Scraping large areas results in requirements for excavation and disposal of large volumes of soil and the method has had only limited success (Abrol et al. 1988). It does not address salinity present in the subsoil, since only the topsoil is removed. It is also expensive to remove and dispose of large volumes of soil.

6.1.2 Leaching

Leaching is the most commonly-used procedure and the only practical method for removing salts from the root zone of the soil profile (Abrol et al. 1988). Leaching is accomplished by surface irrigation in excess of ET demand with water of a relatively low EC on the soil surface and allowing it to percolate. The ability to leach water through the soil profile is dependent on good

drainage through the root zone. Leaching is most effective when the salty leached groundwater is discharged through subsurface drains that can carry the leached salts out of the restoration area. However, leaching is possible when there is sufficiently high aquifer transmissivity and natural drainage. Leaching during the summer months is less efficient because large quantities of water are lost by evapotranspiration (i.e. the amount of water percolated through the rooting zone is reduced), and furthermore the water that percolates has an elevated EC due to evapoconcentration.

The initial salt content of the soil, desired level of soil salinity after leaching, depth to which remediation is desired and soil hydraulic properties are the major factors that determine the amount of water needed for soil remediation. A useful rule of thumb is that a unit depth of water will remove nearly 80 percent of salts from a unit soil depth (Abrol et al. 1988). For example, 30 cm of water passing through the soil will remove 80 percent of the salts from the top 30 cm of soil. The leaching requirement may also be calculated from the following equations:

$$LR = \frac{EC_{iw}}{EC_{dw}} x100 \qquad \textit{Equation 4}$$

$$LR = \frac{D_{dw}}{D_{iw}} x100 \qquad \textit{Equation 5}$$

where *LR* is the leaching requirement (synonymous to *LF*), defined as the percentage of applied water that percolates through and below the rooting zone carrying with it a portion of accumulated salts, EC_{dw} is the EC of the drainage water (equal to EC of the soil water), D_{dw} is the depth of drainage water, and D_{iw} is the depth of irrigation water applied to the surface (USBR 1993; Ayers and Westcot 1994).

Note that Equations 4 and 5 assume no drainage limitations. Thus, if shallow groundwater is present and/or drainage is limited, these equations are not valid, and subsurface drains might be required.

For more reliable estimates, leaching tests can be implemented on a limited area to create leaching curves that relate the ratio of actual salt content to the initial salt content in the soil to the depth of leaching water per unit depth of soil. The quantity of salts removed per unit

quantity of water leached can be increased appreciably if leaching under unsaturated soil conditions, such as achieved by intermittent ponding or sprinkling at rates less than the infiltration rate of the soil (Abrol et al. 1988).

In the MSCP restoration areas, care must be used in leaching salts from the soil because the salts do not disappear from the soil, they are relocated deeper in the soil or in the aquifer. Surface or subsurface drainage might be required, as discussed in Section 6.1.3. Leaching salts from the soil profile could contribute to aquifer salinization (discussed in Section 6.2).

Floodplain salinity remediation may be possible with managed inundation of the floodplain (Lamontagne et al. 2005), though caution must be used due to risk of contamination of downstream water supplies. Although the wash-off of surface salts will be easily diluted by floodwaters, bank discharge and groundwater discharge can persist well after a flood. For example, at the Chowilla floodplain (Murray River, South Australia), the load of salt from the floodplain to the river remained elevated for 18 months following a medium-size flood (Jolly et al. 1994). Both bank discharge and groundwater discharge (induced by localized vertical recharge in the floodplain) were suspected to have contributed to this increased salt load. Excess salt stores in floodplains could be gradually removed with carefully managed successively larger floods to reduce the intensity of salinity increases in the river and down-gradient aquifer (Lamontagne et al. 2005).

6.1.3 Water Table Lowering

Because shallow groundwater contributes to soil salinity (Section 5.3) drainage and resultant lowering of the water table can assist in saline soil prevention and remediation. If the natural subsurface drainage and aquifer transmissivity is insufficient to limit mounded groundwater conditions, the installation of an artificial drainage system may be necessary to reduce the groundwater table to an adequate depth. The principal types of drainage systems are horizontal relief drains, such as open ditches (already extensively used on the LCR), buried tiles or perforated pipes, or vertical pumped drainage wells. Figure 5 shows a conceptual cross-section of a drainage ditch used to lower the water table. The water table will be lowest near the ditch due to the conveyance of water downgradient, and groundwater will be drawn down over an area of influence dependent on soil hydraulic properties. Generally, coarse-grained (sandy) soils will

have a larger area of influence than fine-grained (clayey) soils. Figure 6 shows a cross-section of a subsurface drain used to lower the water table. The processes occurring for a subsurface drain are similar to those for drainage ditches.

Although these methods are effective in lowering groundwater, excessive discharge of drainage water and salt loads being can potentially negatively impact quality of the receiving surface or groundwater (Ayars et al. 2006), and therefore phreatophyte and wetland vegetation. Drainage control structures can reduce the volumes of drainage water by preventing over-drainage, the onset of water stress for plants, and total salt loads discharged (Ayars et al. 2006). The *Drainage Manual* (USBR 1993), which provides a detailed account of the design procedure of subsurface drainage systems, from preliminary field investigation to installation, is the basis of most system designs in the arid, irrigated areas of the United States (Ayars 2006). *Guidelines and computer programs for the planning and design of land drainage systems* (van der Molen et al. 2007) provides tools to design a drainage system including components of a feasibility study; design layouts, requirements, and criteria; system parameters; drainage materials; and drainage calculation programs.

Data required to design a subsurface drainage system include soil layering, depth to layers restricting vertical flow, soil hydraulic properties, cropping pattern, irrigation schedule, type of irrigation system, irrigation efficiency, climate data, depth to water table, sources of drainage water other than deep percolation, and the salinity status of soil and groundwater.

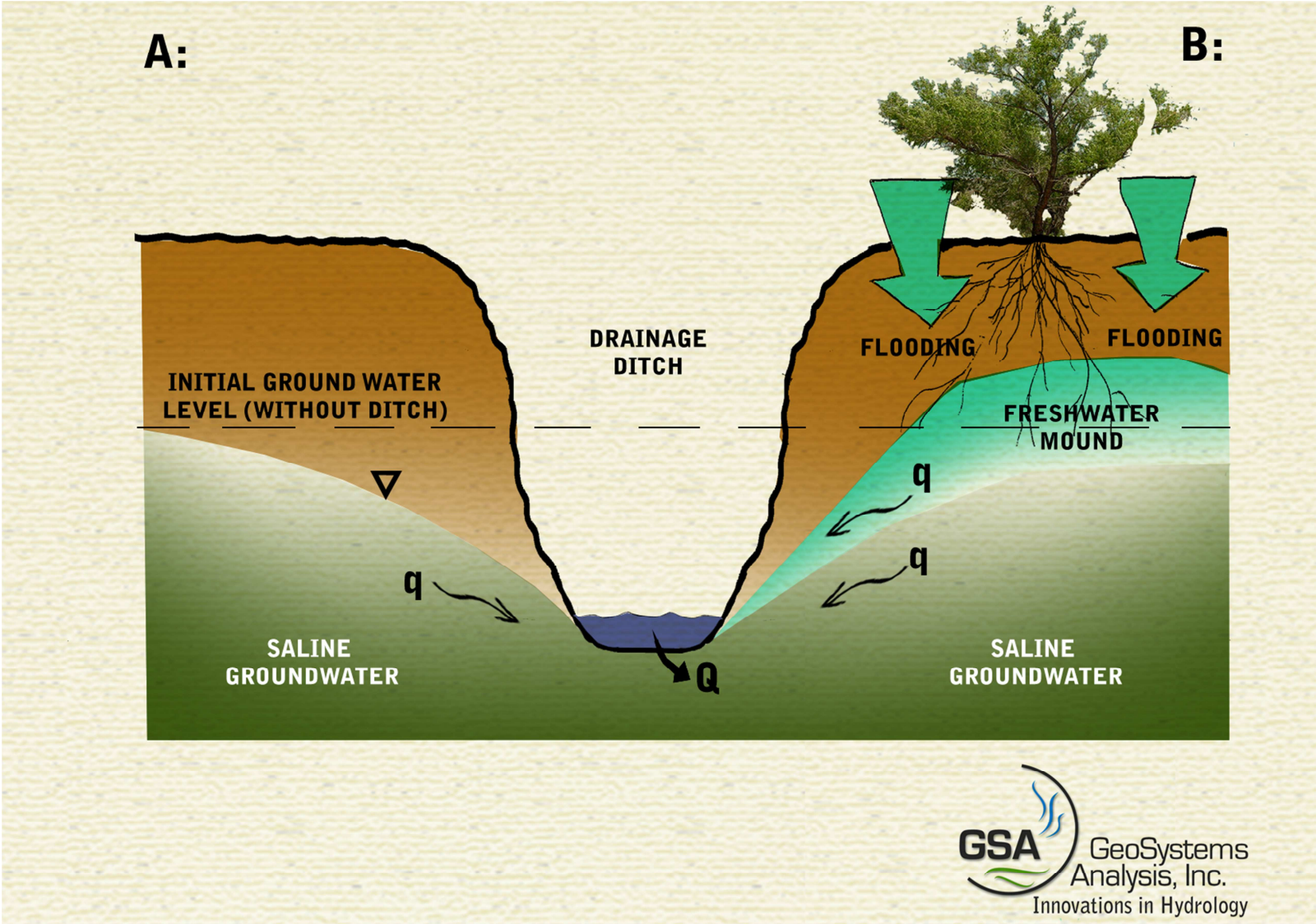

Figure 5. (A) Water table lowering with drainage ditch (B) Water table lowering and groundwater freshening with flooding.

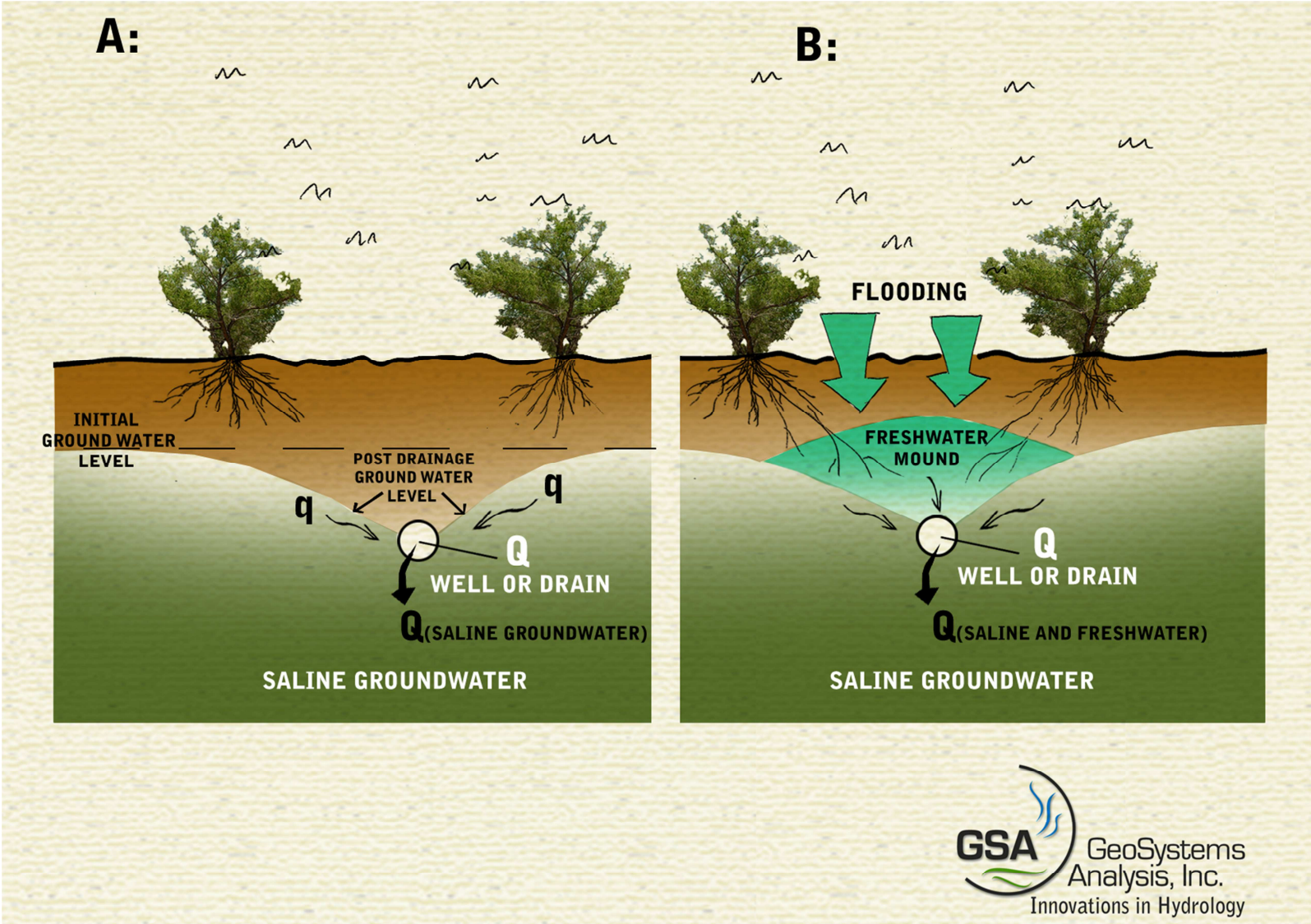

Figure 6. (A) Water table lowering with subsurface drainage (B) Water table lowering and groundwater freshening with flooding.

There are few studies that evaluate drainage system effectiveness. Table 1 summarizes reported changes in groundwater depth, soil salinity, and vegetation health due to various management strategies in arid and semi-arid regions found in current literature. In all the cases where the drainage systems worked properly, soil salinity decreased. The extent of soil improvement was largely dependent on the soil properties; for example, the presence of a clay layer near the soil surface decreases the effectiveness of the drainage system (Holland et al. 2009).

The discharge of saline drainage water may pose environmental problems to downstream areas; the environmental hazards must be considered and mitigated, if necessary. Alternatively, drainage water can also be beneficially utilized to support emergent marshes, for example, which can in turn benefit water quality through phytoremediation. A review of drainage water disposal and/ or reuse exists in the literature (e.g. Dudley et al. 2008; O'Connor et al. 2008; Willardson et al. 1997; Westcot 1988). Current uses of drainage water include blending with fresh water for crop irrigation; direct reuse for crop irrigation, fishery production, or agroforestry; reuse for brackish or saline wetlands enhancement (Westcot 1988). For example, on the LCR, tail water drainage from Cibola NWR is now being used to sustain Hart Mine Marsh via Arnett Ditch (USBR 2009).

Table 2. Changes in soil salinity under different management strategies.

Author/ Year	Study Area	Management Strategy	Zone of Influence	Change in Groundwater Depth	Change in Soil Salinity	Change in Vegetation Health
Datta 2000	Haryana State, India 7 small-scale drainage projects on farmland ranging from 10-110 ha (avg 44 ha)	**GROUNDWATER DRAINAGE** Determined ideal drain depth: 1.75 m Determined ideal drain spacing: 75 m Material: reinforced drain collectors, concrete laterals, gravel for envelope material	N/R	N/R	Soil salinity decreased from 50 dS/m in 1984 to 5 dS/m in 1991	Before drainage, farmland was left fallow due to high soil salinity. After drainage, cropping intensity increased from 0-40% before to 60-100% after.
Holland 2009	Chowilla Floodplain, Southern Australia Annual precip: 260 mm Pot annual pan evaporation: 2000 mm Soils: micaceous cracking clay deposits with low hydraulic conductivity, underlain by sandy clay, then clay	**FLOODING** Water was pumped from the creek into the wetland for 28 days to create a maximum inundation level of 19.1 m.	Transect 1 (1 m of clay at surface): soil salinity decreased 20 m from creek bank Transect 2 (thick layer of clay): <5 m from creek. Transect 3 (thin layer of clay, mostly sand): >40 m from bank	Transect 1: slight increase Transect 2: slight increase Transect 3: increased 1-1.5m	Soil salinity: Transect 1: 28 dS/m to 15 dS/m Transect 2: 40 dS/m to 30 dS/m Transect 3: 26 dS/m to 2 dS/m	Visible improvement in tree health. Artificial watering can be effective mgmt option. Water stored as bank recharge transpired in 3 years, so regular watering is necessary during low-flows.
Manjunatha 2004	Tungabhadra Irrigation Project, Andhra Pradesh and Karnataka India; 62 ha Main crop: cotton Climate: semi-arid, Mean precip: 600 mm Soils: mainly Vertisols Soil depth: 45-90 cm	**GROUNDWATER DRAINAGE** Subsurface drains installed to reclaim waterlogged saline land. The drainage system consisted of 3 pipe drains laid parallel to the valley axis at a spacing of 150 m. Drains 10 cm in diameter, 75 cm deep.	N/R	Mean 16-cm increase in GW depth	Soil salinity: 0-30 cm depth: decrease from 8.4 dS/m to 2.6 dS/m in one year. Decreased to 2.1 dS/m after another year. Drainage effluent salinity: 4 dS/m to 8 dS/m	Crop yield and intensity increased significantly following drain installation.
Singh 2009	Sharda Sahayak canal Uttar Pradesh, India 0.37 million ha salt-affected and barren; 0.5 million ha sodic w/high water table	**GROUNDWATER DRAINAGE** a) install interceptor drain at 1-m deep to remove canal seepage b) bio-drainage: plant Eucalyptus trees to intercept canal seepage and lower water table c) combination of options a+b	After 4 years, none of the options worked satisfactorily. Drains became clogged because there was no outlet to remove drainage effluent. Trees did not have sufficient leaf area for effective transpiration due to highly saline soil.			

6.1.4 Phytoremediation

The conventional method of saline soil remediation through leaching and drainage may not be possible if no safe outlet for drainage water exists or the cost of the leaching and drainage system is too high. In addition, existing soil and/ or groundwater salinity may be too high to support re-seeding with native vegetation. Phytoremediation is an alternative to conventional remediation methods. Trees with a higher salinity tolerance can be used to reclaim salt-affected soils. By removing water from lower layers of the soil, the trees minimize the capillary rise and therefore shift the zone of salt accumulation from the surface to lower layers. The large scale planting of trees can biodrain the excess water and lower the water table (Barrett-Lennard 2002). Some trees may also help to lower the salt content of the soil by absorbing salts from the soil and irrigation water (Chhabra 1996).

Phytoremediation is likely not appropriate for MSCP restoration areas because one of the program goals is to restore cottonwood and willow habitat and native mesquite bosques to promote the recovery of federally protected species under the federal Endangered Species Act (LCRMSP 2004), and these species are not believed to absorb salts. However, extensive planting of phreatophytic cottonwood, willow, and mesquite, for example, might result in a lower water table and an extended leaching zone.

6.2 Saline Groundwater Remediation

Remediation of saline aquifers at the MSCP restoration areas might be needed where salt-sensitive vegetation phreatophyte vegetation is desired. In these areas, it is also important that good quality groundwater is not contaminated by leaching salts from the soil into the groundwater.

Unconfined saline aquifers can be treated by creating a freshwater mound with flooding or excessive irrigation (Figure 7), inducing river recharge (Figure 8), or freshwater injection through vertical or horizontal wells. If the difference in solute concentrations is great enough (i.e. density of saline water is higher than freshwater), hydraulic flow will be density dependent (Essink 2001) and the freshwater mounds on top of the saline groundwater. Flooding and freshwater injection also can be used in conjunction with groundwater lowering (Section 6.1.3,

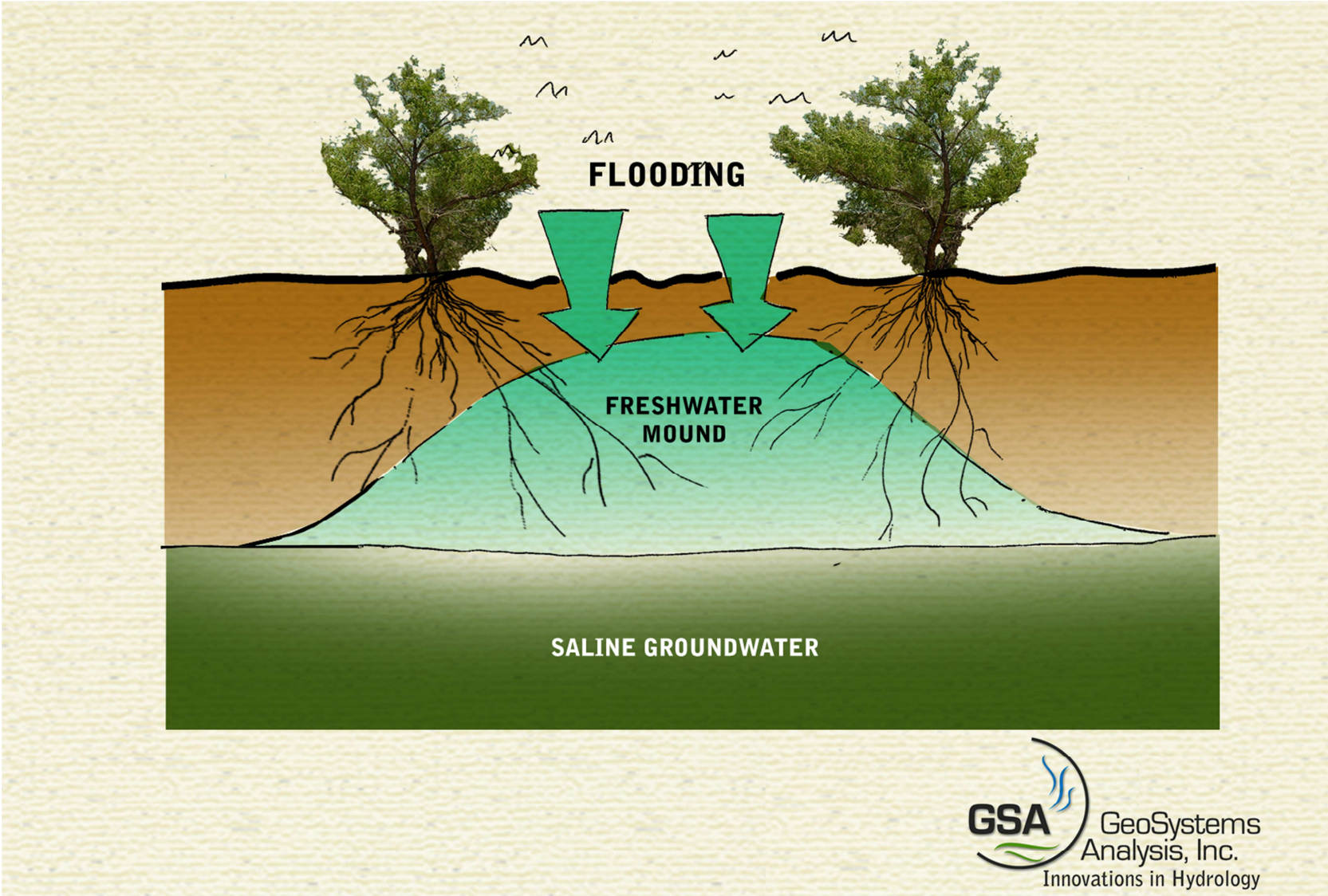

Figure 7. Freshwater mounding by flooding or excessive irrigation.

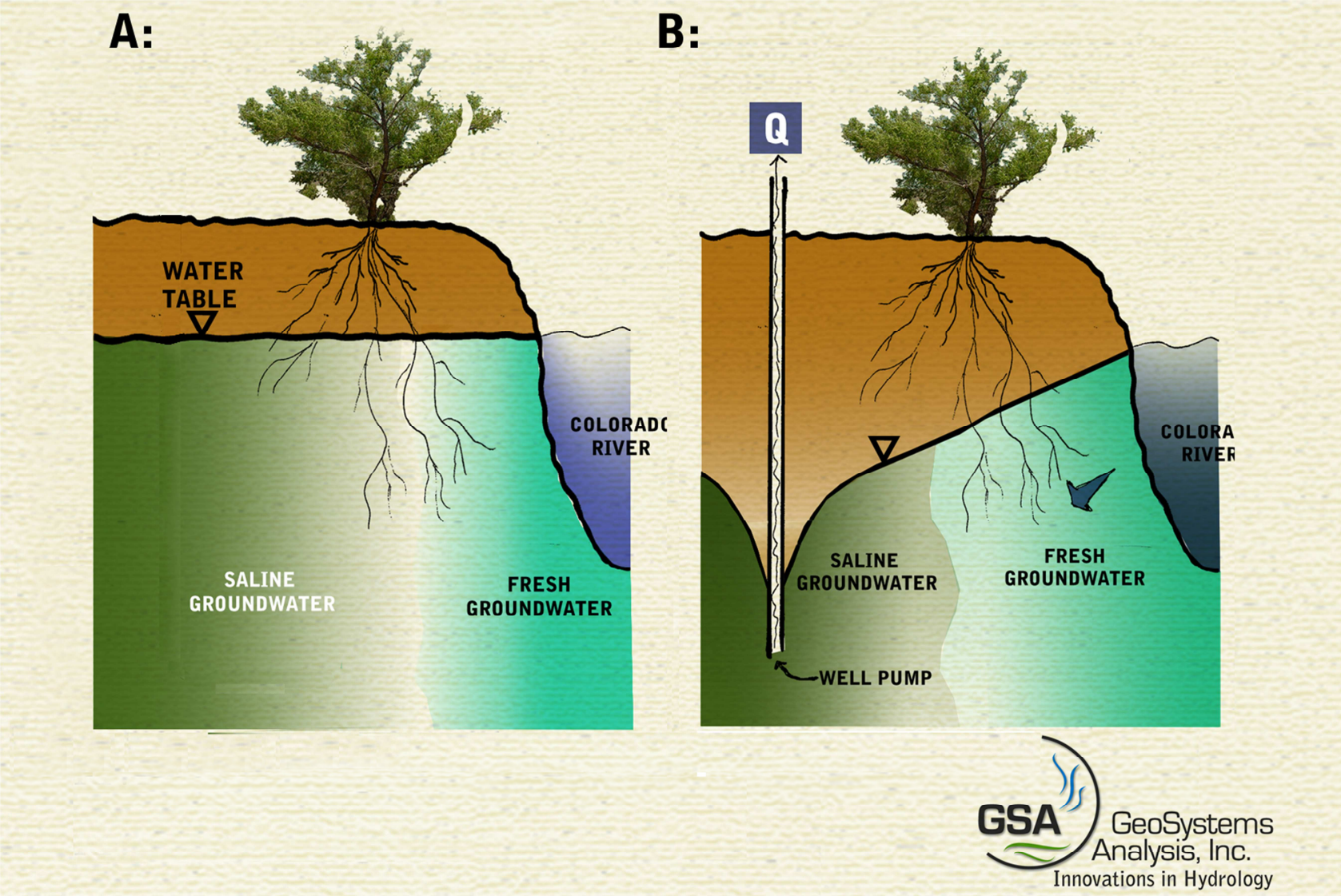

Figure 8. (A) Conditions without pumping and (B) Groundwater freshening by pumping saline groundwater to induce river recharge.

Figures 5B and 6B), particularly where flooding contributes to the formation of a shallow water table. Table 2 summarizes reported changes in groundwater depth, groundwater salinity, and vegetation health due to various management strategies in arid and semi-arid regions. Holland et al. (2009) examined whether water table lowering, water table lowering plus flooding, or water table lowering plus groundwater freshening reduces tree water stress and improves floodplain vegetation health. Water table lowering alone limited groundwater quality improvements to a zone of less than 30 m from the sources of lateral recharge. Water table lowering and flooding with freshwater (e.g. Figure 6B) temporarily lowered groundwater salinity; however, salinity levels returned to original levels one year after flooding was stopped. Water table lowering with a pumping groundwater well designed to induce river water recharge (e.g. Figure 8) into the floodplain aquifer created a freshwater lens above the saline water table over 120 m wide and 6.5 m deep.

Freshwater injection has been used in Florida to store potable water above saline aquifers for recovery later (Merritt 1988). This method potentially could be used to temporarily improve groundwater salinity accessed by riparian phreatophytes. Berens et al. (2009) attempted this method (Table 2) but only achieved localized radial freshening of 10 m due to aquifer constraints and well clogging. Therefore, the zone of influence was minimal, a freshwater lens was not formed, and tree health did not improve.

Groundwater freshening techniques for riparian restoration were found primarily in Australia. Groundwater remediation modeling and field trials are needed to determine the feasibility and long-term success of remediation at MSCP sites.

Table 3. Changes in groundwater salinity due to different management strategies.

Author/ Year	Study Area	Management Strategy	Zone of Influence	Change in Groundwater Depth	Change in Groundwater (GW) Salinity	Change in Vegetation Health
Doody 2009	Bookpurnong Floodplain, Southern Australia. Annual precipitation: 268 mm; Annual pan evaporation: 1900 mm Groundwater salinity: freshwater to seawater; 35,000 mg/L TDS in some places	**GROUNDWATER FRESHENING** **Salt Interception Scheme (SIS)**: network of wells designed to capture saline groundwater before it's discharged to a river or floodplain	Zone of fresh GW increased from width of <30m and thickness of 3.6 m to ~120m and maximum thickness of 6.5m	-0.35 m near river/ farthest from drain -0.65 m, -0.88 m, farthest from river/ closest to drain Bore functioning for 1.5 years	Groundwater salinity: 119 to 203 mg/L TDS (closest to river) 36,700 to 385 mg/L (farthest from river) 36,000 mg/L - control (no change: outside influence of bore)	Trees closest to river were healthy and remained unchanged. Tree health farther from river was poor and improved visibly by end of study period.
Holland 2009	Bookpurnong Floodplain, Southern Australia. SAME STUDY SITE AS DOODY (2009)	**GROUNDWATER DRAINAGE SIS**: network of wells designed to capture saline groundwater before it's discharged in a river or floodplain	GW salinity decreased close to river. Significantly less reduction at test sites 50m and 125m from river	-0.2m near river/ farthest from drain -0.5m, -0.6m, farthest from river/ closest to drain	Groundwater salinity: 22.1 to 4 dS/m near river 53.0 to 55.0 dS/m farthest from river	No improvement in tree health
		GROUNDWATER DRAINAGE AND FLOODING SIS and creeks flooded with ~10 ML river water	GW salinity decreased significantly over 200 m from river	-0.35m near river/ farthest from drain -0.5m, -0.6m, farthest from river/ closest to drain	Groundwater salinity: 1.2 to 0.4 dS/m near river 42.6 to 3.3 dS/m farthest from river	Short-term reduction in plant water stress. *Note: Lasted 1 year, returned to original salinities the following year.*
		GROUNDWATER DRAINAGE AND FRESHENING SIS and single groundwater well	Zone of fresh GW increased from width of <30 m and thickness of 3.6 m to ~120 m width and maximum thickness of 6.5m	-0.35m near river/ farthest from drain -0.65m, -0.88m, farthest from river/ closest to drain	Groundwater salinity: 0.9 to 0.25 dS/m near river 58.0 to 1.0 dS/m farthest from river	Reduction in plant water stress in years 1 and 2
Berens 2009	Bookpurnong Floodplain, Southern Australia. Depth to groundwater: ~3.5m	**INJECTING RIVER WATER** 5-point injection array. Injection rates were based on field pumping and pre-injection testing.	Localized radial freshening of ~10 m at each well	Significantly less volume of river water than anticipated was able to be injected, due to aquifer and well clogging. The zone of influence was minimal, freshwater lenses were not formed and tree health did not improve. The trial represented a high risk strategy for improving stressed tree community health due to aquifer properties.		

6.3 Sodic Soil Remediation

Remediation of sodic soils requires the replacement of part or most of the exchangeable sodium with calcium ions. Methods include applying a chemical amendment followed by leaching or flushing, soil profile modification (e.g. tillage), and/or phytoremediation. Selection of the remediation method depends on local conditions, available resources, and the land use of the reclaimed soils. Applying chemical soil amendments followed by leaching for the removal of salts derived from the reaction of the amendment with the sodic soil, has been used extensively and is often the quickest and most effective technique, but is also the most expensive (Qadir et al. 2001; Abrol et al. 1988).

Soil amendments include gypsum or calcium chloride, which directly supply soluble calcium to replace exchangeable sodium. Other substances, such as sulfuric acid or sulfur, indirectly solubilize solid calcium carbonate available in sodic soils to replace sodium through chemical or biological action. Organic matter (e.g. straw, farm, and green manures), decomposition, and plant root action also help dissolve calcium compounds found in most soils, but these are relatively slow processes. The type and quantity of a chemical amendment used to replace exchangeable sodium in the soils depends on the soil characteristics, extent of soil deterioration, desired level of soil improvement, and economic constraints.

The necessity of amendment is to reclaim salt-affected soils depends on the remediation project goals. Amendment application may not be essential for either desalinization or desodification, but could expedite the process by enabling higher infiltration rates by continuously supplying soluble calcium to the leaching water. Coarser textured soils with good infiltration rates are not likely to respond to gypsum application, whereas it might accelerate remediation of finer-textured (clayey) soils, or soils leached with low-salinity water.

Water infiltration is generally restricted in sodic soils due to fine-grained texture (i.e. excess silt), hard pan conditions, or stratification (Qadir 2001). Tillage alone may increase water infiltration and ameliorate sodic soils. Tillage options include deep plowing to mix fine and coarse-textured layers or to break an impermeable layer; mixing coarse-textured soil into fine-textured soils;

hauling and replacing sodic soil with normal soil; and profile inversions, which can cover sodic soil with better material from underlying soil layers.

7.0 IRRIGATION MANAGEMENT

Irrigation management is a tool that can control salinity and reduce further salt loading since irrigation water is a primary source of salts. Physical improvements that increase irrigation efficiency (and therefore decrease evapoconcentration of salts) include ditch lining or piping to reduce water loss by evaporation and seepage; land leveling for better control and more uniform water application; water control structures such as checks, drops, and divider boxes; automated irrigation systems; flow measuring devices; tail-water recovery systems; and drip irrigation systems. Proper irrigation scheduling improves water-use efficiency through appropriate timing of irrigation and recommendations as to the depth of water applied at each irrigation. Sanchez et al. (2008) developed management tools and guidelines that could increase irrigation application efficiency by up to 40% in the Yuma Mesa Irrigation and Drainage Districts through proper selection of irrigation flow rate and cutoff length or time, changes that do not require reconfiguration of physical infrastructure. Automated irrigation systems exist to maintain a desired soil water range in the root zone based on soil tension or matric potential or that irrigate based on local climate conditions. Water supplied as needed by crops instead of continuous delivery also reduces seepage from unlined canals and leaky structures and evaporation. The success and cost-effectiveness of on-farm management practices in reducing salinity contributions to groundwater aquifers have been demonstrated along the Colorado River Basin (El Ashry 1980).

8.0 CONCLUSIONS AND RECOMMENDATIONS

Changes in the LCR hydrologic regime has contributed to reduction in flooding and subsequent leaching of floodplain salt accumulation. Extensive floodplain irrigation has maintained a shallow water table, and in some areas resulted in evapoconcentration of salts. At this time, there are significant areas within LCR target restoration areas of soil and groundwater salinization and sodification (GSA 2011b). Several attempts at revegetation with cottonwood and willow have failed on the LCR, with most failures attributed to excessive soil salinity (e.g. Ducks Unlimited Restoration Site in Raulston 2003; Briggs and Cornelius 1998). Several current restoration areas also have elevated soil and groundwater salinity (e.g. Cibola NWR Farm Unit #1, GSA 2008b, GSA 2011b).

Native cottonwood and willows are phreatophytes with low salt tolerance that generally use water from both the vadose zone and groundwater. Remediation of these saline soils and groundwater will be necessary for successful re-vegetation with these species if alternate, salt-tolerant species are not an option; in addition, care must be used to (1) prevent salt accumulation in soils and (2) prevent contamination of fresh groundwater or adjacent surface water when leaching salts from the soil.

In general, Reclamation conducts soil sampling at MSCP sites prior to revegetation and if soil salinity appears unacceptable, soils are conditioned through a combination of flooding and phytoremediation with Bermudagrass (*Cynodon dactylon*) and other herbaceous species (Terry Murphy, Restoration Group Manager, LCR MSCP, personal communication). Once trees are planted, follow-up monitoring is generally included in management plans; however, to our knowledge, no standard protocol exists. Groundwater salinity has generally not been monitored at MSCP restoration sites. Additionally, long-term salinity trends have not been modeled.

Irrigation management could maintain or reduce soil salinity through leaching, particularly if developed in conjunction with a water budget analysis for the active MSCP restoration sites. Reclamation might be able to provide sufficient water for vegetation and wildlife while maintaining favorable salinity conditions given favorable irrigation management. Irrigation depth/volume for individually irrigated areas has been documented at the Beal Lake Riparian

Restoration Site (Ashlee Rudolph, LCR MSCP, personal communication) and Field 51 (seeding demonstration field) at Cibola NWR Farm Unit 1 (GSA 2010).

8.1 Proposed Characterization and Remediation Actions

To determine the extent of salinity problems, and to determine the need and potential for salinity remediation, the following salinity-related recommendations are provided for MSCP restoration sites, and summarized in Figure 5 and Figure 6 for existing and proposed restoration sites, respectively:

1. Existing Restoration Sites—Beal Lake, Palo Verde Ecological Reserve, Cibola Valley Conservation Area, Cibola NWR Farm Unit 1:
    a. Determine physical site characteristics: soil and groundwater salinity, soil type, and groundwater depth and compare with previous data where available.
    b. Based on site characteristics, determine if current irrigation and drainage management will promote long-term vegetation success.
        i. If current practices are effective, continue periodic monitoring to detect long-term salinity trends.
        ii. If current practices may result in long-term salt accumulation and vegetation mortality, determine site-specific remediation alternatives. Implement and monitor the effectiveness of the remediation actions.
2. Proposed restoration sites:
    a. Determine physical site characteristics: soil and groundwater salinity, soil type, and groundwater depth and compare with phytotoxicity thresholds of desired vegetation.
        i. If salinity is below thresholds, develop long-term salinity management strategies, and confirm effectiveness with periodic long-term monitoring.
        ii. If salinity is above thresholds, consider alternative, salt-tolerant vegetation. If salt-tolerant vegetation is not acceptable, determine causes of high salinity and the feasibility of mitigation. Implement management actions and monitor for success. If successful, plant desired vegetation and follow up with long-term salinity monitoring.

Through Grant R10AP30003, *Groundwater and Soil Salinity Monitoring Network in Support of Long-term Irrigation and Salt Management of MSCP Restoration Areas*, GSA is designing and implementing soil and groundwater salinity monitoring at three MSCP restoration sites to supplement and compare with pre-existing data and to observe salinity trends from 2010 through at least 2012. Additionally, long-term salt budgets will be modeled for various management scenarios. If possible, GSA will correlate observed soil and groundwater salinity to vegetation success. Therefore, GSA is implementing tasks 1a and 1b for Beal Lake Restoration Site, Palo Verde Ecological Reserve (Phases 2 and 3), and planted portions of Cibola NWR Farm Unit 1. Additionally, through modeling efforts, GSA will be analyzing potential remediation actions (Task 1-b-ii above).

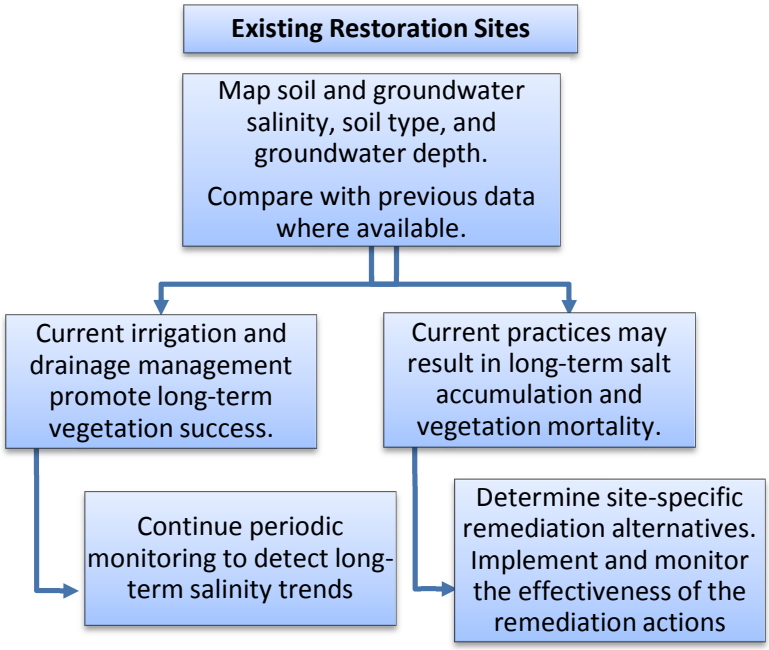

Figure 9. Salinity assessment schema with recommendations for existing MSCP restoration areas.

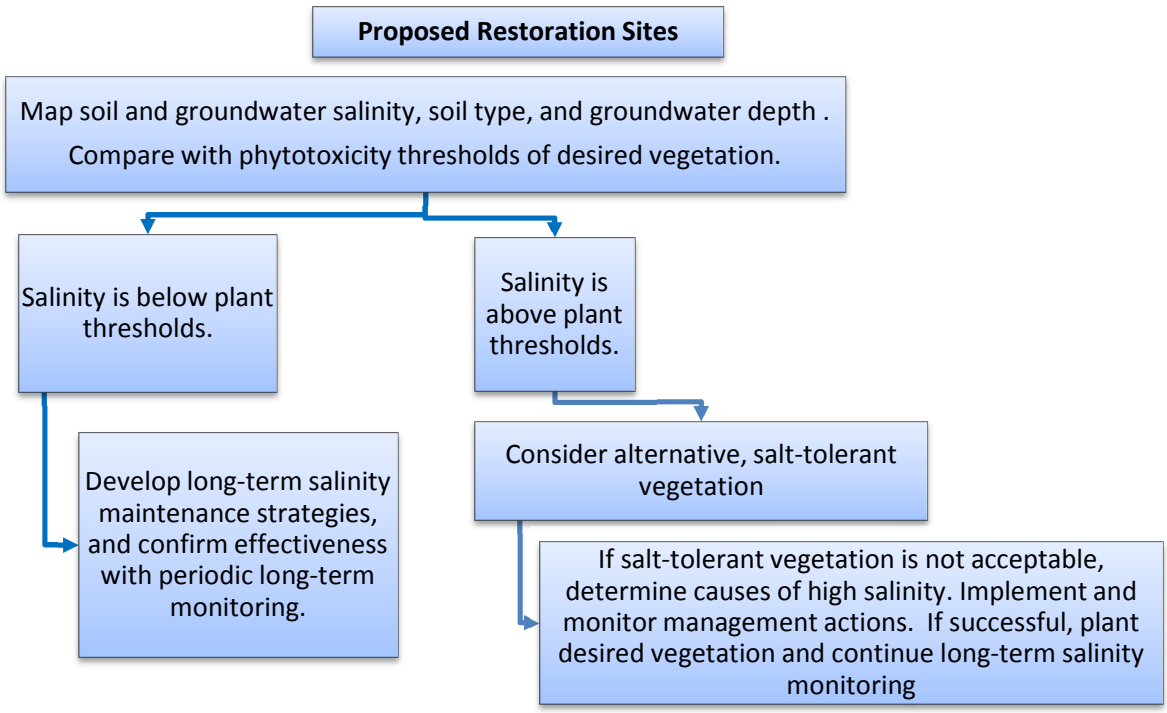

Figure 10. Salinity assessment schema with recommendations for proposed MSCP restoration areas.

8.2 Salinity Monitoring Methods

Of the soil salinity analysis methods presented above, potentially-effective methods include laboratory testing of soil samples, electromagnetic induction (EM), and in-situ electronics (time domain reflectometry or capacitance probes). Direct soil sampling and laboratory analysis provide the most reliable soil salinity data. EM could be a useful tool for observations of large areas; however, EM data should be calibrated to soil sample measurements and will mostly be effective in estimating general levels of salinity—previous attempts to calibrate EM38 readings to soil salinity have been relatively unsuccessful (GSA 2008b). Electronic instrumentation (e.g. TDR, other sensors) methods might be useful for either one-time field sampling using a handheld probe or for long-term monitoring using a data logger. The current state of remote sensing (RS) technology does not provide reliable estimates of soil salinity, especially for vegetated sites;

however, RS might be useful as an initial screening tool for the selection and prioritization of restoration sites.

Regardless of the monitoring method(s) selected, sampling density and frequency should be site-specific, with higher density and frequency required at sites where soil salinity is elevated or where remediation techniques are being implemented.

Groundwater salinity can be characterized and monitored through the installation of monitor wells or piezometers at restoration sites. Again, the required density and monitoring frequency should be determined based on site-specific conditions.

Soil and groundwater salinity limitations for vegetation should be determined through 1) direct comparison with phytotoxicity thresholds; and 2) if soil and/or groundwater conditions approach phytotoxicity thresholds, correlation of salinity conditions with vegetation success.

8.3 Remediation Methods

If active salinity remediation is required, the following mitigation measures are suggested for consideration. However, the appropriate action will be site-specific and dependent on salinity levels, soil physical and hydraulic characteristics, groundwater depth and gradients, and aquifer hydraulic characteristics.

To remediate saline soils, leaching with high-quality irrigation water might be effective where groundwater is relatively deep and/or aquifer transmissivity is high. Where infrastructure permits, leaching could be implemented through the use of extended restoration site flooding to mimic historical hydrologic regimes. Where shallow groundwater and low aquifer transmissivity are present, drainage may be necessary in addition to extended flooding and can be implemented with drainage canals or groundwater pumping. Phytoremediation might be an appropriate alternative or additional management tool.

Sodic soils can be remediated through the addition of chemical amendments and/or tillage of soil to improve drainage. After infiltration has improved, sodic sites can be remediated through leaching and drainage (as above for saline soils).

Saline groundwater remediation might be accomplished through a combination of the following:

- Irrigation management to create a freshwater lens for phreatophyte access.
- For revegetation sites near the mainstem, intentional groundwater drawdown through pumping could induce subsurface recharge from the river. However, the pumped water must then be discharged. Disposal options could include direct re-introduction to the river if water quality is acceptable or diversion to created wetlands (marshes).
- Because freshwater injection has a limited history of success and would not likely enhance MSCP program goals of elevated near-surface soil moisture at restoration sites, this method is not currently recommended.

If fresh irrigation water can be successfully percolated to groundwater, extensive leaching could reduce soil salinity and the eventual development (after salts have been removed from the soil profile) of near-surface low salinity groundwater to provide near-surface soil moisture for understory vegetation, arthropod communities, and favorable microhabitat conditions for target avifauna. The effectiveness of this method might be constrained by soil and/or aquifer conditions as discussed above.

Prior to implementation of any remediation programs, the impacts on adjacent soils, groundwater, and river water should be considered. These impacts can be predicted through numerical modeling as will be done during the current grant, but should also be monitored for the duration of the management action. Modeled salinity trends can be used to develop long-term soil and groundwater salinity monitoring action plans.

Dependent on the outcomes of the current study, there may be value in similar characterization and monitoring of additional MSCP sites, specifically where elevated soil or groundwater salinity is anticipated or observed, revegetation efforts have had marginal success, or where active salinity remediation efforts are being made.

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