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REMEDIATION OF SALT-AFFECTED SOILS AT OIL AND GAS PRODUCTION FACILITIES

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Remediation of Salt-Affected Soils at Oil and Gas Production Facilities

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PREPARED UNDER CONTRACT BY:

DAVID J. CARTY, PH.D., CPSS, STEPHEN M. SWETISH, M.S.
WILLIAM F. PRIEBE, P.E., AND WAYNE CRAWLEY, M.S., CPSS
K.W. BROWN ENVIRONMENTAL SERVICES (KWBES)
501 GRAHAM ROAD
COLLEGE STATION, TEXAS 77845

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API STAFF CONTACT

Harley Hopkins, Health and Environmental Sciences Department

MEMBERS OF THE PRODUCTION WASTE ISSUE GROUP

AND MEMBERS OF THE PROJECT TEAM

M. Scott Mansholt, Chairman, Texaco Exploration and Production, Inc.
Jeffrey C. Conrad, BP America, Inc.
Stephen J. deAlbuquerque, Phillips Petroleum Company
Doris A. Lambertz, Chevron Research and Technology Company
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EXECUTIVE SUMMARY

Water separated from oil and gas during production contains dissolved solids, including salts. If improperly handled, produced water with sufficient salt concentrations can damage plants and soils.

This manual is designed to assist the oil and gas environmental professional and field personnel in (1) assessing sites with salt-affected soils, (2) evaluating remedial alternatives, and (3) conducting remedial activities, if necessary.

Remediation of salt-affected sites can be performed for a number of reasons. Landowner claims; lease agreements; federal, state, and local regulations; reduction in long-term liabilities; company policies; and protection of useable land and water resources may be the driving forces behind the need to assess and restore a site affected by a saltwater release. These driving forces are considered along with site-specific geologic and engineering factors when developing a remediation goal. Often, the remediation goal is a self-sustaining vegetative cover consistent with the land use which avoids groundwater contamination and offsite migration of produced water salts.

The natural capability of land for various uses, its soil, climate, and water, are environmental factors that influence the success of a salt-related remediation project. A review of soil science fundamentals that are relevant to the fate and transport of salt during a remediation effort is provided in this manual.

Total salt and total sodium concentration in a saltwater release can cause the soil to become saline and sodic, respectively. The total salt concentration is of greatest concern to plants; the proportional sodium content is of greatest consequence to soil. Analyses to classify soil salinity (electrical conductivity) and sodicity (exchangeable sodium percentage and sodium adsorption ratio) are discussed.

Excessive soil salinity can inhibit plant growth by restricting plant uptake of water. Excessive sodium can cause soil dispersion, a condition that inhibits water infiltration and drainage, and causes reduced soil aggregation. Dispersed soils may become susceptible to future erosion.

Care must be taken when addressing salinity and sodicity. For example, freshwater applied to salt-affected soil without prior application of chemical amendment can cause soil clays to disaggregate which can lead to dispersed conditions. Disaggregation occurs when salinity is decreased by leaching while sodium is the dominant cation over calcium and magnesium.

Site assessment may be the most critical activity in addressing salt-affected soils. The assessment process includes gathering and organizing data about the site conditions and developing realistic remediation goals. Efficient assessments are geared toward gathering only the information needed to select a remedial option. This manual provides forms for organizing assessment information and conducting sample collection and analysis.

Remediation options for salt-affected soils are divided into three primary groupings: natural remediation, *in situ* chemical amendment remediation, and mechanical remediation. Natural remediation is the process of allowing an affected area to recover with little human assistance. *In situ* chemical amendment remediation involves adding chemical amendments (including water) to the soil to displace sodium and leach salts permanently to a location below the root zone but above groundwater. Mechanical remediation entails removing the soil from the site and disposing of it in a proper manner offsite or mechanical manipulation of the soil onsite in a way that meets the site remediation goals. Mechanical remediation may be selected when neither natural remediation nor chemical remediation are technically viable or cost effective. A decision tree and worksheets are provided to aid in the selection of a remedial option(s). Technical approaches for applying each group of remedial options are discussed.

A number of appendices provide supplementary information on various aspects of salt-affected soil remediation including: techniques for addressing drainage problems, revegetation materials (including halophytic vegetation), types of chemical amendments and amendment application procedures, and procedures for mechanical remediation technologies. The appendices also contain tools to develop customized field manuals for remediation of small areas of salt-impacted soils.

Section 1

INTRODUCTION AND OVERVIEW

The E&P industry uses great care during the handling and disposal of saltwater to avoid possible damage to the environment, including surface land, surface waters, and groundwater. However, unintentional releases of saltwater do occur. This manual is designed to assist oil and gas exploration and production (**E&P**[1]) environmental professionals and field personnel in remediating salt-affected **soils** resulting from saltwater spills. Information is provided for assessment, data interpretation, decision making, and remediation of **surface soils** exposed to saltwater. This includes saltwater containing low levels of petroleum hydrocarbons.

BACKGROUND

Most oil and gas E&P operations produce formation water simultaneously with oil or gas. Salt concentrations of this "**produced water**" vary from water with low salt concentrations, to **brackish water** [i.e., **total dissolved solids** (**TDS**) less than 4,000 parts per million (**ppm**)], to **brines** with salt concentrations greater than 100,000 ppm.

Spills of produced water with high concentrations of total salts (**salinity**) and sodium (sodicity) can have a detrimental effect on terrestrial and **freshwater** environments. Excessive salts can create adverse chemical and physical conditions in soils and damage or kill vegetation.

Spills of Produced Water onto Surface Soils

Oil and gas production sites vary in size from less than 0.25 acre at a single well pad, to a few acres at a tank battery, to many acres at a gas plant. Large volumes of produced water (up to thousands of barrels per day) are routinely handled in many of the production operations located on these sites.

The current practice for disposal of most inland produced waters is by injection into enhanced oil recovery or produced water disposal wells (Class II injection wells). Some inland facilities may use evaporation pits to dispose of produced water.

Surface spills of produced water do occur as a result of equipment failure, pipeline corrosion, weather, or human error. Such mishaps can occur at production sites, along produced water injection pipelines, or at other field locations.

[1] Terms in **bold type** appear in the glossary (Appendix D).

Produced Water Pits

There are several types of pits traditionally associated with oil and gas production. Following are three types of salt-related pits:

- Production pits
- Reserve pits
- Produced water storage (emergency) pits

Historically, production pits were used for saltwater storage, oil and water separation, and solids settling (Moseley, 1983). In arid regions, production pits were also constructed to dispose of produced water through evaporation (API, 1997). Today, evaporation pits are used in a few western states at sites with relatively low-salinity produced water where the potential for affecting underground drinking water sources is also low.

Reserve pits are used for solids separation during drilling and workover operations and for holding waste drilling muds and cuttings. Even when a freshwater mud is used, pit contents can become a source of accumulated salts where saltwater-bearing formations are drilled. As a result of evaporation during drilling and pit dewatering, salt concentrations in reserve pits can be high.

Produced water storage, or emergency pits are constructed to contain produced waters temporarily in the event of equipment malfunction, such as a failure of the injection system or a disposal well. These emergency pits generally serve many wells, a lease, or a field. They usually are in sporadic use during the lifetime of an oil or gas field. Most states require the emergency pit to be emptied after use, but salts can accumulate over time in soil at the bottom and sides of unlined pits.

This manual does not specifically address the remediation of salt-affected pit sites. However, many of the techniques described in this manual can be adapted to various aspects of pit remediation. Spills from overflow, for example, can be remediated using this manual. If the pit is to be closed, and material in the pit must normally be mechanically remediated (e.g., mixing with clean soil or soil removal) it may be possible to handle the closed pit **subsoils** in the same manner as a spill site.

PURPOSE OF MANUAL

The overall purpose of this manual is to assist oil and gas environmental professionals and field personnel in: (1) assessing sites with salt-affected soils, (2) evaluating remedial alternatives, and

(3) conducting remediation activities (if necessary). Included with this manual are tools to create a field manual (Appendix A) organized to provide field personnel with a simplified template for remediating relatively uncomplicated spill sites. The full manual provides more detailed guidance and reference materials.

Scope

This manual focuses on remediation of typical spill sites on common soils and landscapes. The information and concepts provided are applicable to the remediation of some pit sites and some large spill areas. However, the scope of this manual does not address remediation of severe or chronic spill areas, pits deeper than 6 ft or containing non-soil constituents, or groundwater or surface water.

Low concentrations of petroleum hydrocarbons also may be present in produced waters. Remediation of more than very low levels of hydrocarbons (<2%) in soils is beyond the scope of this manual. If high concentrations of hydrocarbons are present (>2%), the user should consult references specific to hydrocarbon remediation.

This manual was intended for use within the United States where resources, such as county **Soil Surveys** and similar data, are readily available to the user. However, the underlying principals of salt remediation make this manual applicable worldwide, with the possible exceptions of predominantly frozen soils, organic soils, and certain soils formed primarily from volcanic ash.

In contrast to **mineral soils** which are composed of inorganic **sand**, **silt**, and **clay** particles, organic soils are composed primarily of decayed vegetation which accumulates in saturated conditions. Although this manual pertains to many soils of volcanic origin, it does not address volcanic soils which contain a predominance of **allophanes**, due to their unusual physical and chemical properties.

Organization

This manual is organized into seven sections. Section 1 provides an introduction and overview. Section 2 addresses non-soil-related issues which may be considered when setting goals for the remediation effort. Section 3 reviews basic environmental factors for which the user should develop some familiarity prior to initiating remediation. Section 4 examines the effect of salt spills on various soils. Section 5 provides an overview of remediation option categories and a Decision Tree to assist in selecting an appropriate remediation option. Section 6 is a guide to site assessment activities. Section 7 provides details of remediation activities, and Section 8 outlines post-remediation monitoring and project termination.

Appendices are included to expand on information provided within this manual. Each appendix is designed to be a self-contained module. Use of the Decision Tree presented in Section 5 will lead to one or more appendices which provide information for making specific determinations or performing certain actions. The following appendices are included:

- Appendix A contains tools for preparing an abbreviated field manual and the general procedures to follow for small, uncomplicated spills in adequate, marginal, and inadequate rainfall areas.
- Appendix B provides blank forms and worksheets for documenting and tracking the assessment, decision making, and remediation/disposition phases associated with each identified spill site.
- Appendix C lists state-specific regulatory agencies.
- Appendix D consists of a comprehensive glossary including acronyms. For the convenience of the user, technical terms and/or acronyms which are defined in Appendix D will appear in **bold type** the first time they appear in Sections 1–7. A number of technical words which do not appear in Sections 1–7 but which the user is likely to encounter during data gathering, are also included in Appendix D.
- Appendix E includes details pertaining to drainage problems and remediation procedures.
- Appendix F provides information on revegetation materials, including use of halophytic vegetation.
- Appendix G contains information regarding site delineation and field sampling.
- Appendix H provides details and procedures for using mechanical remediation technologies.
- Appendix I includes annual precipitation and evaporation quantity maps.
- Appendix J contains information regarding selection of a suitable analytical laboratory, data validation aids, and a list of analytical procedures.
- Appendix K lists and describes chemical amendments and application procedures.
- Appendix L discusses common types and use of mulching materials.

Use of this manual can be optimized by compiling and organizing available soil, climatological, and produced water information for the oil and gas fields in which the user operates. Gathering this information proactively may reduce response time when a spill occurs. This manual has also been designed to minimize the amount of time and data required to select a suitable remedial alternative. With practice, the user should be able to move rapidly through the processes described within this manual.

REMEDIATION GOALS

Setting reasonable objectives for the remediation effort is critical to developing a viable remediation plan. In some cases, the objectives may be established by legal, regulatory, or lease constraints. In other situations, the objectives may be based on more flexible criteria. It is advisable to, at a minimum, review the following factors prior to initiating any remediation effort:

- Lease requirements
- Regulatory constraints
- Corporate policies
- Environmental conditions

The user is cautioned to question whether remediation goals are realistic in situations where physical or climatic factors may be severe. A primary focus of this manual is to help the user assess the physical and chemical limitations of the site to be remediated. For instance, it may not be feasible to attempt to recondition a soil for growing crops if it was not suited for such a function before the spill occurred. Recognition of the fact that time will be required to remediate most spills is also important. It may take several years to return an area to productive use, especially if the spill was large or soil or climate characteristics are unfavorable.

One objective of this manual is to encourage wise utilization of human and physical resources. All actions taken should result in some tangible improvement to the environment. Overzealous goals and excessive attention to poor candidates for remediation often waste valuable resources (which may be more effectively utilized elsewhere), and may even further damage the affected or surrounding area.

Unless eclipsed by regulatory or legal issues, returning a salt-affected area to sustainable productivity with no offsite migration of salts is a commendable remediation objective.

Minimal regulatory or other guidance exists regarding criteria for a successful remediation effort for salt-affected soils. Due to the variety of natural landscapes, it would be difficult to establish any uniform criteria. In general, successful remediation suggests a landscape and ecosystem which have recovered sufficiently to support healthy and self-sustaining plant and animal growth, minimal **erosion**, and negligible long-term impact on usable surface or subsurface water. To the degree feasible, successful remediation should also be consistent with the landowner's intended land use. These indicators of success must also be consistent with any regulatory criteria for salt-affected areas.

This manual attempts to address all of the above considerations. Actions suggested are intended to be practical; protective of health and the environment; cost-effective; and sensitive to various regulatory, legal, and public interests.

REVIEW OF SECTION 1

- This manual is designed to assist E&P personnel in remediating typical salt-affected soils.
- Remediation objectives should be selected only after considering all pertinent factors, including lease requirements, regulatory constraints, corporate policies, and environmental conditions.
- A commendable remediation goal is to return the land to reasonable and sustainable productivity with no offsite migration of salts.

Section 2

FACTORS INFLUENCING THE REMEDIATION OF SALTWATER SPILLS

Remediation of saltwater spills can be conducted for a number of reasons. Landowner claims; lease agreements; federal, state, and local regulations; reduction of long-term liabilities, company policies; and protection of usable water resources may be the driving forces behind a remediation project. These factors should be considered in addition to science and engineering issues when selecting the remediation goals and techniques.

LANDOWNER CONSIDERATIONS

Initiating remediation options should not be undertaken without consulting the landowner. In some cases, the lease agreement specifies the landowner's desires. Landowners will often have opinions on various remediation options.

In rarer cases, the landowner may want no remedial action taken at all. Some landowners prefer that any monies which would have been spent on remediation be paid to them in land damages. Before choosing this option, the operator should be aware that unremediated sites have been the subject of litigation even when damage payments were made and releases were signed by the landowner. The operator should also ensure that remediation is consistent with any applicable regulatory requirements.

Cooperation with landowners should be a high priority. Landowners can often provide suggestions and assistance which can substantially improve or decrease the cost of a remediation effort. A dissatisfied landowner may be in a position to complicate resolution of a spill condition. In any event, operators should be aware of his/her legal standing regarding interactions with affected landowners.

REGULATORY REQUIREMENTS

Federal, state, and local regulations may pertain to various aspects of remediation of produced water spills, including spill response, vegetation, vadose zone, groundwater or surface water impacts, and possibly air emissions. All potentially applicable regulations should be reviewed and documented in appropriate data collection sheets, such as those provided in Appendix B, prior to initiation of a project.

Regulations may influence the choice of remediation technology and the associated costs. A technology which may be suitable for certain conditions in one state may not be well received in an adjoining state. Furthermore, several regulatory authorities with competing criteria may have jurisdiction over the same spill site. For example, in some western states a sovereign Native American nation, a local Native American community, the Bureau of Indian Affairs, the Bureau of Land Management (**BLM**), the U.S. Army Corps of Engineers (**COE**) (e.g., regarding **wetlands**), and other organizations may all have regulations pertaining to a single affected site.

Where they exist, water rights pertaining to interception, withdrawal, addition, and quality and quantity of groundwater and/or surface water may be factors in remediation. Special attention should be given to potential for salt migration into drinking or other potentially usable water.

Regulations in some jurisdictions may be very specific regarding the types of vegetation which may be introduced if revegetation is part of the remediation strategy. Other regulations may address disposition of saltwater, soil, surface water, or groundwater at a salt-affected site.

Some states have specific regulatory requirements. Appendix C contains a list of regulatory agencies and telephone numbers that are current as of the approximate date of this manual. As noted, more than one organization may have some jurisdiction over various aspects related to a remediation effort. Users of this manual should verify the accuracy of the information provided in Appendix C before performing remediation activities at a site.

PUBLICLY SUPPORTED ASSISTANCE AND INVOLVEMENT OF QUASI-REGULATORY ORGANIZATIONS

In addition to those exercising regulatory control, several publicly supported organizations may be in a position to assist with remediation, or to become otherwise involved in resolution of a spill condition. Depending on the circumstances, some of these organizations may have jurisdiction over spill disposition and remediation efforts. Examples include state and federal forestry, soil, water, and wildlife organizations.

A number of individuals in these organizations are well trained technically and are in a position to provide valuable technical insight. The county agriculture extension agent is typically an excellent source of information on vegetative recovery expectations and remediation techniques that have been successfully used in the past.

CORPORATE POLICIES

Corporate polices may include certain specific or general protocols and criteria for addressing a spill. Users of this manual should incorporate these policies into the framework of this manual, or request adjustments to the policies in consideration of new information provided by this manual or other reputable sources.

COMMUNITY CONSIDERATIONS

Local citizens and community organizations may seek input into spill remediation efforts. Concerns may be expressed regarding surface water, groundwater, or aesthetics of sites visible from public areas. The value of public relations and proposed alternative remediation technologies should be considered when local citizens and/or community organizations become interested in spills.

From one perspective, community and environmental proponent groups may provide an opportunity to enhance public relations by joining in public-spirited or "grassroots" remediation projects. Such actions are also being viewed very favorably by regulatory authorities who are making substantial concessions to facilitate such cooperative efforts.

REVIEW OF SECTION 2

Cultural factors provide guidance for remediating salt-affected soils. An understanding of remediation nontechnical factors is as important to the potential success of the remediation effort as are the technical considerations.

- Nontechnical issues that must be addressed when selecting a remediation alternative include landowner considerations, regulatory requirements, publicly supported assistance, corporate policies, and community considerations.
- To be deemed completely successful, a remediation project will prove acceptable to each of the above interests.

Section 3

BASIC ENVIRONMENTAL FACTORS

The natural capability of a land for various uses, its soil, climate, and water are environmental factors that influence the success of a saltwater spill remediation. This section reviews soil science fundamentals that are relevant to the fate and transport of salts after a spill and during remedial efforts. Technical terms and acronyms are defined in the glossary provided in Appendix D.

SOIL

The soil is where most remediation efforts are directed. Remediation efforts require a basic knowledge of soil physical components, **texture**, **layers (horizons)**, **slope** and erosion characteristics, drainage, and chemistry.

Physical Components

Soil has four physical components: inorganic solids, organic matter, water, and air (Figure 3-1). A typical soil consists of about 45% inorganic solids, 5% organic matter, 25% water, and 25% air. Thus, about 50% of a soil is **pore space** which is occupied by water and air. **Soil pores** can be full of water, but rarely contain less than 10% water, even when quite dry.

Texture (Particle Size Distribution)

Inorganic soil solids are a mixture of various-sized particles. Table 3-1 summarizes the characteristics of the particle size ranges: sand, silt, and clay.

Table 3-1. Characteristics of Sand, Silt, and Clay.

Size Name	Particle Diameter Range (mm)	Particle Appearance	Particle Feel	Chemical Activity[a]	Approximate Surface Area (sq ft/g)
Sand	2–0.05	Visible	Gritty	Inactive	0.05
Silt	0.05–0.002	Microscopic	Silky	Inactive	5
Clay	less than 0.002	Submicroscopic	Waxy	Active	5,000

a Chemical activity refers to relative influence on dissolved constituents. For instance, soil clays commonly act as strong catalysts and enzymes to inorganic and organic chemical transformations, whereas the influence of soil silts and sands is much less pronounced in this regard.

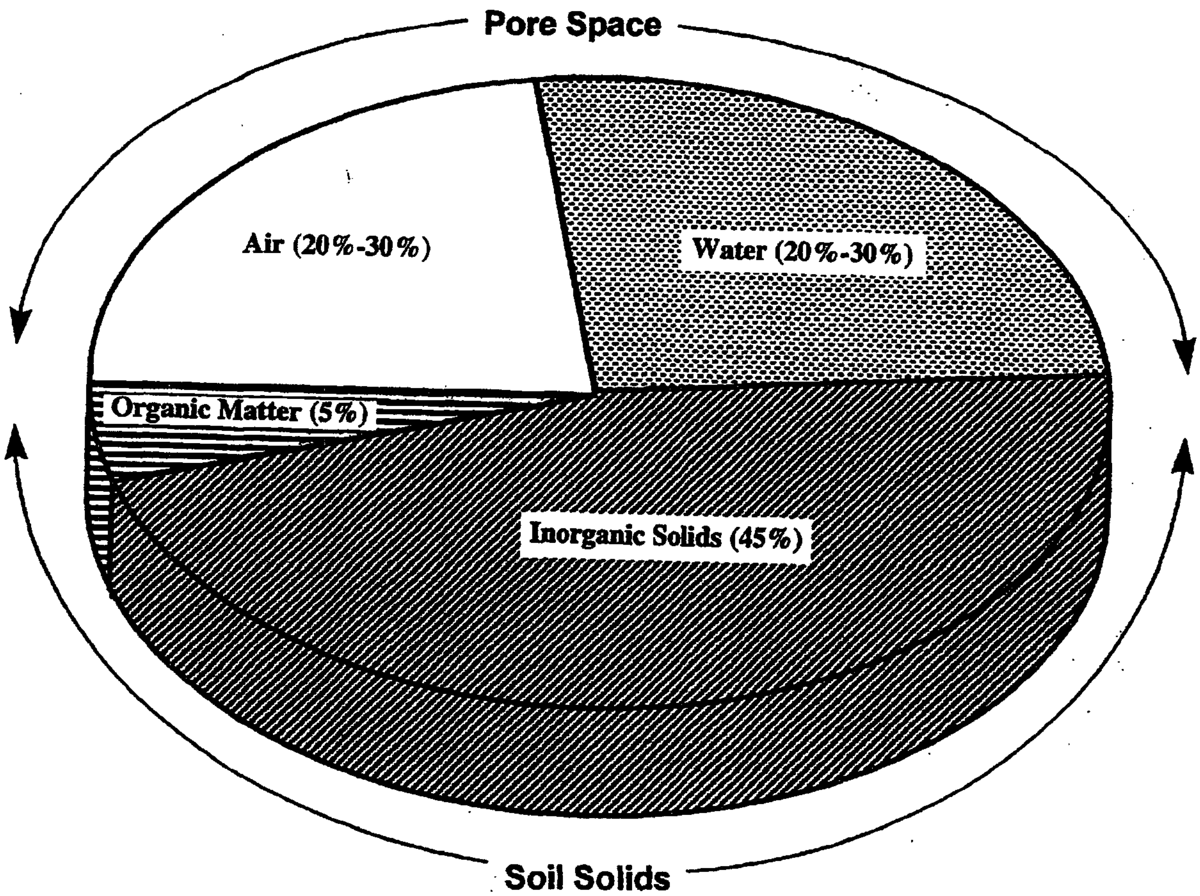
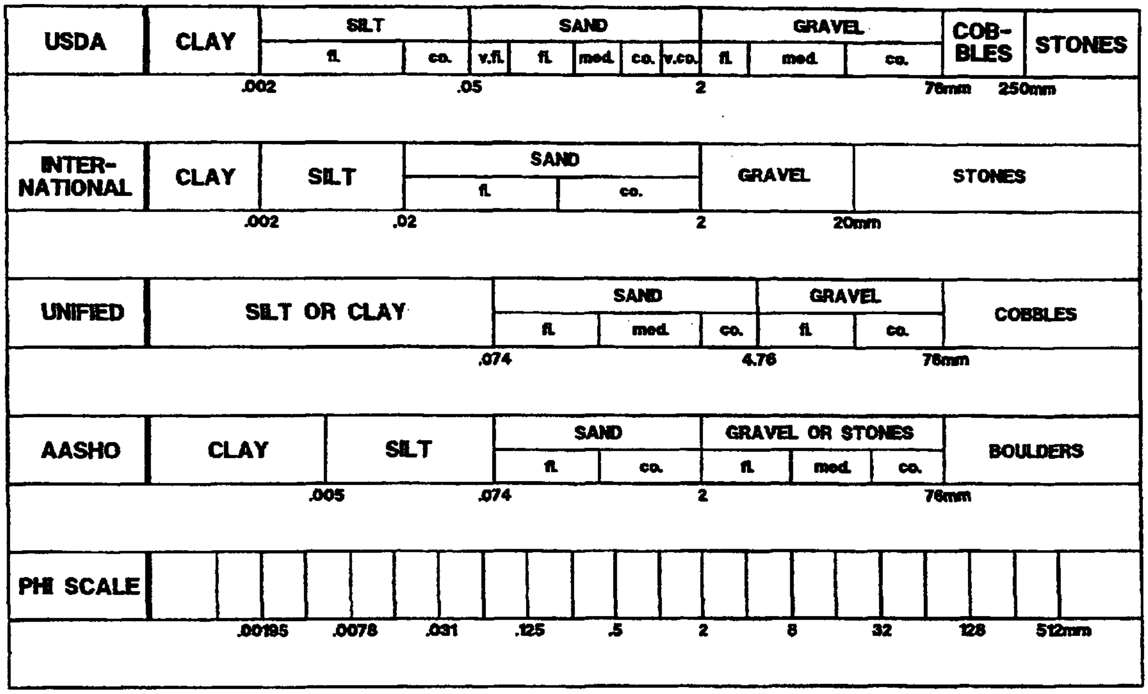


Figure 3-1. Physical Components of a Soil (adapted from Brady, 1984).

Larger-sized particles (greater than 2-mm diameter), such as gravel and **stones**, while occupying volume, are not considered an integral component of soil. Sand and silt also perform primarily a physical function in soil. As discussed in the subsection Chemistry (page 3-9), the high degree of chemical reactivity inherent in clays and organic matter makes them the most important components in determining soil behavior.

Figure 3-2 illustrates the relationships in terminology and units of measure among several particle size classification systems. The terminology associated with specific particle size ranges used in this manual follows the U.S. Department of Agriculture (USDA) system at the top of Figure 3-2.



v.fi.	=	very fine	USDA	=	U.S. Department of Agriculture (used by soil scientists and agronomists)
fi.	=	fine	INTERNATIONAL	=	International Society of Soil Science
med.	=	medium	UNIFIED	=	Used by many agricultural and civil engineers
co.	=	coarse	AASHO	=	American Association of State Highway Officials
v.co.	=	very coarse			

Figure 3-2. Particle Size Classes of Five Different Systems (adapted from USDA, Soil Survey Division Staff, 1993).

The proportion of sand, silt, and clay particles in a soil can be divided into twelve categories called textural classes (Figure 3-3). Soil within each textural class tends to exhibit distinct characteristics unique to that class.

Once the percent of sand, silt, and clay is known, the precise textural class can be determined using the textural triangle as shown in Figure 3-3. In this manual, soil textures have been further condensed from the twelve textural classes into only three groups (Figure 3-4): (1) **coarse**, (2) **medium**, and (3) **fine**.

The chemical and physical composition of different soils is extremely variable and is dependent on the parent rock material, the landscape position, biological interactions, and the amount of time exposed to climatic interactions. Common crystalline clay minerals include **kaolinite**, illite, **montmorillonite** (or smectite), and vermiculite. Although often coalesced into very hard **ag-**

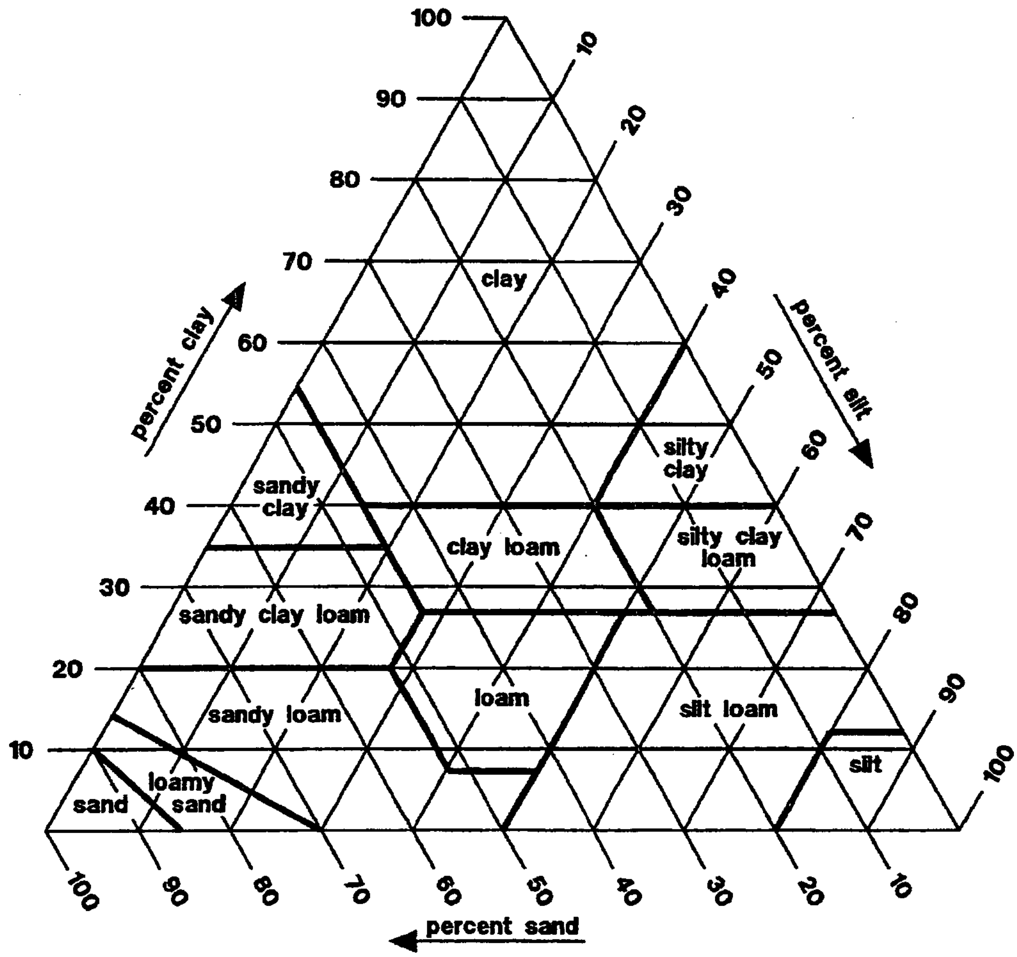


Figure 3-3. Soil Textural Triangle
(adapted from USDA, Soil Survey Division Staff, 1993).

gregates of gravel size or larger, individual particles of iron and **aluminum oxides** actually fall within the particle size range of clay minerals. Sand and silt grains typically consist of minerals such as quartz, mica, and feldspars. Relatively soluble constituents, such as carbonates and gypsum, are not typically included in particle size determinations. Soils with **parent material** of volcanic origins often contain somewhat amorphous clay minerals called allophanes. Another minor physical component found in mineral soils is organic matter. Organic matter is typically not included in particle size determinations.

The vast majority of soils are mineral soils which commonly contain up to about 5% organic matter. However, there is a special category of naturally occurring soils which consist primarily of organic matter. These soils are called "organic" soils. Organic soils do not develop from

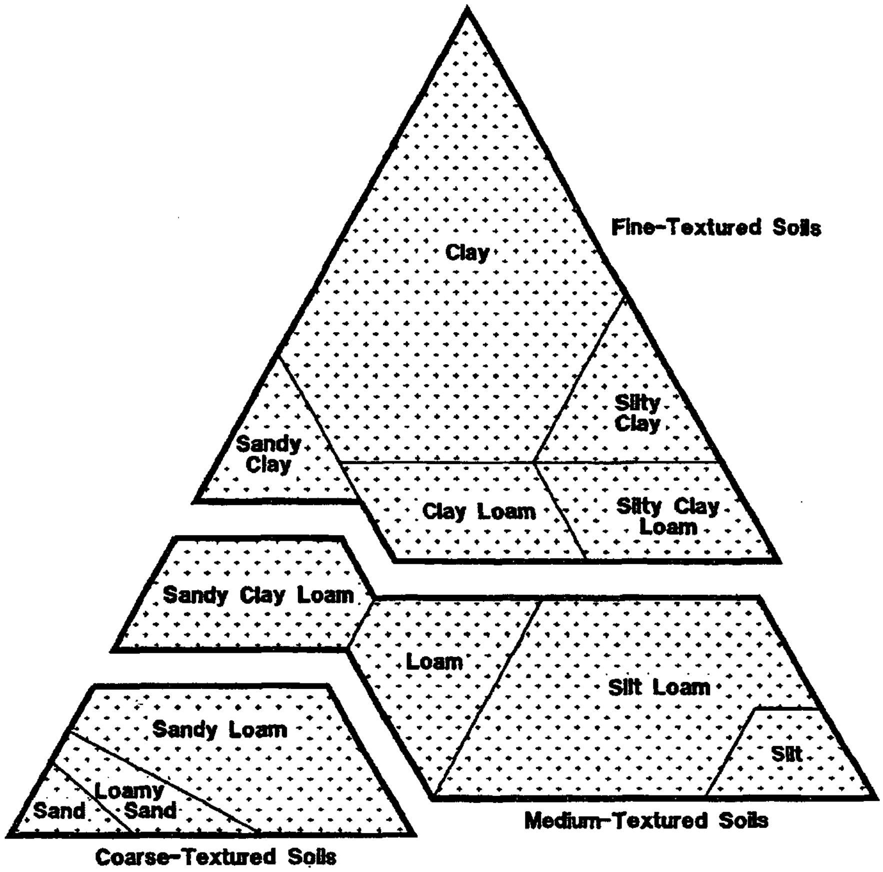


Figure 3-4. Soil Texture Groups (Plaster, 1985).
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geologic materials, but from decomposing plant materials. Other names for organic soils are "muskeg" soils and "muck" soils. Organic soils may form in environments dominated by freshwater, brackish water, or saltwater.

Although organic soils are almost always located in very wet areas, they should not be confused with "hydric" soils. Hydric soils are located in very wet areas and are important regarding wetlands determinations. However, hydric soils are very often mineral soils.

Layers (Horizons)

Examination of a typical vertical section of soil to about a 6-ft depth reveals that it is segregated into layers. These layers are called horizons (Figure 3-5). Three major layers (A, B, and C horizons) are found in most soils.

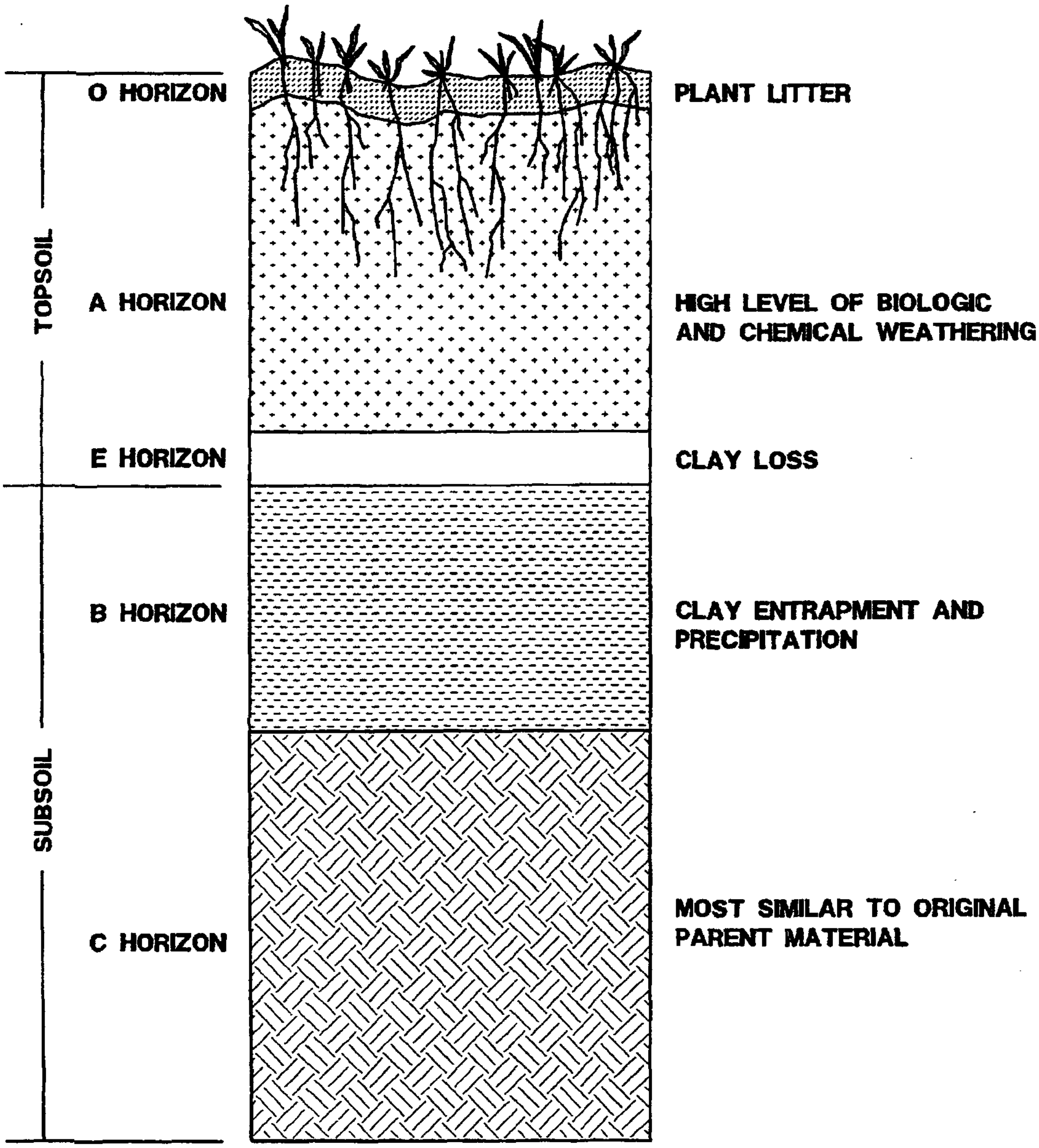


Figure 3-5. Soil Profile and Horizons.

The A horizon can be considered the topsoil or the primary root zone. This is the most intensely weathered portion of the soil profile. It is also the site with the greatest biological activity, and is the richest in plant nutrients as a result of decaying leaf litter or fertilization by humans. An O horizon can be designated above the A horizon if the weight percentage of organic matter at the soil surface is >50%. A light-colored and typically sandy E horizon can be designated at the bottom of an A horizon if most of the clay has leached downward into the subsoil.

One important aspect of the A horizon is that internal biotic activities, including plant growth, help bind soil particles together into stable structural units called aggregates. Soil particles bound in stable aggregates are resistant to erosion and indicative of relatively large and beneficial (macro) pores in the soil. These macropores help the soil efficiently take in rainwater and air which are essential to the survival of most plants and animals.

The B and C horizons constitute the subsoil. These horizons have little organic matter, fewer plant roots, and much less biological activity than the topsoil. The B horizon usually has the highest proportion of clay of any horizon in the soil, and this often greatly restricts the downward migration of water. The C horizon contains essentially no organic matter or buildup of migratory clay from above. However, original parent material in the C horizon has been subjected to chemical **weathering** by water percolating through the soil. Soil salts, carbonates, and reprecipitated silicates often concentrate and sometimes become cemented in the B and C horizons, further decreasing **porosity**. The consolidated or unconsolidated geologic material below the C horizon is often designated R for **regolith**, but is not considered to have been sufficiently weathered to be described as part of the soil.

<u>Slope and Erosion Susceptibility</u>

Different soils have different susceptibilities to erosion. Erosion is related to **slope steepness** and length, plant cover, rainfall, and the texture and aggregate stability of the soil. Erosion is accelerated by raindrop impact and wind, both of which are able to dislodge soil particles.

Erosion can be minimized by good management practices, such as interrupting the slope with small berms, controlling runon, assuring good vegetative cover, and maintaining aggregate stability with good fertility and organic matter content. Factors which cannot easily be controlled are rainfall and soil texture.

Erosion causes several problems. First, it causes a loss of topsoil which contains most of the organic matter and biota, fertility, and seeds for plant regeneration. Second, eroded soil particles which are suspended in runoff water act in a scouring manner on downgradient soils, and eventually settle in waterways.

When subsoil is exposed, it is often even more susceptible to erosion than topsoil. Exposed subsoil is also unprotected by vegetative cover.

Although erosion occurs on all soils which are not flat, soil with slopes of greater than 8% (8 ft of fall over a 100-ft distance) are especially prone to erosion and require special consideration during any type of surface work. As discussed in Section 6, soil impacted by salt spills is also especially prone to erosion.

Drainage

The ability of a soil to drain is a very important feature of any soil, particularly with regard to salt remediation. In addition to initial moisture content, surface slope, depth to **water table**, and the thickness of soil above **bedrock**, soil internal drainage is affected by soil texture, pore size distribution, and low **permeability** layers.

In recognition of the interactions of various drainage factors, drainage categories were created by the USDA Natural Resources Conservation Service (**USDA-NRCS**, formerly the Soil Conservation Service, **USDA-SCS**). More detailed USDA-NRCS categories with attendant data and interpretations are given in USDA, Soil Survey Division Staff (1993). Some of this information is provided in Appendices D and E. For the purpose of this manual, soil drainage (before a spill) can be categorized as:

- Excessively Drained. In an excessively drained soil, water drains so rapidly that the soil retains relatively little water and plants are frequently in drought stress. Wetness is rarely a growth-limiting factor for mesophytic plants (plants which require a moderate amount of water). One or more of the following factors are usually present: minimal rainfall, steep slope, very deep water table, or coarse soil texture. A thin soil (minimum volume for holding water) above bedrock can also be excessively drained.

- Well Drained. A well-drained soil drains readily but not rapidly. Sufficient water is available to mesophytic plants during most of the growing season and excessive wetness is seldom a growth-limiting factor.

- Moderately Drained. In a moderately drained soil, water is removed somewhat slowly during some periods of the year. Growth of mesophytic plants is limited by excess water for only short periods during the growing season.

- Poorly Drained. In a poorly drained soil, water is removed very slowly and the soil is usually wet. Without drainage enhancements, excessive wetness is growth limiting to mesophytic plants. One or more of the following factors are usually present: substantial rainfall, minimal slope or depressional area, very high water table, fine soil texture or low permeability layer, or minimal macropores (large pores). In very poorly drained soils, the water table commonly remains at or very near the surface for long periods of time.

The movement of water and salts in soils is very complex. Under very dry conditions, swelling clay soils (which greatly inhibit **infiltration** and permeability when wet) may develop many large (greater than 1-inch across) and deep (greater than 3 ft) cracks when dry. When it rains after a dry period, rainwater will move readily into these large cracks. Thus, when dry, some clayey soils can have both much larger and much smaller pores than sandy soils.

Coping with poor internal soil drainage presents a major obstacle for remediation of salt-affected soils. Salts must be able to move out of the soil root zone in order to remediate the soil.

Because they move only as dissolved ions in water, salts are able to move out of the soil only to the extent that water can flow through the soil. Low permeability layers, including impermeable bedrock or a near-surface water table, effectively prevent the removal of salts by stopping flow. Drainage is discussed in more detail in Appendix E.

Chemistry

Chemical reactivity in a soil can be generally correlated with particle size. Sand and silt particles are relatively large with a small surface area to weight ratio and consist of minerals with a minimal functional electrical charge. As a result, sand and silt particles are relatively inert chemically. In contrast, organic matter (relatively stable decomposed organic matter called **humus**) and inorganic soil clays have a much larger specific surface and functional electrical charge, and are thus considered very reactive chemically.

Reactive Clay Minerals. Of the two chemically reactive materials, clay minerals are the focal point in most discussions about soil chemistry because they are much more abundant than organic matter in most soils. In this manual, chemical reactivity refers primarily to the magnitude and variety of chemical interactions between clay minerals and dissolved ions in the **soil solution.** A wide variety of clay particles with very different characteristics are found in soil. In increasing order of chemical reactivity, the crystalline clay minerals are kaolinite, iron and aluminum oxides, illite, montmorillonite (or smectite), vermiculite, and allophanes.

Highly reactive clay minerals, such as allophanes, montmorillonite, and vermiculite, have both a high negative electrical charge and substantial interior and exterior surface area. A teaspoonful of some soil clay minerals can have a surface area as large as one-fourth of a football field, whereas the surface area of the same volume of sand may equal only a few square feet. As a result, clay minerals are capable of attracting and retaining a very high number of dissolved cations (positively charged ions such as calcium, magnesium, potassium, sodium, aluminum, and hydrogen). In contrast, kaolinite clay has a very low negative charge and a much lower surface area to weight ratio, but even in kaolinite these features are much greater than in sand minerals. With respect to its own weight, the most reactive component in any soil is organic matter, but organic matter usually constitutes less than 3% of the entire weight of most surface soils.

During their formation, clay particles developed missing some positive electrical charges. Thus, clay particles have a net negative charge. Some clays, such as kaolinite, have a relatively small negative charge [~ 5 **milliequivalents** per 100 grams (**meq**/100 g) of clay, see **equivalent weight** in Appendix D]. Other clays, such as montmorillonite (80 meq/100 g) and vermiculite (110 meq/100 g), have a very large negative charge. Organic humus has the highest negative charge (generally calculated as 200 meq/100 g).

Dissolved Cations. Negative charges inherent in the solid clay particles are balanced at all times by positively charged ions (cations) which are dissolved in the soil-pore water (also referred to as soil water) and move very close to the solid clay surface. The most common of these cations in the soil are sodium (Na^{+}) in very **alkaline soils**; then calcium (Ca^{++}), magnesium (Mg^{++}), and potassium (K^{+}) in soils with a more balanced **pH**; and aluminum (Al^{+++}) and hydrogen (H^{+}) in very **acid soils**. Of these cations, only calcium, magnesium, and potassium are essential plant nutrients. Sodium is notably absent from the group of essential plant nutrients. The negatively charged clays must always be closely surrounded by an equal number of positive charges from dissolved cations.

The dissolved cations, which are very close to the clay minerals and actively balance the negative charges of the clay minerals, exist in dynamic equilibrium (exchanging interaction) with other similar dissolved cations, which are not actively balancing the negative charges of the clay. With the negative charges of the clay particles satisfied by the "adsorbed" cations, the unadsorbed cations are free to migrate in the soil solution (soil liquid water phase). Because free and adsorbed cations continually replace one another at the clay surface, they are called **exchangeable cations**.

The total number of **cation** charges which must remain adsorbed by the clay particles is called the **cation exchange capacity** (**CEC**). Then, if the entire mass of a soil were composed completely of montmorillonite clay, it would have a CEC equal to that of montmorillonite clay (about 80 meq/100 g). However, whole soils rarely have a charge as high as their individual clay minerals or organic matter because some sand and silt are almost always present as well, and these particles have no CEC. As a result, typical whole soils usually have a CEC ranging from 5 to 35 meq/100 g.

The exchangeable cations compete to a predictable extent to occupy "exchange sites" adjacent to the clay particles. Dissolved cations with the highest electrical charge and which are surrounded with the least number of water molecules have the highest charge density and are, therefore, best able to get close to the clay particles. Because of their high charge density, aluminum, calcium, and magnesium cations are the cations which typically spend the most time adsorbed on the cation exchange sites.

Sodium cations have the opposite characteristics. Because it has a single positive charge, and tends to be surrounded with a substantial amount of water, sodium can be competitive only if it can overwhelm the other adsorbed cations by sheer numbers. In most cases, a saltwater spill is easily capable of providing such overwhelming numbers of sodium cations.

Because of its low **adsorption** strength, sodium is also the cation most easily displaced from cation exchange sites by other types of cations. For the same reason, sodium is also the most mobile cation in soil water and can move almost as fast as the water itself.

Anions. **Anions** (negatively charged particles) also exist in the soil solution. Examples are chloride (Cl^-), sulfate (SO_4^{--}), bicarbonate (HCO_3^-), carbonate (CO_3^{--}), and nitrate (NO_3^-). Soils have a modest **anion exchange capacity** compared to the CEC. As a result, these anions are very mobile in the soil and like sodium can move almost as fast as soil water can move.

pH. The degree of soil acidity (pH) controls many functions in the soil. The lower the pH, the greater the acidity, or concentration of hydrogen ions (H^+). Because pH is a logarithmic expression, each pH unit represents a change of an order of magnitude (factor of 10). For example, a soil with a pH of 6 has ten times the concentration of hydrogen ions as a soil with a pH of 7. In terms of pH, the corollary to acidity is alkalinity which represents the concentration of hydroxide ions (OH^-), although alkalinity is also used to relate to the acid neutralizing capacity of bicarbonate and carbonate ions. In similar manner, dissolved aluminum also contributes to acidity. Aluminum, which begins to appreciably dissolve at a pH less than 5.5, is sufficiently strong that each aluminum cation (Al^{+++}) can split three water molecules (process of hydrolysis) into three hydrogen ions (H^+) and three hydroxide (or hydroxyl) ions (OH^-). Over time, each aluminum ion can then combine with the three hydroxyl ions leaving the three remaining hydrogen ions to further decrease the pH of the soil solution. Aluminum toxicity which is caused by this process is a major problem in many soils in humid climates.

The pH of most soil ranges from about 5 to 8, but the pH of some soils is as low as 2 or as high as 11. The pH of a traditional healthy soil ranges from 5.5 to 8.5.

Plant Nutrients. The soil solution (liquid phase of a soil) dissolves and allows other plant nutrients to move toward plant roots. In order for a plant to survive it must have an appropriate amount of each of the plant nutrients listed in Table 3-2. All plant nutrients taken up by plant roots are either cations or anions. The overwhelming numbers of sodium and chloride ions present, and the **leaching** effect of the liquid spilled, often result in deficiencies and/or imbalance of nutrients. For some plant nutrients there is a fine line between too much (toxicity) and too little (deficiency) (Figure 3-6). The **micronutrient** boron (B) is of particular interest in remediating produced water spills. Although a minor constituent in both produced waters and natural soils, boron may be present in sufficient quantities in produced water to create boron toxicity conditions in soil after a spill. Because of the control it exerts on solubility, the availability of many of these nutrients, including boron, is determined by the pH of the soil (Figure 3-7).

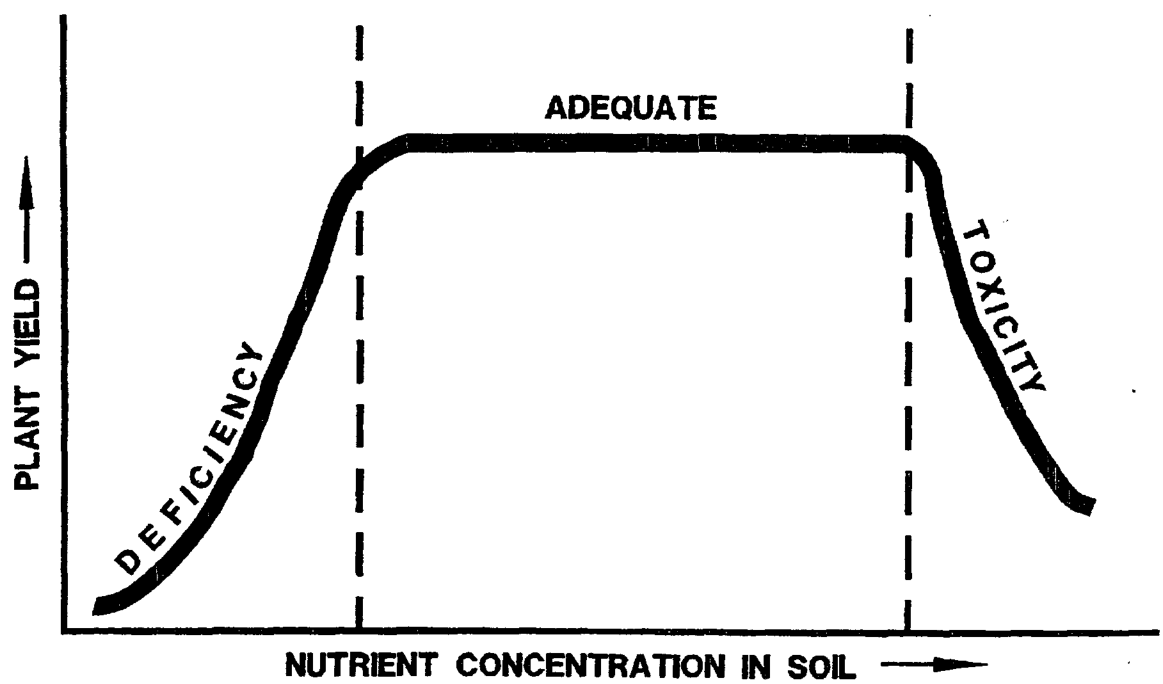
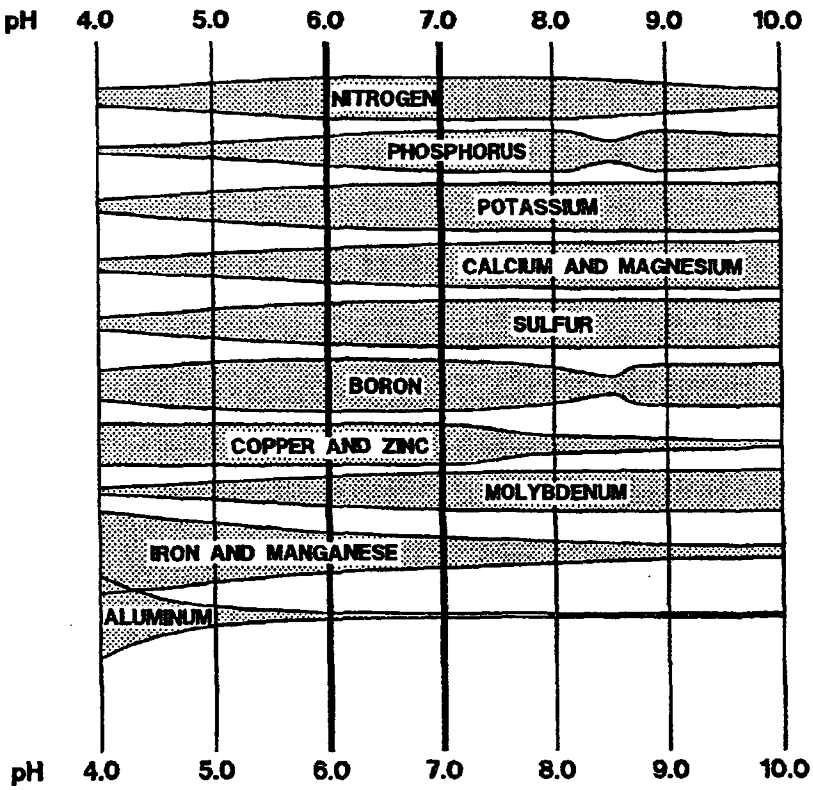


Figure 3-6. Relationship of Nutrient Concentrations, Deficiencies, and Toxicities in Plants.



NOTE: Aluminum is not a plant nutrient

Figure 3-7. Effect of Soil pH on Plant Nutrient Availability (Plaster, 1985). (Reproduced by permission. Soil Science and Management, By Plaster. Delmar Publishers, Albany, New York, © 1985)

CLIMATE

To a great extent, climate determines the type of soil present. Climate dictates the frequency, duration, and quantity of precipitation and evaporation, as well as extremes and duration of temperature and wind.

These factors have a major impact on the fate and transport of salts in the soil. Most chemical **reactions** in the soil occur at a faster rate with increasing temperature. After a rainfall, a portion of the rainwater percolates downward through the soil dissolving and carrying soluble salts with it. During evaporative periods, soil-pore water reverses course and moves back upward through the soil bringing dissolved salts back to the surface. Since salts do not evaporate, they continue to concentrate at the soil surface during evaporation of soil water.

Table 3-2. Plant Nutrients.

Name	Symbol	Nutrient Form	Ion Name
Carbon	C	—	—
Hydrogen	H	H^+ (not used by plants in this form)	
Oxygen	O	—	—
Primary Macronutrients			
Nitrogen	N	NO_3^-, NH_4^+	Nitrate, ammonium
Phosphorus	P	HPO_4^{-2}, $H_2PO_4^-$	Orthophosphates
Potassium	K	K^+	—
Secondary Macronutrients			
Calcium	Ca	Ca^{+2}	—
Magnesium	Mg	Mg^{+2}	—
Sulfur	S	SO_4^{-2}	Sulfate
Micronutrients			
Boron	B	H_3BO_3, $B(OH)_4$	Boric acid, hydrated borate
Copper	Cu	Cu^{+2}	—
Chlorine	Cl	Cl^-	Chloride
Iron	Fe	Fe^{+2}, Fe^{+3}	Ferrous, ferric
Manganese	Mn	Mn^{+2}	Manganous
Molybdenum	Mo	MoO_4^{-2}	Molybdate
Zinc	Zn	Zn^{+2}	

After a spill, climatic factors will influence the selection of a remediation technology, including the types of vegetation which can be established and maintained.

WATER

A basic understanding of water is a prerequisite for understanding the fate and transport of salts in the soil. Water that infiltrates the ground or rises from the water table (due to capillary forces) provides soil moisture. The types of water most important to salt mobility and remediation are applied surface water, groundwater, and soil-pore water.

After a rainfall or irrigation event, water moves downward through the soil and displaces some of the air in the soil pores. With sufficient applied water, soil pores can become saturated with water. Water movement in a soil saturated with water is called saturated flow.

The main impediments to saturated flow are the size of pores, the total cross sectional area of pores through which the water can move, and the circuitous route the water must take around physical obstacles such as sand, silt, clay particles, and organic matter. In addition to gravity, saturated flow water moves in response to additional positive pressure from an applied hydraulic head (e.g., water ponded over a soil).

Gravity is typically effective in moving soil water only within a few days of saturation. After that time, gravity will have drained as much water as possible from the soil. The remainder is retained in the soil due to capillary action. This moist-but-not-saturated condition is called **field capacity** and represents the greatest amount of plant-available water the soil can retain. At field capacity, water is held in pores at about 0.3 atmospheres of tension (a very slightly negative pressure). This moisture content is called field capacity because: (1) gravity drainage has ceased, and (2) most plants cannot take up water from the soil unless there is also some air in the soil pores.

When some soil pores contain air, the soil is said to be in an unsaturated moisture condition, and water moves in accordance with different forces. In a dry soil, water moves toward and is retained in the smallest and driest capillary pores because they exert the most capillary tension. This is an extremely strong force and dominates all other forces acting on soil water. When very dry and very small, capillary pores and bare soil particle surfaces can exert tension on water which is more than 10,000 times greater than atmospheric pressure. This hygroscopic water is bound so tightly that it cannot move. When slightly more moist, water is still very closely drawn toward particle surfaces and capillary pores and the water is capable of moving very slowly. As the soil becomes increasingly moist, soil water will try to distribute itself in the soil such that there is equal tension in all directions.

Other factors also influence the movement of soil water in unsaturated conditions. Evaporation which is also operative in saturated conditions after a rain, **transpiration** (water uptake and release to the atmosphere by plants), and **osmotic** forces exerted by dissolved constituents (including salts) will begin to influence noticeably the **unsaturated flow** of water after the strongest capillary forces are satisfied. In order to overcome the osmotic force that draws water toward salts, a plant must devote a greater proportion of energy to creating its own internal counteracting osmotic potential.

As evaporation removes water from soil pores near the soil surface, water carrying dissolved constituents migrates upward to replace the evaporated water. As salts concentrate near the soil surface, the osmotic potential further increases and exerts even more force on water to move upward. This is especially problematic if the water table is within about 6 ft of the surface because this represents an unlimited supply of water which can carry salts upward with it during evaporative periods.

Most plants are able to pull water out of the soil with as much as 15 atmospheres of tension. When all soil water is held beyond a tension of 15 atmospheres (the permanent **wilting point**), most plants begin to die due to drought stress. However, the soil still contains substantial water at the permanent wilting point—it is just held so tightly that plants are unable to extract it. Because plants are utilizing internal osmotic pressure to draw water into roots, they must also work against the increased salt concentrations in the soil solution. As a result, plants can experience drought stress at soil **moisture tensions** much less than 15 atmospheres in salty soils.

The relationship among moisture saturation, field capacity, wilt point, and dryness are illustrated in Figure 3-8. This figure shows that after a soaking rain, loam, silt loam, and clay loam soils will have the greatest plant-available moisture (between 0.3 and 15 atmospheres of tension), clays and sandy loam soils will have a moderate amount of moisture, and sands will have the least amount of moisture.

Loam and silt loam soils tend to have the best distribution of pore sizes (ranging from micro- to macropores) between particles and aggregates. Clay soils often have an abundance of micropores but minimal macropores. As a result, clay soils often retain a substantial amount of water, but much of it is held under too much tension for plants to utilize. Most pores in very sandy soils are so large that very little water is retained in the soil after a rain, and most of it quickly drains away before plants can utilize it. Maintaining an effective pore size distribution or improving a detrimental pore size distribution is a primary objective in remediating salt-affected soils. It is much easier and less costly to maintain an effective pore size distribution than to attempt to alter a detrimental pore size distribution.

The typical moisture zones that occur in soil are shown in Figure 3-9. The vadose zone is where air and water occur simultaneously below the soil surface. Only water actually below the water table (within the saturated zone after gravity drainage) is called groundwater, by convention. Water above this zone is called vadose water or **unsaturated zone** water. Capillary pores

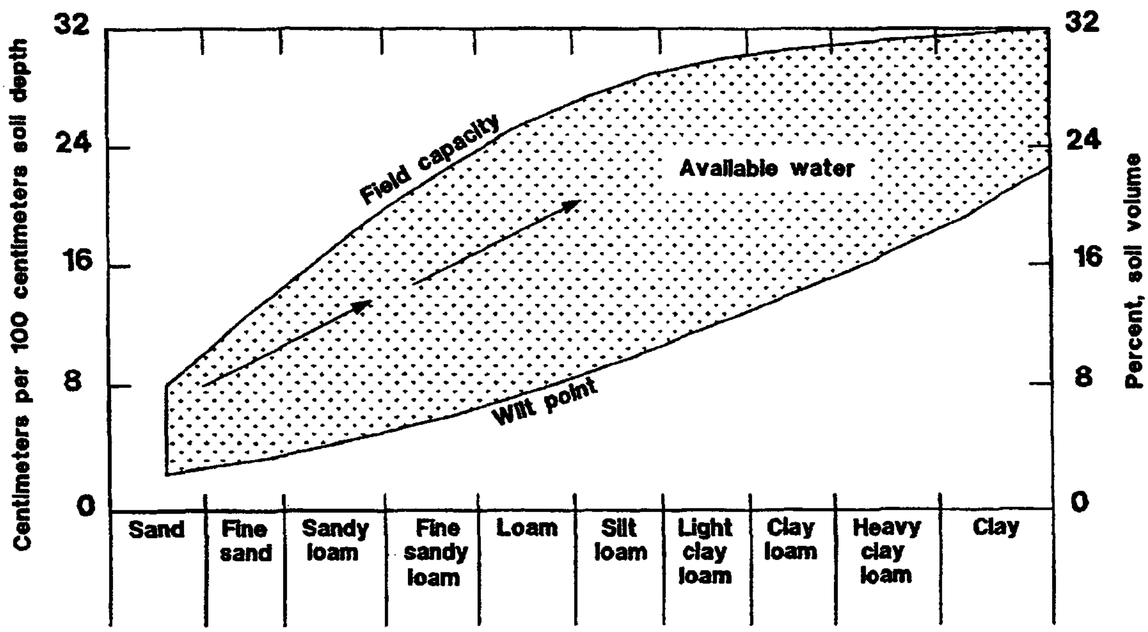


Figure 3-8. Soil Moisture Relationships (Foth, 1984).
(FUNDAMENTALS OF SOIL SCIENCE, H. D. Foth, 1984.
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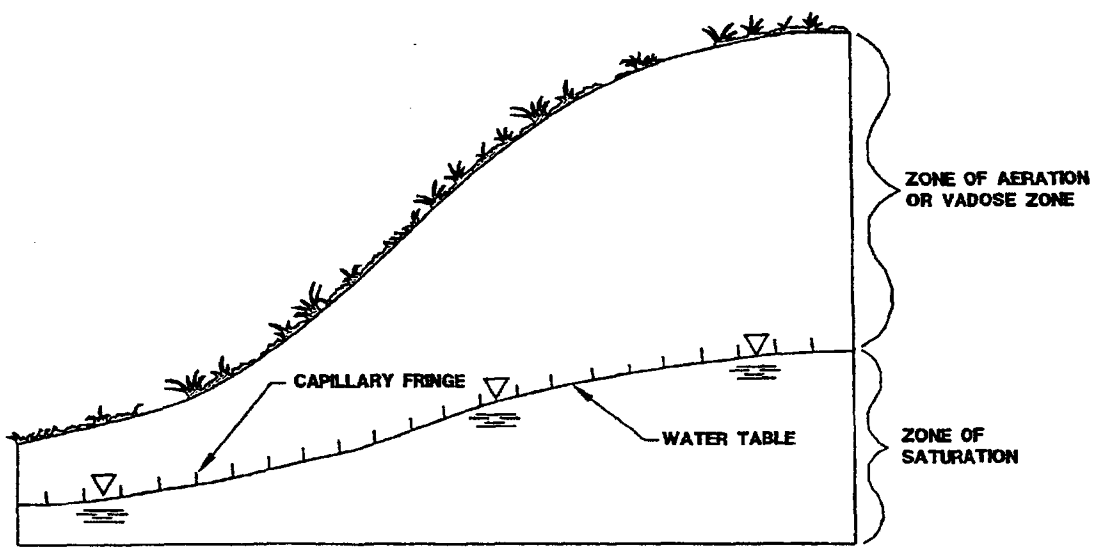


Figure 3-9. Soil Moisture Zones.

exerting tension near the bottom of the vadose zone can pull water from the groundwater to about 1 to 2 ft above the actual water table into a zone called the **capillary fringe**.

Where saltwater spills occur, efforts should be made to minimize surface migration of salts toward surface water and subsurface migration into nearby sediments. Except in very porous soils, surface water generally flows more rapidly than groundwater.

Flow rates of surface water are variable and often dependent on natural or manmade settings. Surface runoff, direct flow into streams, and even dry creek beds and ditches may become avenues for rapid movement of salts.

Groundwater typically moves much slower than surface water because it must continuously pass through a porous media. However, groundwater moves quickly through fractured bedrock and sandy and gravely media. Groundwater can move to some extent in silty zones, and it barely moves at all in clayey materials. However, even clay is a slightly porous media and over time, water will migrate through it.

LAND USE CAPABILITY

Each soil and type of terrain has a natural capability to serve certain uses. As noted above, the variety of soils on which spills can occur is substantial. Even without a spill, some soils would have substantial land use limitations due to natural factors.

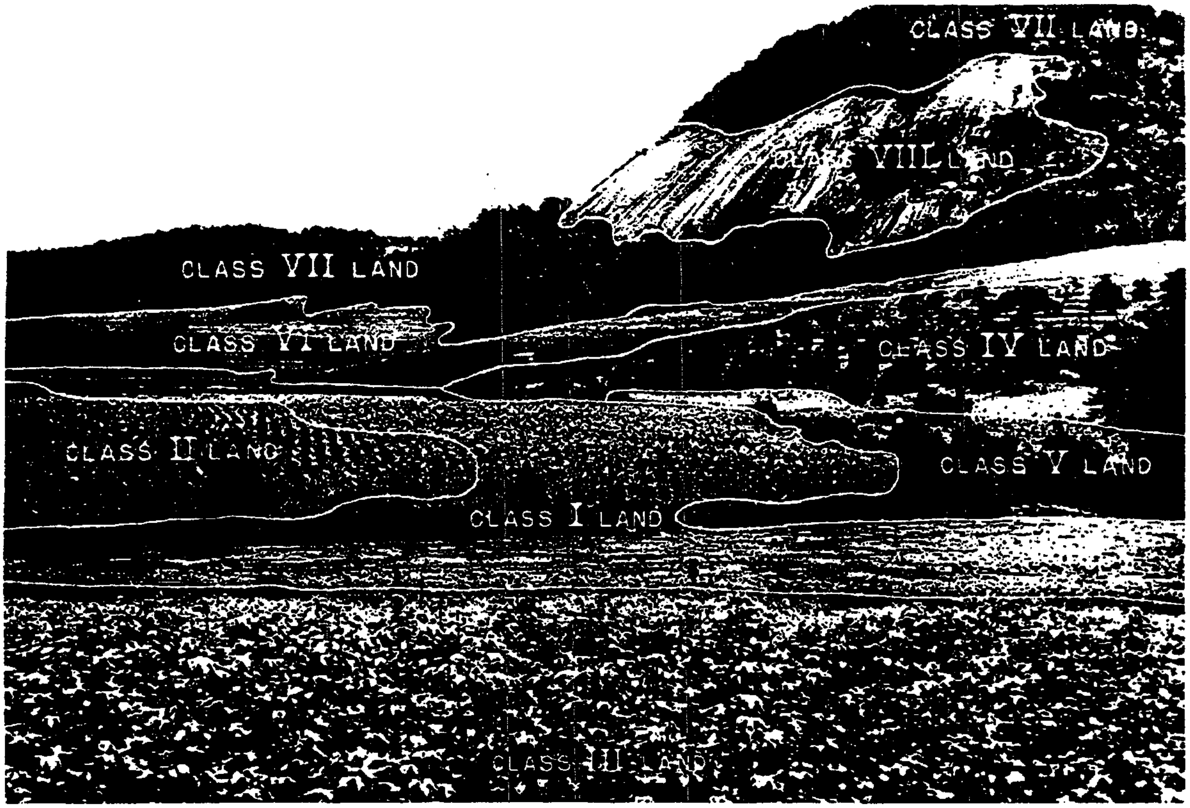
Land capability classifications were developed by the USDA-NRCS to show the ways in which a soil could be acceptably used, and to alert landowners about uses which were impractical due to soil limitations. Climate, erosion potential, slope, and drainage are important factors in land use classifications. The eight land use capability classifications are described in Table 3-3 and portrayed in Figure 3-10.

Land resources can be further categorized by site index. Categories include saltwater wetlands, brackish-water wetlands, freshwater wetlands, uplands, and mountains. Subcategories of uplands may include woodland, prairie, farmland, residential, industrial, and recreational. These categories have important implications regarding the successful remediation of salts and hydrocarbons.

Table 3-3. Land Capability Classification.

Land Capability Class	General Description and Limitations
Suited for Cultivation	
I	Few limitations that restrict its use; no subclasses
II	Some limitations that reduce the choice of plants or require moderate conservation practices
III	Severe limitations that reduce the choice of plants or require special conservation practices, or both
IV	Very severe limitations that restrict the choice of plants or require very careful management, or both
Not Suited for Cultivation (except by costly reclamation)	
V	Little or no erosion hazard but has other limitations (impractical to remove) that restrict its use largely to pastureland, rangeland, woodland, or wildlife habitat
VI	Severe limitations that make it generally unsuited to cultivation and restrict its use largely to pastureland, rangeland, woodland, or wildlife habitat
VII	Very severe limitations that make it unsuited to cultivation and restrict its use largely to grazing, woodland, or wildlife habitat
VIII	Limitations that preclude its use for commercial plant production and restrict its use to recreation, wildlife habitat, water supply, or aesthetic purposes

Source: Klingebiel and Montgomery, 1966.
Note: Except for Class I land, the following subclasses are recognized in which the dominant limitations for agricultural use are the result of soil or climate: *(e) erosion*, based on susceptibility to erosion or past damage; *(w) excess water*, based on poor soil drainage, wetness, high water table, or overflow; *(s) soil limitations within the rooting zone*, based on shallowness, stones, low water-holding capacity, low fertility, salinity, or sodium; and *(c) climate*, based on temperature extremes or lack of water.



Land Capability Classes			
Suitable for Cultivation		No Cultivation - Pasture, Hay, Woodland, and Wildlife	
I	Required good soil management practices only	V	No restrictions in use
II	Moderate conservation practices necessary	VI	Moderate restrictions in use
III	Intensive conservation practices necessary	VII	Severe restrictions in use
IV	Perennial vegetation - infrequent cultivation	VIII	Best suited for wildlife and recreation

Figure 3-10. Land Capability Classes (Courtesy USDA).

REVIEW OF SECTION 3

- Environmental factors of importance to the remediation of a salt spill include soil physical, chemical, and biotic components; climate, especially rainfall and evaporation conditions; water movement in a soil, including the unsaturated zone and depth to the water table; and land use capability which provides a gross evaluation of the potential productivity of a soil and its ability to respond to remediation treatments.

- The four physical components of soil are solid inorganic particles, organic material, air, and water. These components, respectively, occupy about 45%, 5%, 25%, and 25% of the volume of a typical soil.

- Soil texture is the distribution of sand, silt, and clay. Various combinations of sand, silt, and clay result in 12 textural classes which can be simplified to coarse, medium, and fine textural groups.

- The most chemically reactive components in a soil are clays and organic matter. These solid materials have a net negative charge which is balanced by dissolved cations, primarily calcium, magnesium, sodium, and potassium.

- The CEC is a measure of the total number of negative charges in the solid phase of a soil. Organic matter and some soil clays (smectite and vermiculite) have a very high CEC, while others (kaolinite and illite) have a much lower CEC.

- The three most common soil horizons and their typical features are:

- Horizon A	Topsoil	Most biotically active
- Horizon B	Upper subsoil	Most clay
- Horizon C	Lower subsoil	Least developed; most like parent material

- Excessive erosion results in loss of topsoil, the possible need to reshape land, and the possible need to import or rebuild topsoil.

- The ability of a soil to drain internally depends on the amount of water present, the thickness of soil above bedrock, soil texture, pore size distribution, the depth of the water table, soil chemical factors, and the presence of low permeability layers of soil.

Section 4

ENVIRONMENTAL EFFECTS OF SPILLS AT EXPLORATION AND PRODUCTION SITES

Saltwater spills affect the environment as a result of the total salts released and the total sodium concentration, which cause soils to become **saline** and **sodic**, respectively. Although the total salts concentration is of greatest consequence to plants, the proportional sodium content is of the greatest consequence to the soil.

This section discusses the negative impact that total salts and sodium have on soil. Produced water may also have associated hydrocarbons, which are also discussed briefly.

EFFECTS OF SALT SPILLS

Salt spills can cause substantial adverse effects to soils and plants, and can negatively affect the quality of surface water and groundwater. The two major problematic components of salt spills are the total salts concentration, and the presence of sodium.

There are several easily visible symptoms of a salt spill. The most obvious is the wilting or death of plants. Surface **crusts** will also commonly appear at the soil surface, and newly germinated plants will have difficulty sprouting through these crusts. Salt crystals, which form at the soil surface during evaporative conditions, are usually a bright white. If the pH is very high and sufficient organic matter is present, black films of dissolved organic matter can also be seen at the soil surface.

Saline Soils and Osmotic Potential

The initial detrimental effect of a salt spill is due to an excess concentration of total soluble salts. If there is sufficient water present, soil salts will dissolve into positively charged cations and negatively charged anions. When battery-powered electrodes are placed into a solution, the amount of current which develops is related to the total concentration of all dissolved cations and anions. The term used to express the magnitude of the total dissolved salt concentration in the soil solution is salinity, and the most common soil measurement of salinity is called **electrical conductivity** (EC). Electrical conductivity has long been expressed in units of millimhos per centimeter (**mmhos/cm**), but the more currently correct numerically equivalent unit is deciSiemens per meter (**dS/m**).

A somewhat similar sounding term often confused with salinity is TDS. Total dissolved solids is a measure of all dissolved constituents regardless of the presence of an electrical charge. Even though a very fine filter (0.45 µm) is used to remove undissolved solids from a water sample prior to measurement of TDS, very small solid particles called **colloids** pass through the filter and are measured as part of TDS. Total dissolved solids is measured in milligrams of dissolved constituents per liter of solution (mg/L). Total dissolved solids usually correlate with EC since most dissolved solids in soil solutions are cations or anions.

Salinity is correlated to osmotic potential which is the primary cause of plant damage and death. Osmotic potential is the force which causes dissolved constituents to try to retain water molecules. In effect, the salts in the soil compete with the plants for water molecules. The presence of excessive salts in soils causes plants prematurely to go into drought stress even though substantial water may be present in the soil. Osmotic potential is a direct result of the combined concentrations of dissolved sodium, calcium, potassium, and magnesium cations, and chloride, sulfate, bicarbonate, and carbonate anions which are common constituents in salty water. There are also a number of other less common cations and anions in salty water which contribute to osmotic potential. Other dissolved species which are not ionic also contribute to osmotic potential. As a result, osmotic potential is also correlated with TDS.

<u>Sodic Soils and Soil Dispersion</u>

Soil dispersion, the second major problem caused by saltwater spills, is due to the dispersive effect sodium has on soil clays. Sodium is the predominant cation in most produced water. Unless the soil salinity is also high, dispersion will occur in soils having excess sodium. Soils containing excess sodium are called sodic soils. Dispersion is a detrimental electro-chemically induced process which causes soil clay particles to repel each other, physically move apart, and clog soil pores.

Dispersion in soil is the reverse process to aggregation. Although other factors are also involved, aggregation occurs when electrical neutrality is attained very close to the clay particles. Electrical neutrality for each clay particle occurs in the soil solution at the distance from the clay particle where the number of positive dissolved cation charges exactly balances the number of negative charges. When sodium is not present in excess, the other dissolved cations common in soil are able to balance the negative charge very close to the surface of the clay particles. In this condition, the clay particles do not sense each other's negativity and are drawn together (aggregated) by van der Waals forces of attraction.

Aggregation in soils is beneficial because when soil particles "clump" together they leave relatively large vacated areas in the soil called macropores. As a result, water and air can pass most easily through a soil when it is aggregated and has abundant macropores.

Dispersion is induced when the density of dissolved cation charges around the negatively charged solid clay particles is very low. In this event, the electrical balance does not occur very close to the surface of the clay particles. Dispersion is caused under these conditions because the dissolved sodium cation has only a single positive electrical charge and tends to be hydrated by a substantial amount of water, if available. This results in a very low charge density (small charge occupying a large volume of space). Dispersion occurs because the electrical balance of two proximal clay particles is not satisfied in the space between them. The clay particles repel because they sense a similarly negative particle instead of sensing a neutral particle which would be attracted by van der Waals forces. The force of repulsion is sufficiently strong that the clays physically move into the only place they can go which is into soil macropores.

Dispersion does not occur when the soil is still saline because there is less water available for each dissolved sodium cation. As a result, the sodium cations are closer together and the charge density is high enough to resist dispersion. As a general rule in soils, dispersion can be expected to occur when more than 15% of the cation exchange sites of clay particles are occupied by sodium and the total concentration of salts (salinity, or EC) of the soil solution is simultaneously less than 4 mmhos/cm (nonsaline).

After a saltwater spill, the salinity keeps the soil aggregated until it rains or other freshwater is applied. Soil dispersion occurs only after freshwater has been applied to the soil after a spill in which sodium was a major constituent. The abundance of sodium displaces other, more beneficial cations from the cation exchange sites. When freshwater is applied after a saltwater spill, it dilutes the overall salt concentration and also leaches cations not adsorbed on cation exchange sites downward through the soil. A dilute solution of predominantly sodium cations remains in the upper part of the soil, and sodium comprises more (much more) than 15% of adsorbed cations on the clay cation exchange sites. The result is soil dispersion.

Chemical remediation can be used to reclaim **dispersed soils**, but the process is often very slow. The chemical remediation process involves re-aggregating the soil by applying materials which can dissolve in water and supply cations with a high effective charge density (e.g., calcium and magnesium) compared to sodium. The dissolved chemical amendment cations are more attracted to the clay than sodium and easily displace the sodium from the cation exchange sites. The clay particles then re-aggregate creating new macropores, and the displaced sodium is free to be leached out of the soil.

Clay dispersion is actually desirable in some circumstances. For instance, freshwater is often added to sodium bentonite clay (a type of natural soil clay similar to montmorillonite) to make a dispersed slurry. The dispersed slurry is used to seal leaks in geologic media by virtue of the fact that it disperses into the pores of the geologic media and seals them.

The appearance of a dispersed soil differs if it is wet or dry. When wet, a dispersed soil has a "puddled" appearance. Instead of infiltrating the soil, water tends to remain ponded on the surface of a puddled soil. The soil also erodes easily because individual clay particles are much more easily dislodged from the soil and transported by surface runoff. If the soil is also dispersed below the soil surface, there is also minimal permeability in the soil interior. Among other things, this greatly decreases the rate at which salts and sodium can be leached from the soil.

Soil crusts are usually apparent on the surface of a dispersed soil after the soil has dried. On a micro scale, most clay minerals resemble sheets of plywood. While a dispersed soil is drying after being puddled, the dispersed clay minerals settle with flat sides parallel to the ground. The result is thin cohesive wafers of soil a few millimeters thick (and thicker) called crusts. These crusts substantially decrease the rate at which air can move in and out of the soil. Soil crusts are also frequently too heavy and too strong to allow seedling emergence to occur.

Two soils analyses are used to classify soil conditions with regard to osmotic potential and potential dispersivity. Osmotic potential is most commonly discussed in terms of soil salinity, which is measured by EC. Potential dispersive conditions are most commonly discussed in terms of sodicity which is determined by the **exchangeable sodium percentage (ESP)**. Analytical procedures for measuring EC and ESP are provided in Appendix J. The ESP is assessed by measuring the proportion of sodium adsorbed on soil clay cation exchange sites as follows:

$$ESP = \frac{\text{Exchangeable sodium cations (meq/100 g soil)}}{\text{Cation exchange capacity of soil (meq/100 g soil)}} \times 100$$

(Equation 4-1)

Categorization of Soil Salinity and Sodicity Levels

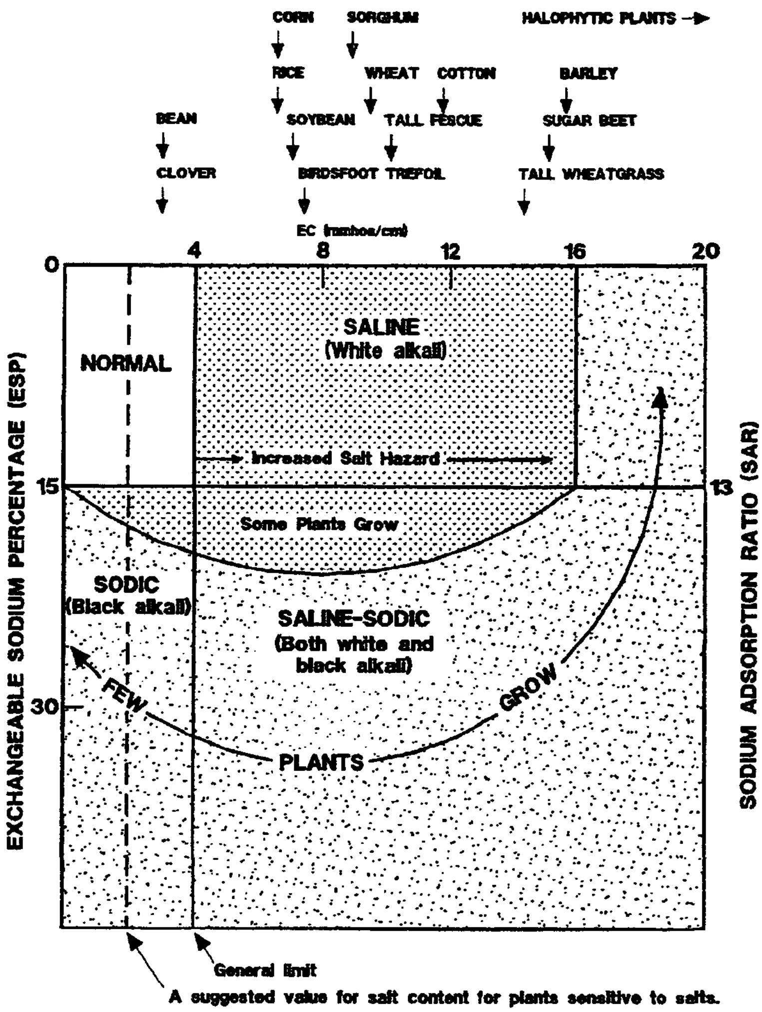
Categorization of salinity and sodicity levels in soils has been developed over many years in response to agricultural needs for crop production, and the occurrence of vast acreages of natural and human-induced saline and sodic soils. Table 4-1 summarizes soil and plant responses to various ranges of salinity and sodicity in the soil solution. The tolerance of various plants to various combinations of salinity and ESP is also illustrated in Figure 4-1. Further discussion about these data can be found in Richards (1954) and Smedema and Rycroft (1983).

Table 4-1. Osmotic and Dispersion Problems in Soils.

Potential Problem	Soil Parameter	Units	Importance
Osmotic Stress	Electrical Conductivity (EC)	mmhos/cm	Ability of soil water to transmit electrical current indicative of salinity
			Osmotic potential indicated by EC increases as salinity increases
			Increased osmotic potential inhibits plant growth
Soil Dispersion	Exchangeable Sodium Percentage (ESP)	%	Proportion of sodium adsorbed on clay cation exchange sites indicative of sodicity
			Potential for dispersion indicated by ESP increases as sodicity increases
			Soil dispersion destroys soil structure, inhibits drainage and vapor exchange, and inhibits plant growth

Soil Condition	Soil Classification	Soil and Plant[a] Response
EC >4 ESP <15	Saline-Nonsodic	Osmotic stress; well aggregated
EC >4 ESP >15	Saline-Sodic	Osmotic stress; potential dispersion after rain
EC <4 ESP >15	Nonsaline-Sodic	No osmotic stress; dispersed
EC <4 ESP <15	Nonsaline-Nonsodic (preferred)	No osmotic stress; well aggregated

a Plant response to EC ranges for most agricultural crops. Many plants can tolerate and thrive in much higher levels of salinity.



Note: Each crop listed at the top of the figure (with the exception of halophytic plants) is placed with its first letter and an arrow at the approximate EC value at which 10% yield reduction occurs.

Figure 4-1. Plant Growth Response to Salinity and Sodicity (adapted from Donahue, *et al.*, 1983).

The most problematic detrimental effect of a salt spill often occurs when rain or freshwater from irrigation is allowed to enter the soil before an appropriate chemical amendment has been applied. Immediately after a saltwater spill, most soils can be expected to become **saline-sodic.** The high salinity helps keep the soil aggregated; this is beneficial during remediation operations involving the application of chemical amendments to the soil. Because a major goal of spill site restoration is to leach excess salts downward out of the root zone, it is important to displace sodium with a chemical amendment before the salinity is decreased by application of rain or irrigation water. Once a soil becomes dispersed, it is very difficult to distribute chemical amendments effectively in the soil, and the cost of remediation is often increased. Once the chemical amendments have been able to interact with soil clays, leaching with freshwater may be considered among the available remediation options.

Saline, Sodic, and Saline-Sodic Soils

Naturally occurring saline, sodic, and/or saline-sodic soils can be found in dry climates, locations with a near-surface water table, depressional areas, saline-seep areas, and along coastal zones. An extreme example of naturally salt-affected soils would be soils bordering the Bonneville salt flats in western Utah.

Soils in climates having substantial evaporation periods, and where the water table lies within a few feet of the soil surface, are especially susceptible to development of high salinity conditions. High soil salinity can develop in such soils even if the groundwater is of relatively low salinity because of the long-term upward migration of even low concentrations of salts over time.

Some human activities have inadvertently created salt-affected soils in some locations. Examples are irrigation with poor quality water and increased water table elevation due to irrigation or clearing of vegetation on adjacent land. Irrigation with poor quality water (high salinity or high sodium) results in frequent applications of salts to soils and may also increase the elevation of a water table. Vegetation consumes considerable soil water which is then released into the atmosphere as a vapor during transpiration. When this vegetation is removed from the land, the water table may be the recipient of much of the water which had previously been consumed by the removed vegetation. There are many instances where removal of vegetation has resulted in formation of salt-affected soils.

Salt-affected soils can also form on hillsides and depressions due to subsurface water movement and landscape position. An illustration of a saline-seep condition is shown in Figure 4-2. Water table elevations typically follow the contour of the surface soil but with less elevational change. As a result, the water table is commonly closer to the soil surface along the side slope or at the bottom of the slope. As rainwater leaches salts into the water table in upslope areas, it connects with and moves as groundwater to lower elevations. When the water table becomes sufficiently close to the surface for evaporation to cause substantial upward migration of groundwater at the side or bottom of the hill, salts will begin to concentrate in the surface soil. Natural and human-caused saline-seep conditions are common in the northern prairie states. A common practice for minimizing and even halting salt buildup in these soils is to plant vegetation which consumes large quantities of water. The consumption of water by this vegetation causes the water table elevation to decrease such that water and salts from groundwater are no longer drawn to the soil surface.

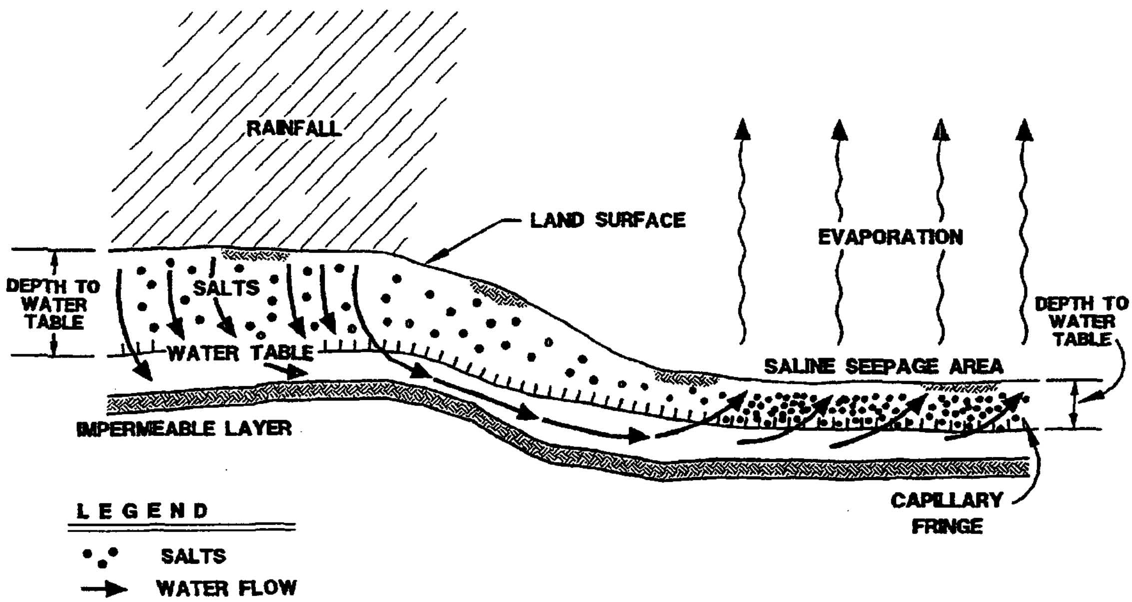


Figure 4-2. Saline-Seep Condition.

Relationships Among Salt Parameters

There are two additional important relationships among salt parameters. These include the **sodium adsorption ratio** (SAR) as it relates to the ESP, and soil pH as it relates to the ESP.

Sodium Adsorption Ratio. The SAR is a measure of the relative competitiveness of sodium versus calcium plus magnesium for adsorption onto clay cation exchange sites. It is calculated from the concentrations of sodium, calcium, and magnesium in the soil solution and irrigation water. The SAR calculation requires the ion concentrations to be expressed in milliequivalents per liter of solution (meq/L). The final calculated result and relative competitiveness are expressed as an essentially unitless ratio. The SAR relationship is calculated as follows:

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

(Equation 4-2)

When the sodium, calcium, and magnesium cations adsorbed on the soil clay cation exchange sites are at equilibrium with the sodium, calcium, and magnesium cations in the more remote soil solution, there is a predictable relationship between the SAR and the ESP. In fact, the SAR was originally intended for use in predicting the ESP which would develop after using various qualities of irrigation water.

Exchangeable Sodium Percentage. The approximate relationship between the ESP and the SAR at equilibrium is presented in a nomogram in Richards (1954) and can be calculated as follows:

$$ESP = [100(-0.0126 + 0.01475\ SAR)]/[1 + (-0.0126 + 0.01475\ SAR)]$$

(Equation 4-3)

There are two drawbacks to overdependence on the SAR. The first is that it takes an indeterminate amount of time for a soil to achieve equilibrium. A soil is certainly not at equilibrium anytime soon after a saltwater spill. The second is that the sodium adsorption is merely a ratio of dissolved cations, and is completely unrelated to the total amount of sodium in the soil or the CEC of the soil. Calculation of the quantity of chemical amendments required is determined by the total amount of sodium which must be removed from the soil.

In contrast, the more useful ESP calculation is determined by dividing the total number of adsorbed sodium ions by the CEC of the soil, and multiplying the result by 100 as shown in Equation 4-1. This calculation indicates the percent of cation exchange sites occupied by sodium. The ESP cannot be calculated without also determining the CEC because this measurement is required in the denominator of the calculation. As a result, all of the data required for determining the quantity of chemical amendment required are provided in conjunction with calculation of the ESP.

Relationship of pH to ESP. There is also a somewhat dependable relationship between the soil pH and the ESP. In general, sodic soils have a pH above 8.5. The pH of some sodic soils has been measured above 11. If a soil has a pH between about 7.8 and 8.4, there is a high probability that there is abundant calcium and magnesium carbonate (together referred to as carbonates) in the soil. As noted in Section 3, a pH above 8.5 can induce deficiencies of several micronutrients.

Effect of Moisture Content. The moisture content (weight of soil moisture divided by dry weight of soil) at which the EC and SAR (also pH and soluble anions and cations) are measured is very important. The ratio of less soluble salts (such as calcium and magnesium salts) to more soluble salts (such as sodium salts) increases with increasing moisture content. The primary objective of the EC, SAR, and pH calculations is to relate to plant needs. The saturation percentage represents the maximum moisture content at which dissolved salts (nutrients) are available to plants, and at which enough soil water can be extracted from the soil to allow measurement of salts. The saturation percentage is achieved when all soil pores are completely filled with water, but there is no water present in excess of that amount. The method for preparing a **saturated paste** is provided in Appendices G and J. After the water has equilibrated with the soil (several hours), it is extracted from the soil under a vacuum (or sometimes positive pressure). The liquid extracted is called the **saturated paste extract**, and pH, EC, soluble cations (Ca, Mg, Na, and K), and soluble anions (CO_3, HCO_3, Cl, and SO_4) are measured in this liquid.

Preparing a saturated paste and collection of the liquid saturated paste extract requires more effort than other moisture contents (e.g., 1:1 or 1:5 soil to moisture ratios). Preparing a saturated paste extract can be especially problematic for sodic heavy clay, high **shrink-swell** soils because the bulk soil volume increases substantially as the water-imbibing soil swells up. In actuality, the pore volume increases as more water is added. As a result, some analytical laboratories are reluctant to go to the trouble of generating data at this moisture content. However, data reported at other moisture contents will incorrectly represent the saturated paste extract EC and SAR due to different solubilities of the various salts involved. It is therefore important that the analytical laboratory used be well trained and experienced in handling a variety of soils.

Plant Responses to Salts in Soils

Within the Plant Kingdom there are plants which are extremely sensitive to even low levels of salinity, whereas other plants are very tolerant to high levels of salinity. Plant tolerance to salinity is largely genetic. To some extent, mature plants are able to adapt to gradual increases in salt levels, but newly germinated plants are less capable of adapting to such changes.

Tolerance to Salinity, Sodicity, and Chloride. Until recently, most literature on salt-affected soils pertained predominantly to rainwater or freshwater irrigated agricultural crops. A general response scale for common agricultural crop response to salinity levels is provided in Table 4-2, and a list of the salinity tolerance (50% decrease in yield expected) of a number of common crops is provided in Table 4-3. More detailed plant salt-tolerance data are provided in Appendix F.

Table 4-2. General Crop Response to Soil Salinity.

Soil Salinity Class	Salinity (mmhos/cm)	Plant Response
Nonsaline	0–2	Salinity effects negligible
Slightly Saline	2–4	Decreased yields in very sensitive crops
Moderately Saline	4–8	Decreased yields in many crops
Strongly Saline	8–16	Only tolerant crops yield satisfactorily
Very Strongly Saline	More than 16	Very few crops yield satisfactorily (halophytes)

Table 4-3. General Tolerance of Common Crops to Soil Salinity.[a]

Type Crop	Tolerant (EC >16)	Moderate (EC 8–16)	Medium (EC 4–16)	Sensitive (EC <4)
Field	Cotton (17) Barley (18)	Sesabania (9) Sorghum (11) Wheat (13) Sugar beet (15)	Peanut (5) Corn (6) Flax (6) Broadbean (7) Rice (paddy) (7) Soybean (8)	Bean (field) (4)
Forage	Tall wheatgrass (19)	Alfalfa (9) Clover (berseem) (10) Orchard grass (10) Birdsfoot small (10) Perennial rye (12) Tall fescue (13) Bermudagrass (15)		
Vegetable		Beet (10) Spinach (9)	Lettuce (5) Sweet potato (6) Potato (6) Sweet corn (6) Cabbage (7) Tomato (8) Broccoli (8)	Bean (4) Carrot (4) Onion (4)

[a] *Salinity levels at which 50% decrease in yield expected. Values shown for saturated paste extract in mmhos/cm. Value by plant name in parentheses ( ) is actual salinity level. Salinity level required for successful germination may be much lower. Data compiled by Ayers and Westcot (1977a).*

Many plants also have specific tolerances to chloride and sodicity levels. Sensitivity to chlorides and sodium is also a function of other environmental factors, such as average temperature, rainfall, etc. Table 4-4 shows the level of chlorides which will result in a 75% decrease in yields in Netherland soils, and Table 4-5 shows the tolerance of selected plants to sodicity.

Table 4-4. Chloride in Netherland Soils Causing 75% Decrease in Yields Compared to Unaffected Soils.[a]

Field Crop	Cl^- (meq/L)	Vegetable Crop	Cl^- (meq/L)	Fruit Crop	Cl^- (meq/L)
Bean (brown and white)	9	Lettuce	17	Grape	10
Pea	9	Bean (dwarf and runner)	26	Mulberry	10
Potato (tuber)	26	Cabbage (red keeping)	34	Pear	20
Broadbean	34	Potato	51	Strawberry	26
Onion	34	Endive	51	Currant (black)	40
Flax	51	Celeriac	68	Currant (red)	70
Red clover	51	Cabbage (red)	68	Apple	75
Wheat (spring)	68	Carrot	86	Blackberry	90
Spinach (for seed)	86	Leek	86	Plum	90
Alfalfa	103	Brussels sprout	103	Raspberry	90
Oat	120	Cabbage (green savory)	103	Cherry (sweet)	95
Beetroot	120	Cauliflower	103	Cherry (sour)	95
Barley (spring)	170	Spinach	103	Peach	95
		Chicory	103	Gooseberry	100
		Kale	137		
		Radish	137		
		Purslane	171		

a Adapted from Keech, 1995.

Table 4-5. Tolerance of Specific Plants to Sodicity.[a]

Sensitive (ESP = 2–20)	Moderately Tolerant (ESP = 20–40)	Tolerant (ESP = 40–60)	Very Tolerant (ESP above 60)
Deciduous fruit	Clover	Wheat	Crested wheatgrass
Nuts	Oat	Cotton	Tall wheatgrass
Citrus fruit	Tall fescue	Alfalfa	Rhodegrass
Avocado	Rice	Barley	
Bean	Dallisgrass	Tomato	
		Beet	

a Damage to the most sensitive crops is due to sodium toxicity. Damage to the tolerant crops is due to poor soil physical conditions. Adapted from Keech, 1995.

Boron Tolerance. As a micronutrient which can be deficient in or toxic to plants, soil boron problems can result from produced water spills and their remediation. Depending on the boron concentration in the produced water spilled and the intensity of leaching during remediation, soil boron concentrations may increase and become toxic or decrease and become deficient after a produced water spill. In general, boron toxicity appears above about 0.7 mg/L for sensitive plants, and only boron-tolerant plants are able to withstand boron concentrations above approximately 1.5 mg/L in a saturated paste extract (Richards, 1954). Like more mobile salts, boron moves upward and downward with water flow. However, it migrates much more slowly and may require more leaching water than sodium for removal. Boron occurs in widely scattered areas, and is frequently present in saline soils. As shown in Figure 3-6, boron availability is also subject to changes in pH. Plant-available boron levels in soil are typically controlled by leaching, pH adjustments, and fertilizers.

Halophytic Plants. Plants which are very tolerant of elevated salt levels (EC above 16 mmhos/cm) are called halophytic plants. Halophytic plants are found in both very wet and very dry environments and many have substantial commercial value (Aronson, 1989).

There is a wide range of salt tolerance among halophytic plants. Some halophytic plants have 50% germination in salt concentrations as high as 24 mmhos/cm, and other plants have 50% yield reductions in salt concentrations above 67 mmhos/cm. Table 4-6 shows 50% seed germination data for some halophytic plants, and Table 4-7 shows 25% and 50% yield reduction data for some halophytic grasses and shrubs. Table 4-8 shows salinity levels at which 25% growth reduction occurs in some tree seedlings. Additional information pertaining to halophytic plants is provided in Appendix F.

It is obvious that a number of plants are capable of surviving, and even thriving in soil salinity levels well above 16 mmhos/cm and in sodic levels above an ESP of 15%. These halophytic plants provide an opportunity to establish soil-protective vegetation in relatively poor saline and/or sodic conditions. It is for this reason that halophytic plants can play an important role in remediation of some salt-affected soils.

The traditionally accepted objective criteria for remediation of saline and/or sodic soils for all plants has been to decrease the salinity and ESP to less than 4 mmhos/cm and 15%, respectively. However, the presence of naturally saline and sodic environments and the halophytic plants which thrive naturally in soils with >4 mmhos/cm EC and/or ESP >15% indicates that more elevated levels of salts may be an acceptable remediation goal in certain situations.

Table 4-6. Salinity of Solutions that May Cause a 50% Reduction in Seed Germination of Halophytic Plants.[a]

Halophytic Plant Species	Common Name	Solution Salinity (mmhos/cm)
Atriplex canescens	Fourwinged saltbush	11–17
Atriplex lentiformis	Saltbush	17–19
Atriplex linearis	Saltbush	17–19
Chloris gayana	Rhodegrass	9–11
Chloris virgata	Snowy chloris	13–16
Dactyloctenium aegyptium	Crowfootgrass	20
Dactyloctenium sindicum	Crowfootgrass	6–7
Digitaria adscendens	Crabgrass	6–7
Dichanthium annulatum	Kleberg bluestem	7–8
Echlnochloa colonum	Jungle rice	7–8
Sesurium sesuvoidies		2–4
Salicomia bigelovii	Saltwort	–
Salicomia brachiata	Saltwort	
Salsola baryosma	Tumbleweed	9
Sporobolus airoides	Alkali sacaton	19–24
Suaeda depressa	Seepweed	19
Trianthema triquetra	Purslane	4–17

a Data adapted from Miyamoto (1996).

Table 4-7. Salinity Levels that May Cause 25% and 50% Reductions in Yields of Grass and Shrubs.[a]

Halophytic Plant Species	Common Name	Solution Salinity (mmhos/cm) 25% Reduction	50% Reduction
Agropyron elongatum	Wheatgrass	15	18
Allenrolfia occidentalis		50	>67
Atriplex canescens	Fourwinged saltbush	17	-
Atriplex barclayana	Saltbush	-	31
Atriplex balimus	Saltbush	20	-
Atriplex inflata	Saltbush	50	-
Atriplex lentiformis	Saltbush	50	>67
Atriplex nummularia	Saltbush	60	-
Atriplex nummularia	Saltbush	44	57
Atriplex patula	Saltbush	>18	-
Atriplex patula	Saltbush	13	67
Bassica hyssopifolia	Mustard	33	50
Batis maritima	Maritime saltwort	-	67
Chenopodium album	Pigwood	-	12
Chenopodium murale	Netteleaf	33	50
Chloris gayana	Rhodegrass	-	11
Chloris gayana	Rhodegrass	7	-
Cynadon dactylon	Bermudagrass	-	17
Cynadon dactylon	Bermudagrass	5	-
Diplachne fusca		10	22
Distichlis palmeri	Saltgrass	46	57
Kochia brevifolia	Summer cypress	12	27
Kochia prostrata	Summer cypress	12	-
Kosteletzkya virginica	Salt mallow	>18	-
Hordeium vulgare	Barley	8.2	11
Mariana brevifolia		33	50
Paspalum vagtinatum	Seashore paspalum	17	50
Phragmites australis	Common reed	17	50
Salicornia bigelovii	Saltwort	30	50
Salicornia bigelovii	Saltwort	50	>67
Sesovium verrucosum		33	67
Spartina longispica	Cordgrass	17	50
Sporobolus aioides	Alkali sacaton	13	-
Sporobolus jirginicus	Dropseed	17	50
Suaeda esteroa	Seepweed	45	57
Suaeda maritima	Seepweed	50	-
Suaeda torrayana	Seepweed	50	>67
Triticum aestivum	Wheat	17	-

[a] Data adapted from Miyamoto (1996).

Table 4-8. Salinity Levels that May Cause Approximately 25% Reduction in Shoot or Tree Growth of Tree Seedlings.[a]

Tree Species	Common Name	Threshold Salinity (mmhos/cm)
Sand Culture w/Seedlings		
Prosopis juliflora, chilensis, articulata	Mesquite	30
Prosopis alba, nigra	Mesquite	20
Prosopis glandulosa, tamarugo & velutina	Honey mesquite	20
Casuaria equisetifolia		12
Soil Culture w/Seedlings		
Acacia nilotica	Acacia	8
Casuarina equisetitolia		5
Eucalyptus hybrid	Eucalyptus	7
Pongamia pinnata		5

[a] Data adapted from Miyamoto (1996).

EFFECTS OF HYDROCARBONS

Petroleum is a complex mixture of naturally occurring hydrocarbon molecules consisting primarily of carbon and hydrogen, with lesser amounts of sulfur, nitrogen, and oxygen. Minor amounts of other elements may also occur, depending on the source of the material.

Once oil is spilled, lighter hydrocarbons begin to evaporate. Hot, dry, and windy weather increases the rate of evaporation. From 20% to 40% (by weight) of a light oil spill that stays on the surface can evaporate within two to four days.

Light petroleum constituents move through the soil profile faster than heavier, more viscous hydrocarbons. During winter, all hydrocarbons move more slowly because the cold temperature increases viscosity.

Heavy hydrocarbons tend to pond at the land surface, whereas lighter fractions drain into the soil. Soil texture and moisture content, among other factors, determine how fast and far hydrocarbons will migrate. Oil moves most quickly in loose sandy soils, and most slowly in tight clay soils.

Soil moisture content is an important factor regarding mobility of oil in soil. Hydrocarbons are attracted to the surfaces of soil particles, but are mostly immiscible in water. As a result, hydrocarbons migrate most rapidly in a soil which is moist—neither saturated nor dry. Hydrocarbons "float" above a saturated soil because they are less dense than water, and therefore, cannot move into pore spaces. Hydrocarbons will readily coat soil particles, but only if they are relatively dry. Therefore, in dry soils, hydrocarbons do not migrate far. In a moist soil, hydrocarbons will rapidly slip through soil pores along the interface between **soil air** and moisture films which are adhering to soil particles. Hydrocarbons also adhere to organic matter in soil.

Effects on Soil

Excessive amounts of petroleum hydrocarbons in soil (e.g., 4% to 5% or more by weight) cause a number of changes in soil characteristics (Rowell, 1975). These changes include:

- The wettability of the soil is altered causing slower water infiltration and decreased water retention by the soil.
- After oil biodegradation, the soil **water-holding capacity** may be improved over pre-spill conditions.

A spill of produced water containing dissolved or emulsified oil would rarely deposit enough oil in the soil to cause observable changes in soil aggregation or wettability. Even when a spill deposits enough hydrocarbon to cause a visible oil sheen or distinctive petroleum odor in the soil, concentrations are unlikely to be high enough to notably affect physical soil characteristics.

The vast majority of physical changes in soil are caused by the saltwater constituents in a produced water spill. However, in produced water pit restorations, limited volumes of soil within the pit could contain high enough levels of oil to display more of the soil characteristics listed above.

Toxicity

Crude oil may impede plant growth by blocking soil pores and obstructing air and water movement to plant roots if oil concentrations are high. If the oil is high in paraffins or asphaltenes, it can completely seal the soil surface creating a paved appearance. Use of oxygen and nutrients by soil microbes during decomposition may also have a temporary growth-limiting effect on plants (Brady, 1984).

In extreme circumstances, petroleum hydrocarbons deposited directly on existing plants may immediately damage vegetation through leaf kill. At a Canadian spill site, vegetation died (all plant tissue was killed) as a result of absorbing petroleum hydrocarbons either through the foliage or from soil containing excessive condensate (Blauel and Lesko, 1975). High oil concentrations in soil can cause altered soil characteristics, poor seed germination, and reduced plant survival (Blauel and Lesko, 1975; Rowell, 1975). The range of potential plant damage is summarized in Table 4-9.

Table 4-9. Approximate Guide to Plant Damage as it Relates to Oil Content in Soils.[a]

Effect on Vegetation	Percent Oil by Weight: Mineral Soils (sands-loams-clays)	Percent Oil by Weight: Organic Soils (mucks-peats)
Slight to Moderate - from little or no effect through reduction in plant growth if no remedial steps are taken to remove hydrocarbons	0.5–2	4–15
Moderate to Severe - only certain plants grow; prudent remediation management is needed; with care, a wider range of plants can be grown	2–5	15–75
Severe to Very Severe - very few tolerant plants will grow; seeding not recommended until oil content has been reduced through stimulated biodegradation	>5	>75

a Data adapted from McGill (1975).

Organic soils make up ~0.5% of the soils in the United States. Organic soils are found primarily in parts of Michigan, Minnesota, the delta of Louisiana, and the Florida Everglades. Large areas of organic soils are also found in northern Canada (Foth, 1990).

A spill of produced water with dissolved or emulsified oil always deposits much lower concentrations of oil onto soil compared to an oil spill. Produced water spills seldom result in observable oil in the soil. Unobservable oil (e.g., less than 0.5% by weight or 5,000 mg/kg in the soil) indicates negligible hydrocarbon effects on plant growth, and relegates considerations of oil to a non-factor in planning site restoration. Some studies consider 1% by weight in soil (10,000 mg/kg) to be the cutoff level for eliminating oil as a factor to be considered in site restoration (Conoco, 1993; Deuel, 1993). Current work suggests higher levels may be acceptable.

In less frequent cases, spills that cause visible oil sheens or distinctive petroleum odors in the soil may correlate with a measurable deposit of oil. Even in these cases, hydrocarbon levels would rarely exceed 3% oil by weight in the soil. However, this level could be high enough to impede growth of vegetation.

Biodegradation of Hydrocarbons

Medium to high API gravity crude oils (>30 API) are readily biodegradable by naturally occurring soil microbes (McMillen, *et al.*, 1995). Soil bacteria and fungi utilize petroleum hydrocarbons as substrate and biodegrade oil constituents into carbon dioxide (CO_2), water (H_2O), and biomass or other byproducts during the process. The rate of decomposition by soil microbes depends on the availability of air, water, and nutrients such as nitrogen and phosphorous. Because there is little nitrogen or phosphorous in crude oil, hydrocarbon-degrading microbes must compete with plants to obtain these nutrients from the soil. These microbes also compete with plants for soil oxygen. As is the growth of most plants, biodegradation is optimized when the pH is near neutral (6 to 8).

Depending on the quantity of oil and rate of decomposition, the microbial uptake of nutrients also required by plants may inhibit plant growth unless nitrogen and phosphorus are applied as fertilizer. Applications of water and **tillage** to aerate and mix the soil will also stimulate biodegradation.

Biodegradation of oil may be minimal where oil has migrated below the topsoil because oxygen may be too limiting. It is therefore advisable to attempt to retain oil in the upper portion of the soil if possible. Under good conditions, soil microorganisms may be capable of biodegrading as much as 5% oil in soil by weight depending on the type of hydrocarbons.

EFFECTS OF TIME

The appearance of a "fresh" spill area is usually very different than the appearance of an "aged" spill area. The change in appearance over time demonstrates that the "time" between the occurrence of a spill and the time that remediation is initiated is a factor of some importance.

The negative effects of age on an untreated spill are of most consequence to soil biota and the physical and chemical condition of the soil. Major factors involved in the "rate" of soil deterioration after a spill are the intensity of atmospheric weathering, **soil erodibility**, soil texture, strength of soil **structure**, and type of clay minerals present, as well as the volume and concentration of salts in the spilled material and the volume of soil which received the spilled material. In addition to seasonal influences, the aging processes of a spill of sufficient magnitude to cause plant death can be visualized in three general stages: (1) during the first month, (2) during the first year, and (3) during the following years and decades.

During the First Month

After a produced water spill, a decline in the vitality of vegetation may be the first indicator of negative impact to the soil. Under some circumstances, many plants may wilt and die during this period. Although many chemical and physical processes are occurring simultaneously, the principle reason that vegetation declines is drought stress induced by the high salinity (osmotic potential), even though there may be substantial water remaining in the soil. In turn, vegetative decline further upsets the biological balance in the soil and many plant and animal organisms which interact with the vegetation will also begin to decline in health. As a result, the stabilizing effect of these biota on soil structure also begins to decline. However, some salt-tolerant biota may become more competitive and dominant if the spill is not too severe.

Additional rainfall can be expected both to dilute the salts in the spill area and to increase the total volume of soil affected. The salt-migration front may continue to percolate downward in the soil even with minimal rain. Salts may also migrate overland in runoff water or in groundwater under certain circumstances.

Although the high salinity has an initially beneficial effect on soil structure, the sodium ions will have immediately begun to displace calcium, magnesium, and potassium ions from clay mineral cation exchange sites. Water from the spill and subsequent rainwater carry these nutrient ions deeper into the soil and farther from the most dense plant roots. Corrosion of metals may begin to intensify.

The soil will maintain structural integrity as long as the salinity is high, but the soil will increasingly become susceptible to dispersion due to the increasing sodium saturation of clay cation exchange sites. Since the capillary pores are small, this time is utilized by sodium cations which continue to migrate deeply into micropores and internal cation exchange layers in certain clay minerals. The farther sodium moves into the interlayers, and the greater the total volume of clays affected, the more difficult a subsequent chemical remediation effort will become. As often happens, a sufficient rain could quickly decrease the salinity of the sodium-saturated clays sufficiently to disperse the clays at the soil surface. Once the dispersed clays seal the soil surface, neither water nor air can move effectively into the soil.

The soil is most readily remediated during this initial phase of salt and soil interactions. The topsoil has still retained a substantial number of viable organisms, seeds, and organic matter. Petroleum hydrocarbons are most easily volatilized, decomposed, and biodegraded. Erosion above normally occurring levels has probably not yet affected surface contours sufficiently to require earth-moving equipment to reshape the soil surface so that a seed bed can be prepared. In addition, landscape drainageways have also not yet begun to silt up noticeably with eroded material from the spill site. As a result of the relatively short duration of time since the spill occurrence, the level of post-spill attention required of the remediation manager is at its lowest during the first month.

During the First Year

By the end of the first year after a substantial saltwater spill, the vegetative canopy may be completely gone except perhaps for debilitated trees and shrubs which continue to struggle. Some very salt-tolerant vegetation may also remain or have suddenly appeared. The affected area may have expanded in area and depth within this time period. The color of the soil may have become lighter as organic matter was oxidized but not replaced by the stressed biota. Salt crystals may have appeared at the surface during predominantly evaporative conditions. The appearance of the spill area may seem to have improved or worsened in response to initial seasonal changes. Corrosion may be expected to remain intense from the salinity, and the pH could have begun to increase into the strongly alkaline range (common to many salt-affected soils) further adding to the intensity of metal corrosion. If drainage is good, the soil is coarse textured, and the rainfall is high, nature may have begun to remediate the area. However, the soil nutrient status will be expected to improve only slowly without assistance from humans. The petroleum hydrocarbons remaining would have probably become more difficult to biodegrade.

Erosion is very likely to have become a serious problem at the site, and much of the topsoil could have eroded away during this time period. Substantial seeds and biota would also have washed away with the eroded topsoil. Some of the spilled salts may have migrated offsite as entrained constituents in eroded runoff, but most of the salts would be expected to continue upward and downward with seasonal cycling or perhaps predominantly downward migration in the soil in association with infiltrating rainfall. Any erosion which began as **sheet erosion** may now have advanced to rills and gullies which cut both downward and upgradient. The intensity of erosion would be expected to have accelerated by increased volume and speed of runoff water due to less vegetative impedance to water velocity, increased surface crusting, and the scouring action of suspended soil particles. During this time period, it is likely that sodium has migrated well into the interior of clay particles. Soil which may have resisted structural dispersion soon after the spill becomes more easily dispersible due to the decline in biomass.

At the end of one year, any remediation effort to be undertaken probably will have become much more difficult at many sites. It is likely that earth-moving equipment, which was not required during the first month, may be required to reshape the soil surface. Additional heavy equipment also may be required to clean eroded material from the spill area out of downstream drainageways. Addition of mulch, fertilizer, and seeds or sprigs during the remediation effort may well have become more of a necessity than an option. Remediation of silted-up downstream drainageways also may be required before the first anniversary of the spill is reached. It is increasingly possible that erosion controls may be required while the soil recovers because there is minimal vegetation to prevent erosion. The appearance of the site may have continued to deteriorate and the duration of lost productivity of the land may have also continued to accrue.

During the Following Years and Decades

Spill sites which may have merely appeared stressed during one or more previous years under favorable weather conditions, may have finally succumbed under one of the harsh yet predictable years which followed. Sufficiently salt-affected trees may also have finally succumbed yet their stumps may remain in the ground. It is possible that all of the topsoil has eroded away by this time and that remaining subsoil may resemble denuded mounds or ridges surrounded by deep gullies—some of which may range from 25–50 ft deep and extend well downgradient and upgradient of the original spill site. The high salt levels may continue to inhibit nature's efforts at natural remediation, and erosion may still be continuing unabated—at least until a resistant stratum is reached. By this time, downstream waterways could be substantially silted up with eroded material. Without frequent anode replacement over the years, there may be little metal remaining to be corroded in the soil. Depending on circumstances, the salt may have reached groundwater and a plume of saltwater may have migrated to nearby wells. Saltwater from very large spills or from leaking brine pits in porous soils and geologic strata may have migrated several miles in an **aquifer** during this time period. However, if drainage were good, the surrounding vegetation were aggressive, and the rainfall were high, nature may have clearly begun, or already succeeded, in remediating the area. However, the soil nutrient status may continue to be slow to improve without assistance from humans.

After this period of time, site remediation is likely to be extremely difficult. Large earth-moving equipment could be required to reshape the soil surface and clean eroded material out of downstream drainageways. Addition of mulch, fertilizer, and seeds or sprigs during the remediation effort could now be an absolute necessity for downstream drainageways. Due to the loss of soil from the salt-affected area, erosion will also begin to progress upgradient and downgradient.

Installation of major erosion controls could be essential while the soil recovers. The duration of lost productivity of the land likely has continued to accrue, and this problem could have expanded onto adjoining land being undercut by erosion. It is likely that any remediation effort initiated after several decades would require the trappings of a major project and require use of remediation specialists to cope with severe site conditions which were not present within the first month after the spill.

REVIEW OF SECTION 4

- Excessive salinity from saltwater spills on soil can inhibit plant growth by restricting plant uptake of water.
- Excessive sodium from saltwater spills can negatively impact the soil by causing soil dispersion which limits water permeability.
- A few highly salt-tolerant crops and halophytic plants can survive with acceptable yields in very strongly saline soils (EC >16).
- Application of freshwater to a salt-affected soil prior to application of chemical amendments should be avoided because it can cause a soil to disperse.
- Although hydrocarbons may degrade over time, high concentrations of hydrocarbons can initially detrimentally affect soil and vegetation. As the organics degrade, plant growth may be limited by microbial competition for nutrients and oxygen.
- Increased delay prior to initiating and completing the remediation effort usually equates to increased environmental damage, increased complexity of remediation, and increased cost.

Section 5

PROCESS FOR SELECTING A REMEDIATION ALTERNATIVE—AN OVERVIEW

In this manual, selection of remediation alternatives is accomplished using a Decision Tree. The Decision Tree breaks complex remediation alternative selection into a step-type series of manageable decisions. The Decision Tree addresses both cultural and technical (physical, chemical, and engineering) conditions and options, and is followed until one of three categories of remediation is selected.

OVERVIEW OF REMEDIATION OPTIONS

Remediation options are divided into three primary groupings: natural remediation, *in situ* chemical amendment remediation, and mechanical remediation. Natural remediation is the process of allowing an area to recover with little or no human assistance. *In situ* chemical amendment remediation involves adding chemical amendments (including water) to the soil and allowing those chemicals to assist the remediation process without removing the soil. Mechanical remediation entails removing the soil from the site and either disposing the soil or treating the soil elsewhere.

Natural (Unenhanced, Passive) Remediation

Natural remediation is most applicable in situations where the salt effects are minor, and the natural processes require little, if any, assistance, or where any action taken would either be pointless because of technical impracticability or would further deteriorate the environment. Natural remediation should be considered only after careful review of site-specific conditions, including the nontechnical issues discussed in Section 2.

In circumstances where the volume spilled or the salt concentrations are very low, or the land area receiving the spill is very large compared to the amount spilled, it is likely that the effects of the spill will be negligible. These areas tend to recover rapidly by natural means, and any attempt to enhance the remediation process is not only of little value, but may cause additional, unnecessary damage.

Natural remediation may also be the option of choice if the area was initially, or has become, too badly damaged to benefit from any reasonable attempt at chemical or mechanical remediation. Many times in heavily affected areas, the efforts to remediate the site actually damage the environment and result in delayed recovery. However, an operator may, because of one or more non technical issues, choose to remediate a site that would not be justified from a solely technical perspective.

Natural remediation or remediation involving halophytic plants may also be warranted if there is shallow groundwater which cannot tolerate increased salt levels. Chemically or physically remediating these sites may result in greater deterioration of the groundwater as the salt leaches through the soil.

Risk to surface water is another consideration. Remobilization of salts with chemicals or erosion due to the impact of additional water could affect nearby bodies of water. The disturbance to the topsoil by the chemical application equipment may also increase erosion.

Occasionally, situations occur in which any attempt to enhance remediation may cause greater environmental damage than the original salt effect. These situations often occur in wetland situations where the area typically will remediate rapidly even where high salt concentrations are present. Any attempt to bring large equipment into these areas to speed or improve the remediation may cause significant habitat damage.

With natural remediation, the operator may choose to keep records monitoring the site to verify that natural remediation is occurring at an acceptable pace.

In Situ Chemical Amendment Remediation

The objective of *in situ* chemical amendment remediation is to remove the salts from the root zone. The chemicals remobilize the salts so they can be leached by percolating water to a subsoil below the root zone. Generally, *in situ* chemical amendment remediation is somewhat more expensive than natural remediation, and depending on circumstances, may be the most difficult of the three techniques to apply successfully.

In situ chemical amendment remediation is the option selected in the majority of salt-affected remediation projects. The Decision Tree concentrates on the process of determining when *in situ* chemical amendment remediation may be appropriate, and on developing the data required to select specific amendments and techniques which have the greatest probability of success.

There are a variety of chemical amendments which can be added to remobilize salts, the best known of which is gypsum ($CaSO_4{:}2H_2O$). When applied properly, gypsum has proven to be effective for treatment of many salt-affected soils. Organic amendments, such as mulches, and the application of water are discussed in Section 7 in addition to chemical amendments. A detailed discussion of alternative chemical amendments is provided in Appendix K.

Mechanical Remediation

Mechanical remediation is the term given to a number of remediation techniques that involve mechanically disturbing the soil, other than drainage-improvement techniques, such as tilling, **subsoiling**, and installation of subsurface drains. Often, mechanical remediation involves excavation of the salt-affected soil from the site and replacing or mixing it with unaffected soil. A more comprehensive discussion of the mechanical remediation options is provided in Appendix H. Drainage improvement techniques are discussed in Appendix E.

There are two basic types of mechanical remediation in common use—dilution and disposal. In the dilution process, the salt-affected soil is mechanically mixed with unaffected soil to attenuate the salt effects. Diluted soil may then be returned to the excavation site or moved to another site. If the affected soil is removed, the excavation would be filled with unaffected soil.

Land spreading may be the most cost-effective form of mechanical remediation for the majority of spills. It can be combined with other techniques to make it more cost effective. In land spreading, salt-affected soil is spread over a nearby area and incorporated into the soil such that the final salt concentration is acceptable, or at least more amenable to treatment. Care must be taken so that the land spreading rates are at or below the values calculated in Appendix H, or the effect may be creation of a larger affected area.

The disposal remediation procedure removes the soil from the affected site and places it into an approved disposal area. The approved disposal area may be a nearby location where burial is appropriate, or it may be an offsite commercial facility. After excavation, the salt-affected site is filled with unaffected soil. Any site remediation technique that involves burial must consider groundwater effects.

Disposal remediation tends to be the most expensive approach and is often considered the technique of last resort. However, it may be the only option which will remediate the site if other options are untenable, or it may be required to meet one of the criteria discussed in Section 2.

Recently, there have been investigations into soil-washing (both *in situ* and *ex situ*) techniques for restoring the soil. Initial data suggest these techniques (especially *ex situ*) are more expensive, but may be preferable in specific situations.

Mechanical remediation tends to be somewhat more expensive than *in situ* chemical amendment remediation and much more expensive than natural remediation. Table 5-1 provides a comparison among natural, *in situ* chemical amendment, and various mechanical remediation techniques.

Table 5-1. Remediation Cost Comparisons.

Technique	Advantages	Disadvantages	Cost
Natural Remediation			
	Low cost Convenient No environmental disturbance	Slow	Low
***In Situ* Chemical Amendment Remediation**			
	Rapid Easy to apply Minimal environmental disturbance	High failure rate Limited use in arid regions Possible multiple treatments	Low to moderate
Mechanical Remediation			
Disposal in Landfill	Convenient Rapid	Potential latent landfill remediation expense	Moderate to high
Deep Burial	Low cost Rapid	May require a liner Does not dilute	Low to moderate
Road Spreading	Low cost Rapid Convenient	May not improve roads in some cases Regulatory restrictions Length of lease road	Low to moderate
Land Spreading	Good dilution Low liability Low cost	Expands affected area Difficult application	Low to moderate
In Situ Soil Washing	No earth moved Low cost for large projects Salts actually removed	High cost for small projects Dependent on rainfall Water disposal	Low to high
Ex Situ Soil Washing	Rapid Salts actually removed	Water disposal	Moderate to very high

Salt-affected pits typically are remediated mechanically. Often, pits have salt concentrations significantly in excess of levels which may be remediated successfully with chemical amendments. In these cases, it may be impractical to apply chemical amendments and water in the amounts necessary to effectively displace sodium. In mechanical remediation efforts, pit contents normally are removed, diluted with soil or deep buried, and the surface is remediated as the last step of pit closure. Often a combination of mechanical and natural or chemical amendment remediation techniques can be used cost effectively.

REMEDIATION DECISION TREE

Salt remediation involves six basic steps as depicted in Figure 5-1. Listed with each step in Figure 5-1 are the forms, worksheets, and figures designed to aid in accomplishing each step. After the spill has been discovered, the six steps are:

1. Prepare initial spill report and identification
2. Gather and review desktop data
3. Conduct onsite assessment and sampling
4. Interpret data and select remedial action
5. Perform remedial action
6. Conduct post-remediation monitoring and project termination

The first four steps, from initial site data collection through selection of an appropriate remedial action, are covered at the end of this section. The fifth step (performance of remedial action) is covered in Section 7 and the final step (post-remediation monitoring and project termination) is covered in Section 8.

The steps listed in Figure 5-1 are expanded and clarified by Decision Tree branches in Figures 5-2 through 5-4. The Decision Tree branches lead to tasks and remediation alternatives. Figure 5-2 outlines the tasks involved in the site visit (Step 3). Figure 5-3 (Step 4A) covers data assessment for the initial technology selection process, and Figure 5-4 (Step 4B) completes the selection process.

Supplementing the Decision Tree is a series of forms and worksheets which are contained in Appendix B. The forms serve as checklists and consolidated documentation for recordkeeping. The worksheets also provide the operator with a simplified method of performing the calculations required to develop the information used in decision making. These forms and worksheets are provided as examples of ways to organize and archive information on the remedial process. Instructions for completing each form and worksheet are provided also. Operators are free to complete them as they see fit or develop their own strategies for documentation.

As the operator becomes more familiar with remediation of salt-affected soils, some of the steps discussed in the remaining sections of the manual may be abbreviated or quickly dispatched. The level of relative importance of information requested is provided for each data blank on the forms in Appendix B. The levels are (E) for essential, (I) for important, (H) for helpful, and (C) for administrative convenience. The "essential" level pertains to information which, if omitted, could lead to selection of an inappropriate remediation technology. The "important" level indicates data

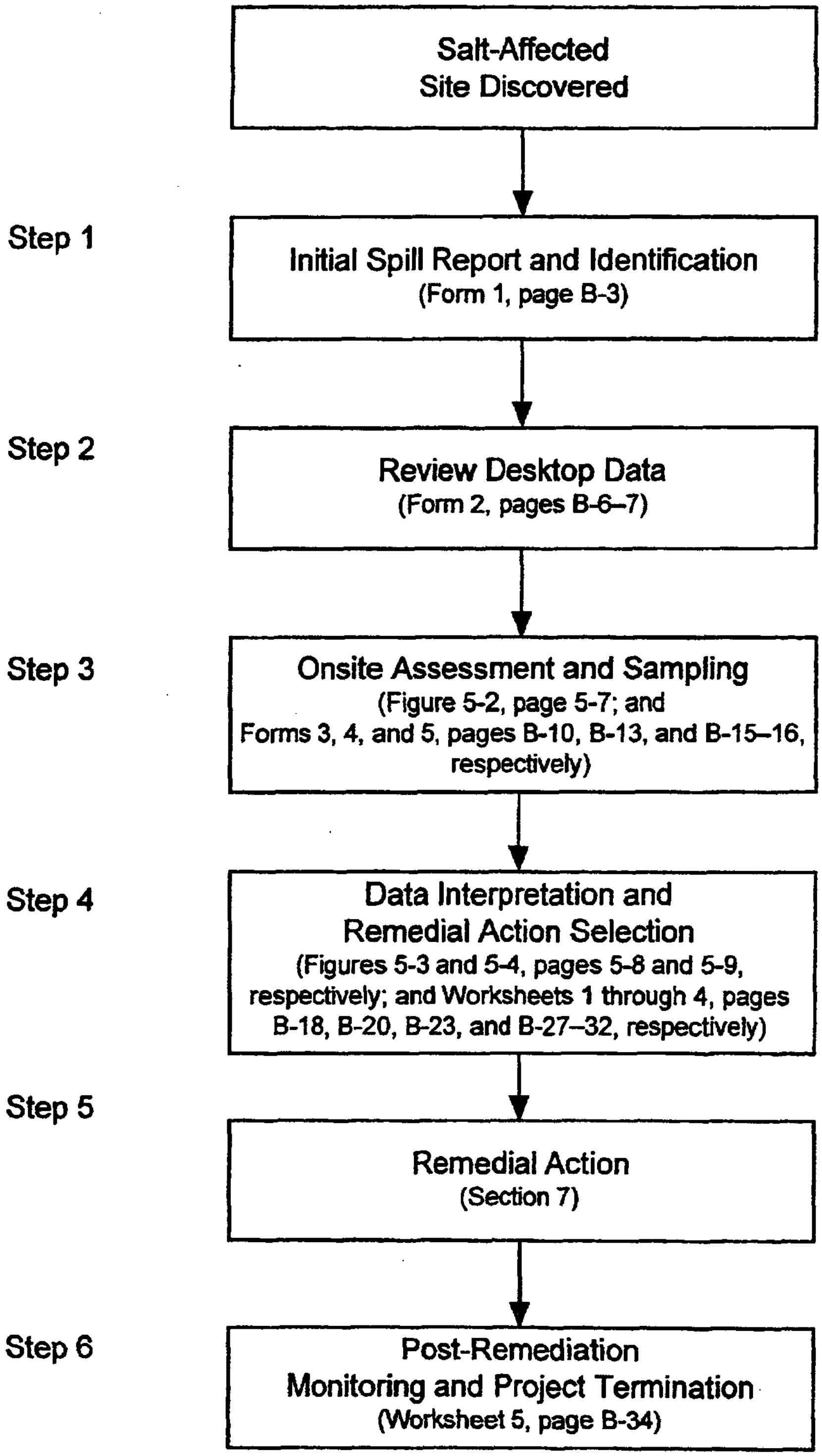


Figure 5-1. Overview of Remedial Action (Decision Tree).

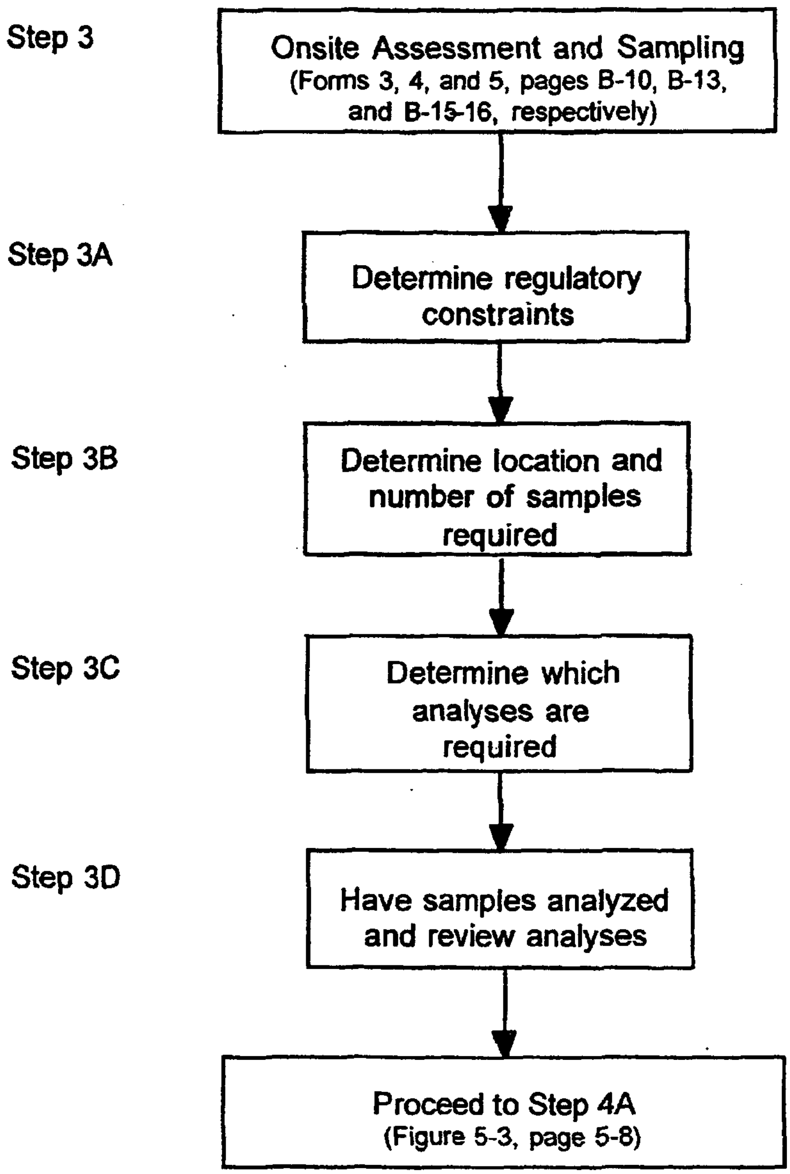


Figure 5-2. Step 3 Onsite Assessment and Sampling.

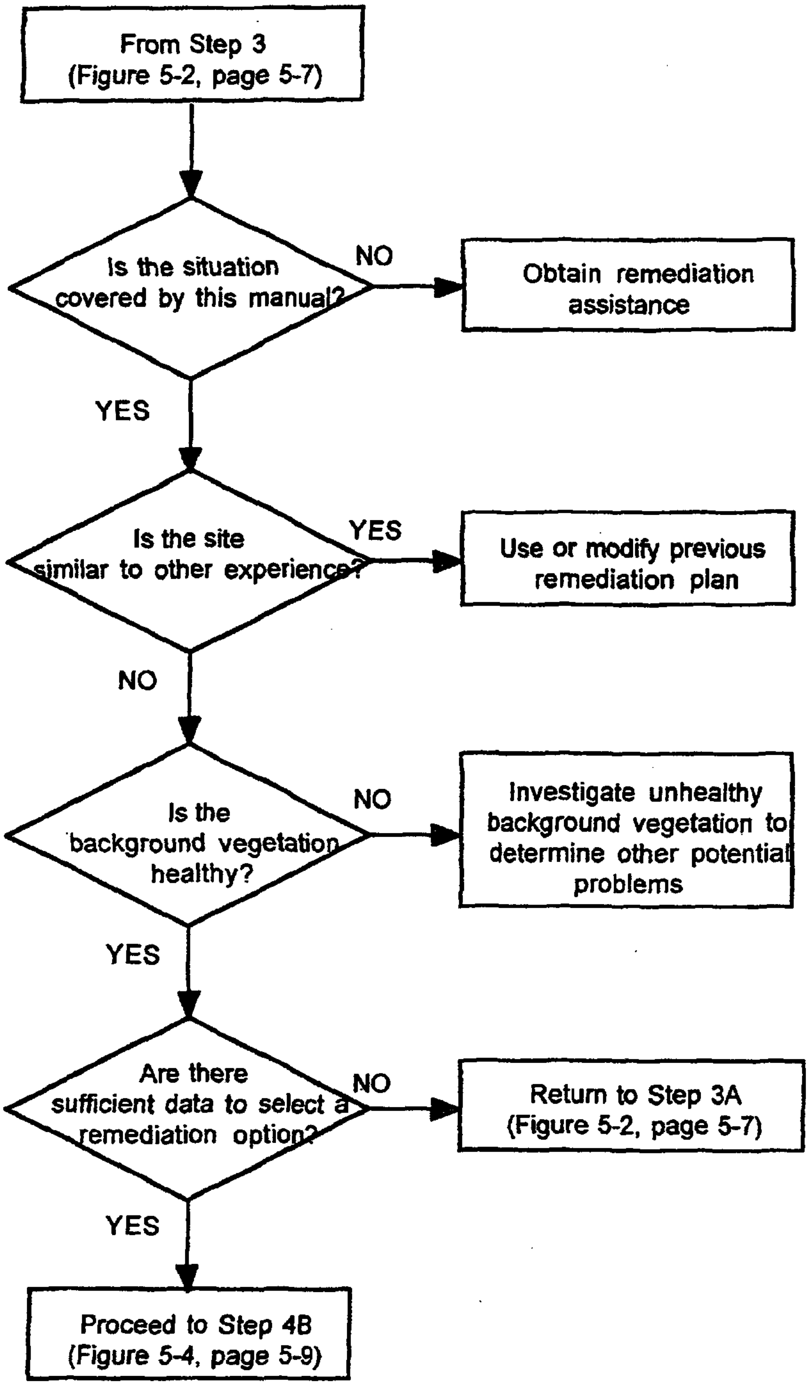


Figure 5-3. Step 4A Site Data Interpretation.

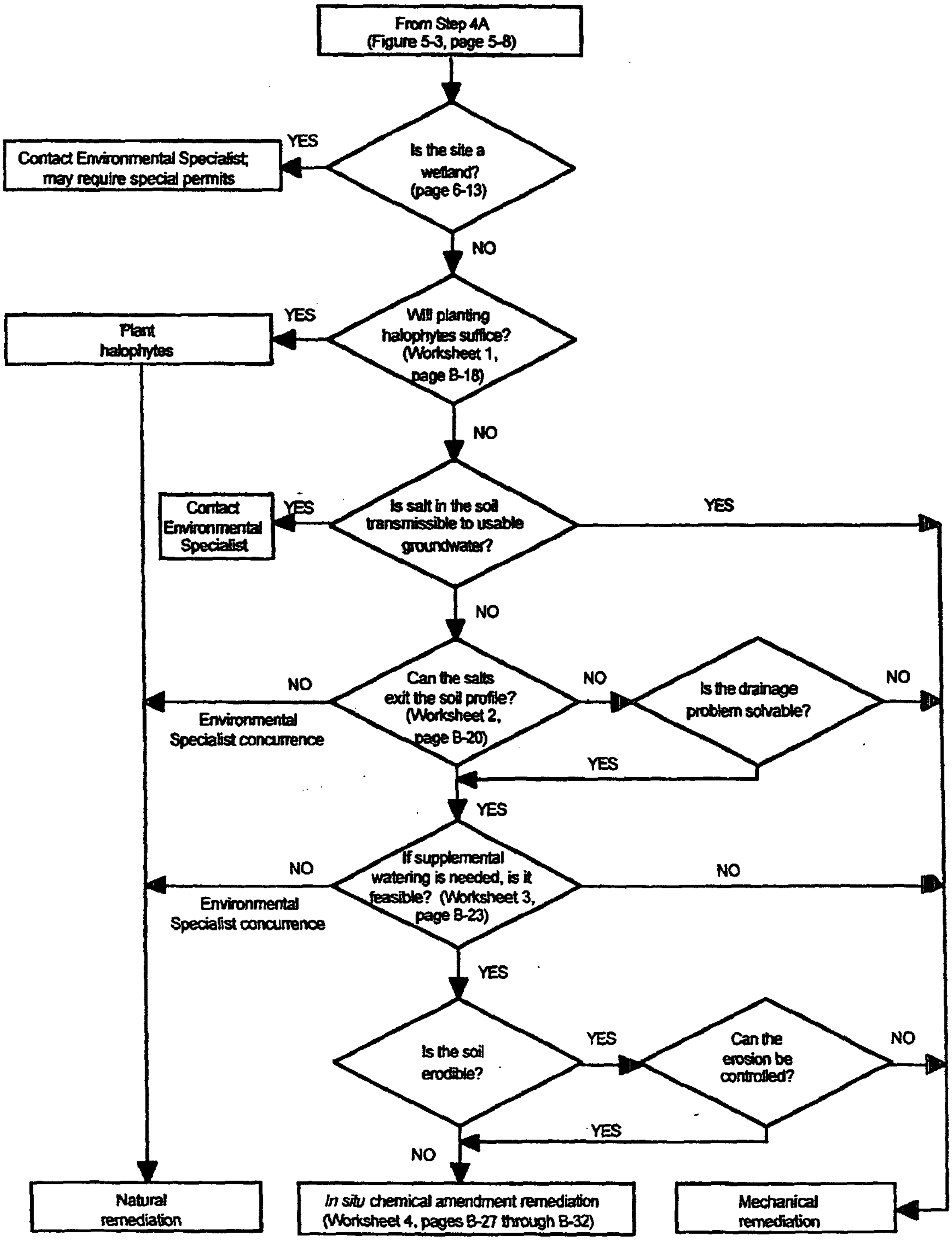


Figure 5-4. Step 4B Remedial Action Selection.

which should be obtained to provide confirmation of essential data obtained by other means. The "helpful" level designates information which may assist with interpretations. The data blanks with a "C" designation are of little to no importance regarding the chemistry, physics, or engineering of the remediation effort, but will assist in maintaining logically arrayed records for administrative purposes. Careful consideration should be given before eliminating any steps. Failing to properly assess the site before choosing a remediation alternative may result in wasted resources or inadequate remediation of the site.

REVIEW OF SECTION 5

- Natural remediation is the preferred remediation technology and it can be selected when mostly unassisted natural processes can be expected to remediate the site.
- *In situ* chemical amendment remediation may be selected as the remediation technology if sodium can be displaced from the soil cation exchange sites and salts can be permanently leached to a location below the root zone but above groundwater.
- Mechanical remediation may be selected when neither natural remediation nor chemical remediation are technically viable nor cost effective. Mechanical remediation involves physical relocation of the salt-affected soil.
- The Decision Tree is a useful tool for selecting a workable remediation option. It offers a logical step-type evaluation of the most critical potential constraints to remediation. The principal steps in the Decision Tree are:

  1. Site assessment (Section 6)
     a. Prepare initial spill report and identification
     b. Gather and review desktop data
     c. Conduct onsite assessment and sampling
     d. Interpret data and select remedial action
  2. Perform remedial action (Section 7)
  3. Conduct post-remediation monitoring and project termination (Section 8)

Section 6

SITE ASSESSMENT

This section provides suggested procedures for obtaining and organizing data, developing realistic remediation goals, and selecting a specific remediation plan for salt-affected sites. Although cost is an important consideration in selecting remediation technologies, the cost of remediation alternatives varies extensively from area to area, and therefore, costs are not included in this manual.

STEP 1 - INITIAL SPILL REPORT AND IDENTIFICATION

In Step 1, the process of selecting a remediation alternative begins with internal notification of the spill. Oversight of the spill situation then becomes the responsibility of a first-level supervisor or an environmental professional. The salt-affected soil may be the result of a recent spill, an older spill, or a decision to close a pit. Sometimes older, closed pits cause problems that require remediation of salts.

Once a site has been identified and reported to the field supervisor or an environmental professional, a project manager should be designated and Form 1 (Appendix B) completed.

Form 1 constitutes the beginning of the administrative and site remediation record. Information on Form 1 includes a description of the type and intensity of the spill and any initial attempts to respond to the spill. If the site is older, some of these data may not be available.

Regulations governing spills of crude oil or produced water typically fall under the authority of a state oil and gas commission or equivalent. However, other state or federal authorities may require notification. Rules and regulations among states often differ on reporting requirements, reportable spill levels, time frame for filing reports, and site remediation requirements. Table C-1 in Appendix C summarizes the state-specific agencies to contact and provides their telephone numbers (only those states having E&P operations are listed). However, there may be additions or changes to this list. It should be considered an aid to determination of agency contacts, which are subject to change. Verification of the accuracy of this information is the responsibility of the user.

STEP 2 - REVIEW DESKTOP DATA

Step 2 is designed to gather and summarize important soil, climate, and regulatory information which may be available prior to the site visit. This may be considered a desktop site characteristics review. Much of this information may be published and easy to obtain, and other information requested should also be available from local individuals. Form 2 (Appendix B) is used for gathering this information.

Soil Survey

U.S. Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS) Soil Surveys are available for nearly every county in the United States. In counties that do not have published Soil Surveys, the USDA-NRCS can often provide interim data for the lease or field if provided with the section, township, and range.

Soil Surveys contain a great deal of general information which will be relevant to the salt-affected site. This soil information is available on CD ROM from the USDA-NRCS and frequently includes:

Texture	Shrink-Swell	Hydrologic Group
pH	SAR	Flooding Potential
Permeability	Erodibility	High Water Table
Carbonates	CEC	Land Capability
Gypsum	Drainage	Salinity
Depth to Bedrock	Impermeable Layer Depth	Sodicity
Suitable Plants	Slope	

Soils vary substantially with depth and an awareness of this variation is critical to selection of an appropriate remediation technology. Soil horizonation is especially important if an *in situ* remediation alternative is selected. When multiple soil horizons are involved, as is common, then more than one Form 2 may be needed to record the necessary information for each soil horizon.

Climatic Data

The amount of precipitation received at a particular site is a critical factor for *in situ* chemical amendment remediation. The amount of rainfall correlates with the potential for migration of salts offsite due to overland runoff, or into groundwater by **percolation** through the soil.

Insufficient precipitation or excessive evaporation may severely limit the opportunity to utilize chemical *in situ* treatment. Included in Appendix I are climate maps that provide the normal annual rainfall and pan evaporation averages for the United States. The **precipitation evaporation index (PEI)** is calculated by subtracting the mean annual class A pan evaporation from the normal annual total precipitation (all values are in inches).

A highly negative PEI, indicative of much greater evaporation compared to precipitation, eliminates some remediation alternatives unless supplemental water is supplied. A high PEI, indicative of substantial rainfall, may allow for a passive remediation plan at less expense. For example, the Drumright Oilfield near Tulsa, Oklahoma, has a mean annual class A evaporation rate of 75 inches per year and a normal annual total precipitation of 36 inches per year. The PEI is therefore 36 inches minus 75 inches, or -39 inches per year. This highly negative PEI indicates the need for supplemental irrigation water if chemical amendment techniques are to be applied.

Regulatory Constraints

Remediation requirements of crude oil and produced water spills differ widely from state to state and are typically handled on a case-by-case basis. The majority of states require that the spill sites be remediated to a level that will, from a regulator's perspective, present little harm to the environment and will sustain natural vegetation. States such as Louisiana, New Mexico, and Oklahoma have specific guidelines and levels of remediation that need to be attained and documented.

The state oil and gas commission (or equivalent) typically regulates spills of crude oil or produced water. However, depending upon the spill circumstances, other state or federal authorities may also require notification. Table C-1 in Appendix C summarizes the state agencies to contact and provides their telephone numbers.

Remediation Alternatives

The last portion of Step 2 (Form 2) involves elimination of remediation alternatives which are easily recognized as inappropriate for the locale or specific spill conditions. Remediation alternatives which may be suitable in some areas may be unsuitable in other areas if experience has shown them to be ineffective; landowner restrictions prohibit their use; or chemical, equipment, or freshwater availability makes them inappropriate.

Eliminating unsuitable alternatives early in the selection process saves time and money. For example, in arid areas where supplemental irrigation may be prohibitively expensive, remediation with chemical amendments may be impractical because of the lack of available water. In situations where a shallow soil covers bedrock, mechanical remediation by burial may not be a viable option.

STEP 3 - ONSITE ASSESSMENT AND SAMPLING

An assessment visit to a salt-affected site is suggested before selection of any remediation option. The site visit includes a general site reconnaissance and collection of surface and subsurface data and samples. Step 3 utilizes Forms 3, 4, and 5 (Appendix B). Laboratory interactions and analyses are discussed later in this section.

Site Overview

Form 3 (Appendix B) is used to summarize data generated during the Step 3 site visit and includes space for a site sketch. An initial survey of the landscape and land use are helpful for identifying any unforeseen factors which may affect potential remediation activities. During the site assessment, the operator should look for any site characteristics which would limit remediation alternatives or create an unusual remediation situation. The operator should also look for anything that may help assess the practical value of the property.

Form 3 may be used in conjunction with Form 2, which relies on the Soil Survey. The Soil Survey provides general information about conditions that can be expected at the site. This general information may need to be refined or corrected in accordance with actual conditions found during the site visit. For example, the Soil Survey may indicate a medium or steep slope or a coarse surface texture, whereas the actual site may be relatively flat and have a clay topsoil. Examining the site for evidence of periodic flooding, a shallow water table, saline-seep conditions, or erosion problems will minimize the risk of inadvertently overlooking these important factors.

Form 3 provides space for noting the typical vegetation present, as well as a statement regarding its apparent health. Any attempt to revegetate the area should be done in recognition of the type and apparent health of the surrounding vegetation. If the vegetation is sparse or stressed, it may indicate that there are other soil or environmental problems, such as low fertility, which could limit remediation options and impact the final remediation effort.

Observation of conditions that could affect the use of heavy equipment in the area may be useful in logistics of the remediation. Conditions that affect heavy equipment use include severe erosion, potential soil load-bearing problems, seasonal precipitation changes, etc.

On Form 3, the presence of buildings or other man-made features, such as water wells or stock tanks, should be noted. The operator should note if the area appears to be a special animal habitat or if remediation efforts could affect endangered species which may be in the area. There may be other constraints, such as tribal or BLM rules or lease issues, which must be integrated with site physical, chemical, and landscape conditions during the process of selecting an appropriate set of remediation options.

Form 3 provides a section for noting any physical hazards, such as buried pipe or concrete, which could impact tilling, mechanical removal, or *in situ* chemical amendment remediation. Rock outcrops, which may not be readily discernible from the Soil Survey, may be apparent during the site visit. For example, prairie potholes could significantly alter the remediation selection because of wetland regulatory constraints or transmissiveness of surface water to usable groundwater.

To the extent possible, the effect which site conditions and land use may have on remediation activities should be visualized at this time. For instance, if it is apparent that cattle will continue to use part of a spill area as a wallow, it may be an inappropriate site for temporary or permanent revegetation. Likewise, the grazing habits of horses or sheep (as opposed to cattle) may influence the specific revegetation seed mix chosen.

<u>Site Sketch</u>

An alpha-numeric grid is provided in Form 3 to illustrate spatial relationships at the site. Example site sketches are shown in Figures 6-1 and 6-2. A good site sketch shows the areal extent of the spill and a rough estimate of the likely spill depth. Additional data pertaining to spill depth are collected on Forms 4 and 5.

Sampling should exceed the depth of the spill. One method of determining the depth of the spill is a field EC meter. Field EC meters are relatively easy to use and can quickly indicate if sufficient depth has been sampled. Another method involves use of **electromagnetic-imaging (EM) devices**. The areal extent and depth can be quickly determined using this equipment, although there can be interferences (e.g., power lines, buried metal, shallow salt zones, etc.).

The location and sample number of any samples collected should be identified on the site sketch. Any impediments to remediation equipment should also be shown on the site sketch.

Site Name (C): ______________________ **Date (C):** ______________

Form Prepared By (C): ________________ **Spill ID No. (C):** ____________

Landscape (E): ____________________ **Land Use (E):** ______________

Slope of Affected Area (E): __________ **Typical Vegetation (E):** ____________

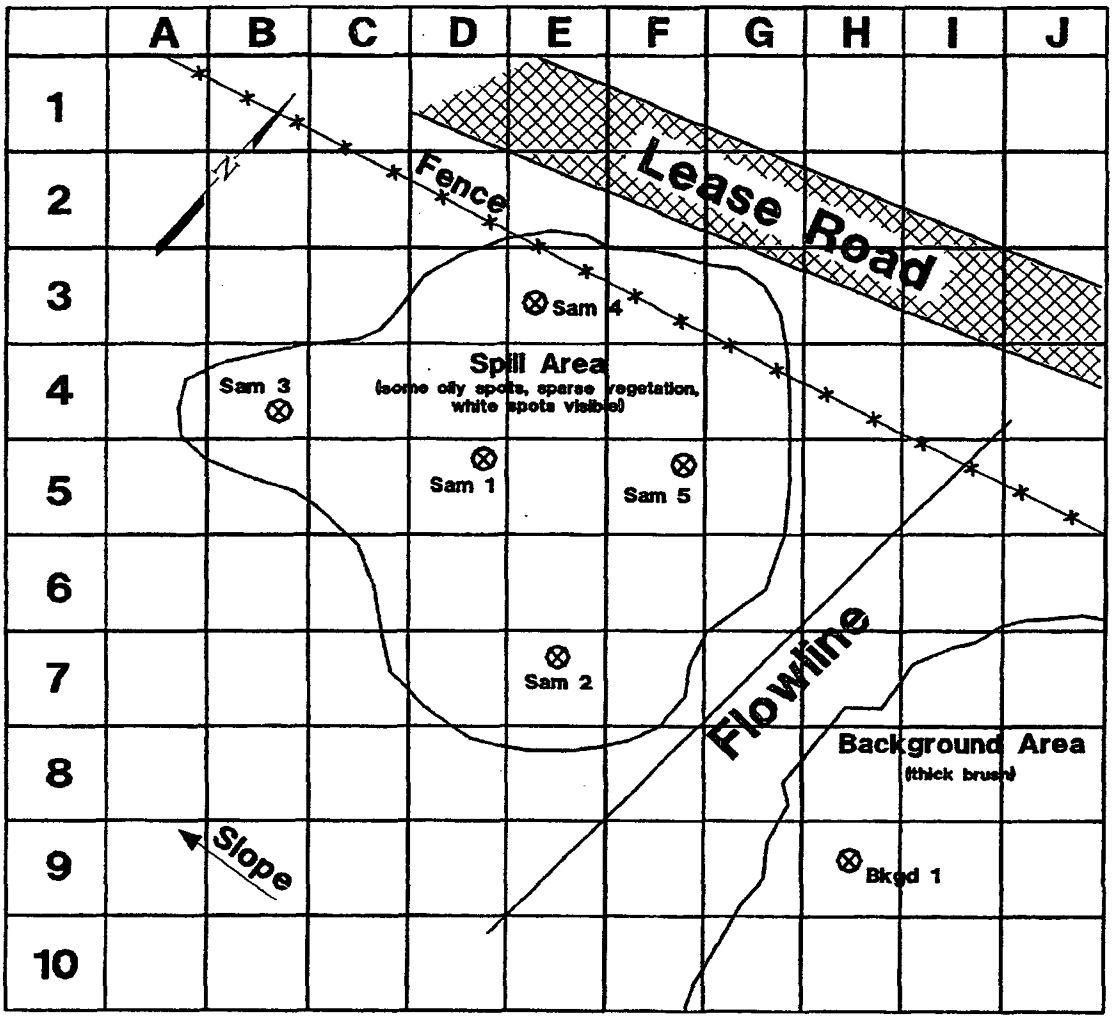
Physical Hazards and Equipment Limitations (E): ________________________

Other Issues (E): ____

Observable Spill Area (E): ________ (sq ft) **Observable Spill Depth (I):** ________ (ft)

Scale (I): ________________

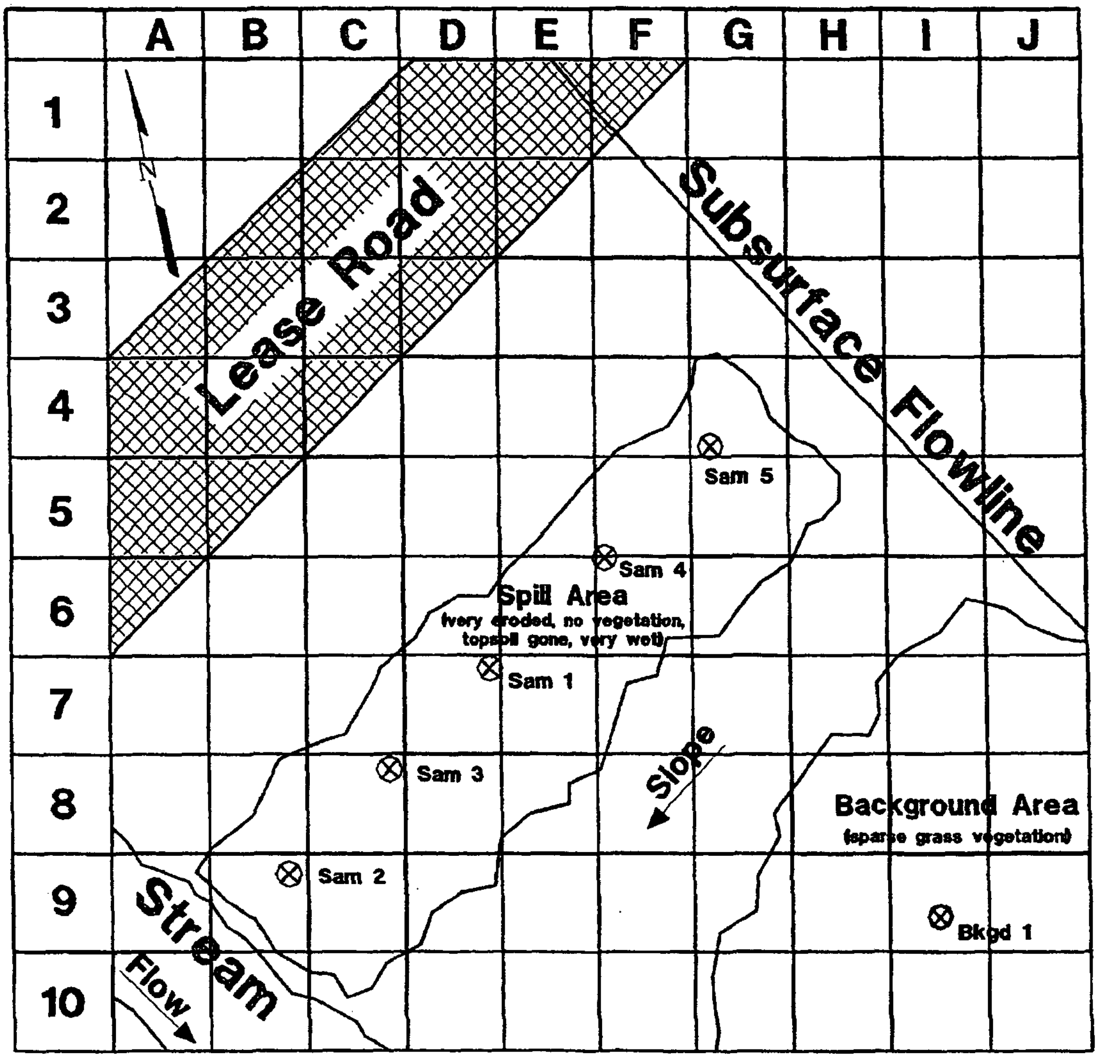
Site Sketch (E):



⊗ Sample Location
Sam 1 at 0-1 and 1-2 ft
Sam 2 through 5 at 0-1 ft
Bkgd 1 at 0-1 ft

Figure 6-1. Example Site Sketch for Circular Spill.

Site Name (C): ______________ Date (C): ______________
Form Prepared By (C): ______________ Spill ID No. (C): ______________
Landscape (E): ______________ Land Use (E): ______________
Slope of Affected Area (E): ______________ Typical Vegetation (E): ______________
Physical Hazards and Equipment Limitations (E): ______________
Other Issues (E): ______________
Observable Spill Area (E): ______________ (sq ft) Observable Spill Depth (I): ______________ (ft)
Scale (I): ______________
Site Sketch (E):



⊗ Sample Location
Sam 1 at 0–1 and 1–2 ft
Sam 2 through 5 at 0–1 ft
Bkgd 1 at 0–1 ft

Figure 6-2. Example Site Sketch for Elongated Spill.

Sample Location Designation

If the spill area is somewhat circular, a five location sample pattern (example in Figure 6-1) is one approach for selecting sample locations. At a minimum, this pattern entails surface samples (0–1 ft) at all five locations, and an additional, deeper sample (1–2 ft) at the center. If the spill area is noticeably longer than it is wide, a more linear five sample pattern (example in Figure 6-2) may provide better coverage. A number of site-specific factors may suggest alternative sampling schemes. Such factors include deeper than expected salt penetration or the need to determine subsoil characteristics that may impede drainage. The pattern may need modification if the salts appear deeper near one edge of the area as opposed to the center.

In sampling a pit, care should be taken to obtain representative samples of various segregated areas of the pit. Although pits may seem to be more homogeneous than accidental spill areas, pit contents may vary in volume in different pit locations. Pit sampling often entails more numerous and/or deeper samples compared to accidental spill areas.

A background sample taken in a similar soil type, upgradient from the salt spill, can be used to assist in establishing remediation goals consistent with local surroundings. It may also be valuable to identify the type and health of the surrounding vegetation so that its potential salt tolerance can be estimated.

Sampling Location Data

Form 4 (Appendix B) may be used to record information related to specific locations where samples are taken. Most of the information requested in Form 4 is readily observable as the samples are being collected.

The information requested on Form 4 will help determine the capability of the soil to be remediated. Potential positive attributes and/or disadvantages inherent in the soil and landscape position can also be identified. General information that can be documented on Form 4 includes surface features (such as crusting), vegetative type and condition, erosion, and evidence of runon and runoff after rainfall events. Space for more detailed information related to delineation of the spill-affected area and depth is also provided. Finally, as samples are being collected, features such as horizonation, **total petroleum hydrocarbons** (TPH), and EC may be field determined and recorded. Obvious soil characteristics, such as the presence of roots, rocks, carbonates, oiliness, wetness, and impermeable layers, as well as soil texture can be noted. If possible, an estimate of permeability may be noted for each soil horizon. Suggestions for completing Form 4 are provided in Appendix B.

Sample Collection

Reference materials on sample location selection, tools, procedures, and handling are discussed in Appendix G.

Laboratory Analyses

Soil samples collected during the site visit may be grouped as shown in Table 6-1. Detailed analyses are suggested for the 0–1 and 1–2 ft samples collected at the point of the greatest suspected salt concentration (hot spot). A list of suggested parameters for hot spot analysis is in Soil List 1 (Table 6-1).

Table 6-1. Laboratory Analyses.

Soil List 1 (Central Hot Spot)	**Soil List 2 (Spill Areal Extent)**	**Soil List 3 (Soil Fertility)**
		Basic fertility (plant available)
As received moisture %	As received moisture %	Nitrogen
pH	pH	Phosphorus
Saturated paste moisture %	Saturated paste moisture %	Potassium
EC	EC	Calcium
SAR	Optional: Oil and grease (O&G) (or TPH)	Magnesium
CEC		Sodium
ESP		Sulfur
If pH <5.5, then lime requirement		EC (optional)
If pH >8.5, then sulfur requirement		Optional micronutrients:
Optional: O&G (or TPH)		Boron
Optional: Chlorides		Zinc
		Iron
		Copper
		Manganese

As shown in Soil List 2 (Table 6-1), fewer analyses are suggested away from the hot spot. If the background vegetation is stressed, or there is reason to suspect that fertility may be a problem in the spill area, then the parameters given in Soil List 3 (Table 6-1) may be used for analysis. The operator may also choose to test for background EC and SAR in case salt stresses indicated by these parameters are occurring in background areas.

A laboratory that provides chemical amendment and fertility data quickly and accurately will provide fertilizer recommendations, if requested. A fertilizer dealer can convert the fertilizer recommendations into combinations of appropriate fertilizers. The fertilizer dealer will often prepare a custom blend and also may apply the fertilizer upon request. Allowing the laboratory and fertilizer dealer to provide these services decreases the chance of error.

Laboratory Considerations

Significant errors can occur in the selection of remediation alternatives if the laboratory analyses are not performed correctly. A qualified laboratory should be used to perform the analyses. A laboratory which routinely performs the analysis of interest often is more qualified than one for which the technique is unusual. Some considerations in selecting a laboratory are:

- Experience and competence in soil analyses
- Demonstrated reproducibility and accuracy of results on split samples and standard samples
- Readily available **quality assurance/quality control** (QA/QC) procedures
- Readily available method citation list and technician procedure instructions

After a laboratory has been selected and used for some period of time, it is often unwise from a technical standpoint, to switch to another laboratory unless the data obtained from the first laboratory are suspect. Analytical results of soil samples are often dissimilar among laboratories due to differences in personnel and QA/QC procedures, and the database used for predicting soil behavior will reflect any change in laboratories.

By using the same laboratory, analytical costs may also be decreased via a volume discount based on repeat business. The data should be carefully evaluated and the potential error determined until confidence in the laboratory results can be established.

A comparison of the data with expected results based on field observations will provide an indication of the reasonableness of the data. If samples at the edge of the spill area have higher EC than samples in the center of the spill area, and the center of the spill appeared to be more heavily impacted by the spill during the initial site assessment, the data should be considered suspect. It may be an inaccurate representation of the salt-affected area or a sampling or laboratory error. Further information on these issues is provided in Appendix J.

Form 5 (Appendix B) may be used to consolidate published information, site assessment data, and laboratory data gathered in Forms 1–4. Form 5 is provided merely for the convenience of the user. The previous four forms were arranged according to the nature of the data-gathering processes involved. Data taken directly from Forms 1–4 or reproduced in Form 5 can be used in conjunction with the Decision Tree and associated worksheets for decision making.

STEP 4 - DATA INTERPRETATION AND REMEDIAL ACTION SELECTION

As noted previously, Steps 1, 2, and 3 in the Decision Tree involve basic data gathering. After the operator becomes familiar with salt-remediation procedures, these three steps may functionally become a single, initial evaluation step. The formal process of decision making begins with Step 4 (Figures 5-3 and 5-4).

Manual Limitations

The first determination in Step 4 (Step 4A, Figure 5-3) is to ascertain whether the remediation selection procedures covered in this manual are appropriate for the site. This manual is designed to cover remediation of spills of produced water, and in limited situations, saltwater pits. For instance, this manual does not address the disposition of heavy metals which may be contained in spent drilling muds, nor problems associated with **naturally occurring radioactive materials (NORM)**.

Remediation of hydrocarbon spills by bioremediation is discussed briefly because hydrocarbons are often associated with salt spills. However, this manual was not designed to provide rigorous treatment of remediation techniques for hydrocarbon spills. The operator should decide if the use of this manual addresses the spill and site conditions, or if a different approach, beyond the scope of this manual, is warranted.

Reference to Similar Remediation Scenarios

Substantial amounts of time may be saved if a salt-affected area can be handled similarly to a previous experience. Although no two salt-affected areas will be exactly the same, spills in relatively similar settings and on the same soil types may be subject to remediation by similar techniques.

In attempting to rely upon previous experiences, care must be taken to ensure that the soil and drainage conditions are sufficiently similar to warrant using the same remediation techniques. Many salt-affected areas which appear similar on the surface may be quite different below ground.

If the spill and site circumstances are similar then minor modifications to previous remediation efforts may be possible. For instance, adjustments to previous remediation activities may be based on different factors such as different areal extents and salt and sodium concentrations.

Background Vegetation

Observing the type, relative coverage, and health of background vegetation will provide a reference point for monitoring the progress of the remediation effort by comparing the spill area to the background area. An understanding of the background vegetation is especially important as climate conditions change seasonally.

The appearance of background vegetation also may affect selection of appropriate remediation goals. Remediation may fail if the land will not support the remediation vegetation envisioned. Poor health of background vegetation may also indicate that the site has other problems that may influence the operator's choice of a remediation alternative.

Background vegetation may also influence the selection of chemical amendments. If the area is prime farmland, hay may be an inappropriate organic additive because of the foreign seed it may introduce. In infertile soil, calcium nitrate may be preferable to calcium carbonate and a source of calcium because it supplies nitrogen to stimulate biota. The county agriculture extension agent is often an excellent reference for selecting plants compatible with background areas. Additional information on appropriate plants is given in Appendix F.

Sufficient Data

A detailed assessment of remediation options is usually preceded by a determination of whether sufficient data have been obtained for making a knowledgeable decision. Examples of situations where field personnel may decide not to proceed without additional information may be as follows:

- The laboratory data appear inaccurate or inconclusive.
- Sampling indicates that salt effects are deeper or more severe than originally perceived, and additional sampling may be required.
- The background sample shows high salt levels or other significant problems.
- A wetlands determination has not been made.

As shown in Figure 5-3, if additional data are needed, field personnel may wish to obtain the missing information before continuing. To gather additional data, they may decide return to Step 3A (Figure 5-2). If field personnel feel that they have sufficient data to perform an accurate assessment of the site, they may decide to proceed to Step 4B (Figure 5-4).

Wetlands

Because of their unique status as waters of the United States, wetlands may have different legal limitations from uplands near the same location. For example, COE permits or other requirements may apply. These alternative requirements and limitations should be evaluated before selection of an alternative.

Wetlands are areas which are periodically inundated and exhibit vegetation, soils, and hydrologic characteristics which are typical of commonly water-saturated conditions. Although previously developed wetlands maps are available which can give a general indication of wetlands locations, they cannot be entirely relied upon. Because it is important to be certain about the wetland or non-wetland status of a spill site (Figure 5-4, Step 4B), a wetlands delineation should be performed by a qualified specialist if there is any doubt. The COE can also make a wetlands determination. However, depending on the COE's workload, this determination may add a month or more to the project timetable. Although this manual is applicable to wetlands, there are significant issues involved in remediation of wetland sites which may not be covered. In particular, wetlands merit special attention because of potential regulated technical restrictions on remediation choices.

Wetlands do not have to look like wetlands to be covered by the Clean Water Act. Many areas which would be normally considered upland or dry land are considered wetlands simply by definition. The only authority for determining whether an area is a wetland is the COE; however, the determination is largely based on submission of a formal wetland delineation report.

Halophytes

The second question in Step 4B (Figure 5-4) relates to possible use of halophytic vegetation (salt-loving plants) as part of the remediation process. Where the situation is appropriate, use of halophytic vegetation is an excellent and potentially inexpensive option for remediating salt-affected soils. Halophytic vegetation may also serve as an interim measure in remediating more highly affected soils. A procedure for determining if halophytic vegetation is a viable option, or useful with other options, is presented in Worksheet 1 (Appendix B).

Halophytes are plants which are extremely salt tolerant or which may actually prefer saline soils. Use of halophytic vegetation provides a modified form of passive remediation due to their often prolific growth in salty soils. One of the limitations of the use of halophytes is finding an appropriate commercial seed/seedling source.

Although halophytes may remove some salt from the soil and transfer it into the overlying foliage, very little salt typically is removed from the site each growing season. However, over a number of growing seasons, the amount of salt removed by halophytic vegetation may be significant. In addition, halophytic plants provide ground cover which may prevent erosion. If halophytic plants match land use conditions (Appendix F), they may provide a relatively inexpensive alternative if natural remediation is insufficient.

Worksheet 1 is provided to assess the suitability of using halophytic vegetation as part of the remediation strategy. Information on anticipated growth conditions is used to generate a list of candidate plants suitable to those conditions. A determination may then be made regarding whether use of one or more of these halophytic plants would be suitable based on any other constraints.

Appendix F provides reference material on the seeding and tolerance of various plants. As with other remediation techniques, when using establishment of halophytic vegetation as the sole remediation technique, a determination that salts will not migrate into usable or sensitive groundwater should be made.

<u>Groundwater</u>
In general, any impact on groundwater should be avoided unless it is known that the strata receiving salts will not be unacceptably degraded by the salt effects (e.g., shallow saline aquifer; a brackish, poor quality aquifer which cannot be used as a source of usable water; etc.). Migration of salts into groundwater could increase the potential for legal action and may also violate regulatory requirements. The migration of salts into groundwater may also result in the involvement of other agencies with concurrent escalation of project administrative costs.

Decision Tree Step 4B (Figure 5-4), involves evaluation of whether the salt has the potential for migrating to the shallowest usable water table. "Usable" is a loose term in both regulatory and technical respects. In some states, the groundwater criterion for total salts is set at 10,000 mg/L TDS which corresponds to an approximate EC of 16 mmhos/cm. In some states, even when the shallowest groundwater exceeds 10,000 mg/L TDS, it is still protected as "treatable" groundwater.

In locations where the shallowest groundwater exceeds 10,000 mg/L TDS, the aquifer may be considered by regulators as unusable. Additional salt contamination of these aquifers may not be considered environmentally harmful. It may be advisable to attempt to document such a determination in writing.

Groundwater also may be impacted even when it is relatively deep. Fractured bedrock, porous limestone rock, and sands may provide large unobstructed pathways through which saltwater can percolate into a freshwater aquifer.

Under optimal conditions, a thick clay layer of low transmissivity will be present in the deep subsoil to halt the migration of salts between the soil surface and the groundwater.

If the salt could potentially impact groundwater and there is no realistic method of preventing that migration, remediation alternatives may be limited to mechanical techniques.

Salt Movement

The next issue in Step 4B (Figure 5-4) is to establish whether salts can migrate out of the root zone. This is principally a matter of soil drainage. One of the most common causes of remediation failure is neglecting to assure that displaced salts can permanently move out of the root zone.

Although migration of salts into usable groundwater is generally avoided, the objective of chemical amendment remediation is to leach the sodium ions below the root zone so they will have minimal effect on vegetation. For this to occur, the soil must have sufficient porosity to allow migration of water from the surface to a depth several feet below the root zone. If the salt is not leached deeply enough, it could return to the surface with upward-moving water by means of capillary action during evaporative periods.

The determination of whether the salt has migrated to a depth below the root zone can be expensive. In semiarid to arid areas (highly negative PEI), the salt must typically migrate to greater than 5 ft in depth to prevent capillary action from bringing it back to the root zone.

The main barriers to movement of salts to beneath the root zone usually are a shallow water table or impermeable layers. In these cases, rain or added leaching water can move the salts downward only as far as the impermeable zone or into the top of the shallow or **perched groundwater** table. In these instances, the salt can remain in the upper saturated zone until evaporative forces move it back up into the root zone and soil surface.

Worksheet 2 (Appendix B) provides a mechanism for determining whether the salts can be expected to exit the soil depths which typify the root zone. For further information, Appendix E provides a detailed discussion for improving poor drainage.

If soil drainage is sufficient or can be improved such that the excess salts and displaced sodium ions can leave the root zone, then an *in situ* chemical alternative is possible. If salts cannot exit the root zone, remediation may be limited to mechanical alternatives. The presence of poor soil drainage characteristics may also provide a reason to reconsider the use of wetness-tolerant halophytic vegetation in the remediation strategy.

Generally, older spill sites will tend to have poorer drainage when compared to fresh spill sites because they have had a longer period of time to become dispersed and topsoil may have already eroded away. Dispersed soil can result in lower water transmissivity, and the loss of topsoil may leave a less permeable subsoil exposed at the surface and decrease the depth to water table.

To achieve adequate salt leaching to a depth below the root zone, any dispersed layer must be re-aggregated, any cemented impermeable layer must be fractured, and any near-surface water table must be lowered sufficiently to allow the salts to migrate to a depth below the root zone. Otherwise, chemical amendments may not permeate the soil, leaching water may become perched above the restrictive zone, or the elevation of an already shallow water table may be even further elevated. Methods for accomplishing these site alterations are described in Section 7.

<u>Supplemental Water</u>

In situ chemical amendment remediation requires sufficient water to dissolve the chemical amendments and permanently leach salts through several soil horizons to a location below the root zone. Much, if not all of this water is available from rainfall (and melting snow) in the eastern United States. However, in the more arid regions, rainfall is often insufficient to permanently move salts to a deep enough location that they will not return to the surface during evaporative periods. Inadequate rainfall must be supplemented with good quality irrigation water if chemical amendment treatment is to be successful.

Care should be taken in irrigating dry region spill sites. Surface or subsurface irrigation water itself is often high in dissolved salts (TDS >1,000 mg/L) and can contribute to the soil salt load if not managed properly.

The issue regarding the need for and feasibility of applying supplemental water is addressed in Step 4B (Figure 5-4). Worksheet 3 (Appendix B) provides a method for determining the need for supplemental water.

In arid areas, good quality freshwater may not be available at reasonable costs. If additional freshwater is required for *in situ* chemical remediation and this water is not available or practical to apply, then natural or mechanical remediation techniques may be the only remaining alternatives. It may also be advisable to reevaluate the possibility of utilizing dryness-tolerant halophytic vegetation in the remediation strategy.

In summary, the cost effectiveness of supplemental watering as a remediation alternative will likely be a key factor in the decision of whether to use irrigation at a site. Further information on utilization of irrigation in the remediation effort is presented in Donahue, *et al.*, (1983) and Tanji (1990).

Erosion

For *in situ* chemical amendment remediation alternatives to be viable, the soil must remain in place. Soil retention can be a problem where the soil is susceptible to erosion, and excessive salts and sodium increase soil erodibility.

The issue of potential soil erosion is addressed near the bottom of Step 4B (Figure 5-4). No worksheet is provided to work though the erosion question because it is relatively straightforward.

Erosion can be problematic on even slight slopes, but is a potentially severe problem if the slope is steep (e.g., greater than 8%). Loss of vegetative cover as a result of excess salinity removes the principal mechanism of slope interruption and the physical protection of the soil surface. If subsequent rainfall decreases salinity at the soil surface, the soil can disperse and become extremely susceptible to erosion.

If the area is subject to erosion, one or more erosion-control options may be implemented to minimize erosion. Chemical amendment technology will be most effective if erosion is controlled. Some erosion control methods include:

Berming	Mulching
Terracing	Rapid establishment of vegetation
Prevention of runon and runoff	Contour tillage
Leveling	Hydromulching
Erosion-control fabrics	Biodegradable nets

If erosion cannot be controlled, or efforts to control erosion are impractical, then mechanical remediation alternatives may be the only viable options.

Alternative Selection

Completion of the Decision Tree should lead to one of the three categories of remediation options at the bottom of Step 4B (Figure 5-4). The three categories of remediation options are natural remediation, *in situ* chemical amendment remediation, and mechanical remediation.

If natural (unenhanced, passive) remediation is a viable alternative, it normally presents the least expensive option. For this reason, the natural remediation option is the technology for first consideration. Selection of this option is denoted by being directed to the natural remediation box in the lower left corner of Figure 5-4. Selection of the natural remediation option should be with the understanding that the cost of proceeding with natural remediation may entail some monitoring or other closure expenses.

If use of the Decision Tree has culminated in the center box on the bottom of Figure 5-4, then *in situ* application of chemical amendments has been selected as the preferred option. Even though *in situ* chemical treatment appears (from the Decision Tree) to be a viable alternative for only a narrow range of parameters, it is a common remediation method for salt-affected soils. *In situ* chemical amendment remediation often offers the best compromise between speed of remediation and cost.

The critical element in successfully applying *in situ* chemical amendment remediation is a sufficient understanding of the spill site. *In situ* chemical amendment remediation is most likely to succeed if sufficient investigation is undertaken to ensure that the chemical addition and other parameters are appropriate for site-specific soil, landscape, and climate conditions. If *in situ* chemical amendment remediation is selected, Worksheet 4 (Appendix B) will provide a method for calculating amounts of chemical amendments.

If the mechanical remediation box in the lower right corner of Figure 5-4 was the end result of working through the Decision Tree, then the primary thrust of the remediation effort will involve physical relocation of the spilled material. Except for onsite land spreading, mechanical remediation alternatives are normally somewhat more expensive than natural or chemical amendment remediation alternatives. Onsite mechanical remediation may impact previously unaffected land during soil relocation or treatment. It is for these reasons that mechanical remediation is considered the last resort and is selected by elimination of the first two options.

Mechanical remediation techniques are discussed in more detail in Appendix H and are considered to be quite reliable. Removal of the salt-affected soil and replacement with fresh soil will usually remediate the site. Once the mechanical remediation alternative is selected, it may then be implemented according to the procedures provided in Section 7.

REVIEW OF SECTION 6

The site assessment may be the most critical aspect of the entire remediation process. Essentially all of the remediation decisions made will depend on data generated during the site assessment. Section 6 is summarized as follows:

- Site assessment procedures include obtaining and organizing data, developing realistic remediation goals, and selecting a specific remediation plan for salt-affected sites.
- Data gathered in the initial spill report include the type, intensity, and date of the spill, any initial attempts to respond to the spill, and a review of notifications submitted.
- Preliminary data obtained include soil and agricultural information from the Soil Survey, climatic data, regulatory information, a list of regulatory constraints, and elimination from consideration any obviously inappropriate remediation options.
- During the site assessment, a site sketch should be prepared describing the physical interrelationships of important site features and a notation of sample locations.
- Among other determinations, observations associated with collection of samples provide an opportunity to estimate the ability of the soil to drain. There are physical, chemical, hydrological, and biotic methods for improving soil drainage.
- It is important to use an analytical laboratory with a well-trained staff that is experienced in soil analyses.

- Some spill circumstances may extend beyond the scope of this manual.
- Information and experience gained in remediating similar spill scenarios on similar soils can be used to streamline the decision-making process regarding new spills.
- Poor health of background vegetation may indicate that the site has problems which extend beyond the saltwater spill in question.
- If remediation decisions are made based on insufficient data, the risk of remediation failure is also increased.
- Additional considerations become important if the spill affects wetlands. It is therefore important to determine if the spill site is in a wetland.
- When appropriately used, halophytic vegetation can provide temporary or permanent vegetative cover as well as other remediation benefits.
- It is important to determine if salts will move into groundwater. Salts which migrate into groundwater may migrate with groundwater. Salts should be allowed to move into groundwater only if it is determined that this will be acceptable under the circumstances.
- For chemical remediation to succeed, salts must be permanently leached below the root zone. A rule of thumb is 5 to 6 ft below the surface.
- In areas of inadequate or possibly marginal rainfall, supplemental water may be required to permanently leach salts below the root zone. Except for humid areas in the western United States, soils west of the longitude of Houston, Texas, will probably require supplemental water for sufficient salt leaching.
- Erosion occurs on even relatively flat soils, but is especially problematic on soils with slopes in excess of 8%. Erosion-control measures are often required to keep the soil in place until vegetation can be reestablished. There are a number of methods for controlling erosion.
- In general and when appropriate, natural remediation is often the preferable method of remediation, followed by chemical remediation which is the most commonly selected method. Mechanical remediation is usually the method of last resort, but depending upon site conditions, may be the most effective.

Section 7

REMEDIAL ACTION (STEP 5)

As noted in Sections 5 and 6, there are three main categories of remedial action. They are natural (unenhanced, passive) remediation, *in situ* chemical amendment remediation, and mechanical remediation. By using the Decision Tree and associated forms and worksheets, the operator should have identified one of these remediation methods as the most suitable for the site in question. There may be some circumstances under which a combination of methods are most suitable, for instance a mechanical remediation technique and use of chemical amendments. In selecting a remediation option, the nature and cost of post-remediation monitoring should also be considered.

NATURAL (UNENHANCED, PASSIVE) REMEDIATION

Natural remediation involves remediating the spill site with negligible to minimal input from humans. Allowing nature to recover on its own is also called "unenhanced" and "passive" remediation. Because input is minimal, use of halophytic vegetation without additional chemical inputs is also included as a form of natural remediation. Natural remediation includes:

- Unassisted recovery
- Unwarranted input
- Halophytic vegetation

Unassisted Recovery

Natural remediation refers to sites where nature is expected to aggressively or slowly revegetate an area. Depending on the severity of the spill and the aggressiveness of surrounding vegetation, natural revegetation is most easily accomplished in areas where soil is naturally fertile, rainfall is high, drainage is adequate, the site is frequently flooded, and/or the area is naturally associated with brackish or salty water. As complex as the interaction of variables and as varied as natural conditions are, it is difficult to state that there are any environments where natural remediation will absolutely not occur. However, it will be extremely unlikely in many areas.

Unwarranted Input

Another situation which falls into the natural remediation category is when attempts to remediate an area would have no beneficial impact on the environment or where remediation activities would only further damage the affected site or surrounding environment. It is important to recognize that there may be some situations which may best be left alone—where any resources expended would be wasted.

Halophytic Vegetation

Use of halophytic vegetation is included in this section because it represents only a minor adjustment to natural processes. Halophytic vegetation is specialized for both wet and dry conditions, and for both cold and warm regions. Prior to use of halophytic vegetation, it should be determined that the plant(s) will be suitable for the site conditions and is unlikely to become a nuisance. A number of halophytic plants are excellent cash crops. To illustrate an extreme example, there exist some intensively managed agricultural systems where seawater has been successfully used to irrigate crops for long periods of time (Glenn, *et al.*, 1996). Such systems tend to work only if irrigation is maintained on a frequent and long-term basis because excessive salt buildup due to evaporation is a significant risk within days after irrigation is stopped. General parameters of some halophytic vegetation are provided in Appendix F, and substantially more detail regarding use of halophytic vegetation is included in Choukr-Allah, *et al.* (1996).

At a site selected for natural remediation, valuable information can still be obtained by documentation. Information about the spill event, initial site conditions, and progress toward recovery provides a basis for considering the same passive techniques for other spills which may occur in the area. On some sites with previously existing severe natural disadvantages, documentation may be as simple as noting that the salt-affected area is not expanding. For sites where natural conditions result in revegetation, or where establishment of halophytic vegetation has been utilized, documentation may consist of a description of the rate of revegetation or the change in surface EC. Worksheet 5 (Appendix B) has been provided to document the recovery process.

IN SITU CHEMICAL AMENDMENT REMEDIATION

In situ chemical amendment remediation of salt-affected soils has been used extensively in agricultural settings. Chemical amendment remediation may include one or more of the following activities:

- Improvement of drainage
- Application and incorporation of chemical amendments and other soil additives

- Installation of erosion controls and irrigation
- Bioremediation and revegetation

Improvement of Drainage

If the results of Worksheet 2 (Appendix B) and Step 4B (Figure 5-4) of the Decision Tree indicate that improved drainage is required, and improvement of site drainage is feasible, then installation of drainage enhancements may be the first remediation step to be taken in preparation for *in situ* chemical amendment remediation. Improvement of site drainage is employed to create a route sufficiently interconnected and open to allow salts to be effectively leached from the root zone.

Causes of drainage problems include the presence of a hard impermeable layer or shallow bedrock, a dispersed soil or tight or high shrink-swell clays, and/or a high water table. These three types of drainage problems are handled in different manners.

If a hard impermeable layer is the cause of poor internal soil drainage, then there are two principal methods for overcoming this problem. The subsoil can be: (1) mechanically ripped by deep chisels, ripper shanks, or a giant slip plow; or (2) fractured with hydraulic injection of water or preferably a chemical amendment. Examples of some of this equipment are depicted in Appendix E.

If shallow bedrock is the drainage-limiting feature, then the potential environmental impact and practicality of attempting to breach it may be considered. However, it may be counterproductive to breach shallow bedrock if it overlies usable or sensitive groundwater, or if it could lead to migration of the salts to a sensitive offsite area. Fracturing or breaching bedrock sufficiently to enhance drainage may also be physically unrealistic. Under these circumstances, alternatives such as use of halophytic vegetation or mechanical remediation may be reconsidered.

Drainage restriction due to a dispersed soil, heavy clay, or high shrink-swell subsoil usually can be overcome by addition of chemical amendments and bulking agents. Use of chemical inputs and bulking agents is covered below in the discussion on chemical amendments.

If a high water table is the cause of the drainage problem, then the water table must be lowered to use chemical amendments effectively. Use of a perimeter trench drain and two types of subsurface drains are discussed in Appendix E. In northern prairie states, high-water-consuming, deep-rooted vegetation (such as alfalfa) has proven effective in lowering the water table during the growing season (Halvorson and Reule, 1980; Halvorson and Black, 1974 and 1976).

Subsurface drains placed beneath the salt-affected area can be used to intercept saltwater which may be migrating toward usable or sensitive groundwater. Plans may include provisions for collection and disposal of the saltwater collected in the drains. Although perimeter trench drains may be effective for lowering the water table, they may not be very useful for the purpose of intercepting downward migration of salts.

The correct placement of subsurface drains is critical to their efficiency, and a number of interrelated factors are involved. By working with a drainage expert designing and installing drains in a given type of soil, the user may quickly discern the interrelationship of critical drainage factors and become proficient at designing and installing drainage controls for other spills on similar soils. Information on design and installation of very basic subsurface drainage systems is provided in Appendix E.

<u>Application and Incorporation of Chemical Amendments and Other Soil Additives</u>
After drainage improvements have been installed (where required), chemical amendments and other materials, such as mulch and manure, may be incorporated into the soil during tillage operations.

Chemical amendments are used primarily to displace sodium. Organic materials provide bulking materials to improve drainage, minimize erosion, and stimulate biotic activity. Incorporation of organic materials is advisable in most spill conditions, except on organic soils.

Addition of 2 to 4 inches of organic material will normally be adequate in low organic, mineral soils. It is difficult to add too much organic material and usually mulch addition is controlled by cost and availability. The type of organic material added should be consistent with land use. Obtaining advice from the landowner or other knowledgeable individual(s) regarding preferred local mulches and manures is advisable. For instance, hay from certain fields may contain excess undesirable seeds.

Broadcast fertilizer can be incorporated with mulch if the salts concentration is sufficiently low that plants and seeds already present in topsoil could revive after a short period of leaching, or if oil is present which also requires bioremediation. However, if substantial leaching must occur before plant growth is likely to recur, then it may be advisable to postpone fertilizer addition until the salts level has declined and most leaching has been accomplished. This will prevent leaching away the fertilizer together with the salt.

It is best to apply chemical amendments to the soil before any leaching commences. Although it is possible to perform some leaching prior to chemical amendment application in highly saline soils, it is critical to monitor intensively the rate of decrease of EC during the leaching process. This is important because of the difficulty in predicting the rate of salt leaching from soils and the potential for inadvertently inducing dispersion due to lack of chemical amendment.

Chemical amendments and mulch and manure (if recommended) are typically spread uniformly over the soil surface. If more is required, it should be applied incrementally. If calcium nitrate is to be used, it should be applied only in increments which will allow the nitrate to be intercepted and consumed by soil microbes or plants, unless no surface water or usable or sensitive groundwater will be affected by the nitrate.

Depending on the depth of incorporation (0–1 or 1–2 ft), a plow, agricultural disc, chisel plow, industrial disc, or deep rototiller may be utilized. Liquid amendments, such as some of the proprietary chemicals, can also be applied over the soil surface with or without mechanical incorporation. If minimal water is used with liquid chemical amendments, tillage may also be used to more deeply incorporate amendments.

The objective of the chemical amendments is primarily to treat the upper 0–1 and/or 1–2 ft depth increments. The cost of applying chemical amendments for deeper treatment may be prohibitive. Soil deeper than 2 ft is treated primarily with leaching and by deep percolation of dissolved chemical amendment placed closer to the soil surface. As displaced salts move below 2 ft in the soil, their concentration should be sufficiently high to prevent the subsoil from dispersion. Worksheet 4 (Appendix B) provides the calculation procedure for determining application rates for chemical amendments.

When gypsum is incorporated into the soil, it is possible that the amount remaining at the very surface of the soil may be insufficient to interact with the uppermost soil particles. However, a final topdressing of gypsum and mulch can protect the soil surface from dispersing after a rainfall or irrigation event. The importance of this step cannot be overemphasized. Use and application of chemical amendments are discussed further in Appendix K. Use of mulch and manure is discussed further in Appendix L.

Mechanical implements used in conjunction with placement of chemical amendments can also be used to enhance drainage physically. For instance, tillage helps to break up dispersed surface soils. Subsoilers, slip plows, and chemical injectors can help quickly to improve drainage problems caused by heavy clays and high shrink-swell subsoils. Although flocculating materials which supply aluminum, calcium and/or magnesium cations, and polymers will ultimately migrate into intimate contact with dispersed clays, incorporation by these physical methods will often decrease remediation time.

There may be a very easy way to deep-incorporate chemical and bulking amendments into high shrink-swell soils. Although the database is incomplete and more confirming studies need to be performed, it has been suggested that chemical amendments and mulch could be applied in a manner which encourages these materials to fall or wash into the deep cracks in these soils during the dry season when the shrink-swell cracks are wide and deep. Shrink-swell soils are called "self-mulching" soils because they churn internally as wet and dry seasons alternate. Because the biggest problem with these soils is getting the chemical amendment deeply enough into the soil to have it aggregate the clay in order to open macropores, the natural actions of these soils may provide sufficient deep-mixing action. Treating shrink-swell soils in this manner is not necessarily advocated at this time, but the rationale is presented for consideration by the user.

A number of vendors of proprietary chemicals have entered the field of remediation. While many of these chemicals may enhance remediation, others are merely expensive versions of commonly available chemicals. The operator may choose to review documented comparative studies carefully before investing in expensive proprietary amendments. Equally important is an understanding of the conditions in which each chemical amendment will function effectively. Chemical amendments which may work well in some circumstances may be ineffective or even harmful if used in inappropriate circumstances. This manual may help to provide a basis for discussing the applicability of proprietary chemicals to specific spill sites.

Installation of Erosion Controls and Irrigation

Depending on the extent of erosion, controls can be installed before or after application of chemical amendments and mulch. If the soil salinity is high enough to prevent bioremediation or revegetation quickly enough to control erosion, then installation of erosion controls and irrigation should be initiated first. Otherwise, it may be more efficient to apply bioremediation and revegetation materials before installing erosion controls and irrigation-associated devices which may interfere with fertilizing and planting equipment.

Erosion Control. It is important to install any necessary erosion controls as soon as possible under any circumstances, even in dry regions. It takes only one rainfall event to remove sufficient topsoil or create erosion gullies which can substantially increase the difficulty involved in remediating a site. This is especially important for erosion-prone soils, such as soils on steep slopes or with high erosion K (internal erodibility) factors.

The objective of erosion controls is to interrupt and shorten the slope, minimize velocity of the surface water, minimize volume of runon water, and protect topsoil. Erosion controls therefore inhibit surface water from running onto the site (runon), surface water from running off the site (runoff), and the erosive action of water on the salt-affected site.

Runon and runoff controls may be as simple as staked hay bales upslope and downslope of the salt-affected perimeter, or small berms in the same locations. Like hay bales, fabric silt fences can trap runoff sediments downslope of the salt-affected area. **Terraces**, land contouring, and land leveling can also be used to control water flow, and these techniques may work best if the slope angle is more than 8%. Another technique useful for steep slopes is erosion-control blankets which can be stapled into the soil slope. Erosion-control blankets very effectively decrease the rate of water flow over the soil and they can also be custom-impregnated with a specific seed mix. If the salt-affected area has an excessive **slope length**, these erosion controls may also be installed inside the salt-affected area.

Even simpler techniques for controlling erosion include application of mulch on the soil surface. Mulch is very effective, typically inexpensive, and commonly available. In most cases the more that is applied the more effective the remediation effort, especially with regard to rapid soil recovery time and drainage improvement. Application rates of 30 tons/acre are not uncommon. However, there may be a limitation to the degree of slope on which mulch can be expected to remain without being incorporated. Mulch incorporated or tacked into place is less likely to float away with surface runoff. All of these practices will improve water-use efficiency by increasing hydraulic head and infiltration of leaching water and decreasing evaporative losses.

Irrigation. Some equipment and techniques used for erosion controls can also be used for irrigation controls. Berms can be used to provide a perimeter for retaining water above the site for ponding purposes. Berms can also be used to intercept upgradient runoff water and focus it onto the spill site. For supplemental water to be applied evenly over the affected area, during ponding the soil surface should be somewhat leveled by terraces or other devices. Otherwise, sprinkler irrigation may provide more even distribution.

One cost-effective option for applying supplemental irrigation water is the pulse-flooding method. The amount of supplemental water, if any, can be determined on Worksheet 3 (Appendix B). In pulse flooding, only a portion of the total supplemental water required is applied at any one time. For instance, if 12 inches of supplemental water are required, only a few inches of water are applied at a time. If it will be evenly distributed, chemical amendment can be applied in this supplemental water in dissolved or slurry form.

Once the ponded water has infiltrated the soil, an additional week is allowed for the water to percolate downward and into soil micropores. Toward the end of this period, salts in the micropores will have been able to migrate to the surfaces of the macropores; this is the ideal time to apply the next increment of water. The increments of water should be spaced about a week apart to keep the predominant water flow downward. If more than a week or so transpires between additions of water, then evaporative forces may begin to cause salts to reverse course and rise toward the soil surface. The benefits of pulsed leaching (intermittent ponding) are described in numerous publications including Tanji (1990) and Abrol, *et al.* (1988).

If the cost of supplemental water is high, it is better to undertake leaching when plants in the affected area are in a slow growth phase. The objective of leaching is more to move salts permanently down below the root zone than to grow plants, which becomes more important later. When plants are actively taking up water during aggressive growth stages, the water and the salts carried in the water may be moving toward near-surface plant roots.

The quality of supplemental water applied is of great concern. In a number of locations around the country, surface water and/or groundwater contains more salts or suspended solids than are advisable to apply to soil. In general, the quality of water applied should be such that the EC is less than 1 mmho/cm, the SAR is less than 10, and the total suspended solids are low. "Hard" water which has an EC greater than 1 may also be acceptable if the salt cations are principally calcium and magnesium. The county agriculture extension agent or local irrigation specialists can be valuable resources regarding the suitability of surface or groundwater for irrigation.

Keeping a record of the amount of rainfall and the amount of supplemental water used will help in tracking when sufficient supplemental water plus rainwater has been applied and calibrating irrigation to local conditions for future remediation activities.

Bioremediation and Revegetation

Bioremediation and revegetation involve management of living organisms. Bioremediation involves the decomposition of organics (e.g., petroleum hydrocarbons) by soil microbes, and revegetation involves planting and/or revitalization of plant life which extends above the soil surface. Both are linked by the common need for fertilizer, **aeration**, and moisture, and preference for a low salt content.

After drainage improvements have been installed and if the salinity of the surface soil is or will soon be tolerable for plant growth, bioremediation and revegetation activities can be initiated. Soil salinity should be sufficiently low to begin bioremediation and revegetation activities when the soil has been lowered to an EC of <16 mmhos/cm, unless plants with a higher germination and seedling salt tolerance will be used.

Soil microbes participating in bioremediation of oil and decomposition of incorporated organic mulches compete with plants for fertilizer, aeration, and moisture. As a result, sufficient fertilizer should be applied to facilitate both activities. The amount of fertilizer required when both bioremediation and plant growth are simultaneously underway is based on the carbon to nitrogen to phosphorus ratio (C:N:P ratio). Many petroleum hydrocarbon consuming bacteria also have a greater tolerance for salt than most plants.

Revegetation is the reestablishment of vegetative cover. Topsoil remaining on the site may already contain substantial seed. During appropriate seasons and wind directions, plants outside the spill area will also disperse seed onto the spill site. The objective of revegetation is to promote the growth of these plant materials or other specifically selected plants.

In the event that more rapid revegetation is required, or a certain species is preferred, new seed may be planted. In order to plant new seed, a seedbed should be prepared. If erosion-control features involving substantial movement of soil to prepare berms or to level land are called for, it may be preferable to delay planting until after these controls are established. As noted below, erosion control and site seeding can be accomplished in the same step. Otherwise, seeds or sprigs should be applied to the soil in accordance with local practices.

For small sites, the hand-operated fertilizer spreader can apply fertilizer and chemical amendments over rough terrain. A hand-operated rototiller or small tractor with discs can then be used to till to a depth of approximately 6 to 12 inches. Tillage to this depth will also ensure that the soil amendments and oily soil will be thoroughly mixed together and to the proper depths.

MECHANICAL REMEDIATION

Mechanical remediation may be appropriate when natural remediation (including halophytic revegetation) or *in situ* chemical amendment remediation is not advisable. However, in some circumstances, mechanical remediation will be the least complex and least costly option. It usually provides the fastest and most reliable method of remediating a spill site, and is normally the preferred technique for pit remediation. Categories of mechanical remediation are:

- Land spreading
- Burial
- Road spreading
- Soil washing
- Offsite disposal

Most mechanical remediation involves excavation and relocation of the salt-affected soil to a suitable location for treatment or ultimate disposal. After excavation, clean soil is typically brought in to replace the excavated soil. New subsoil can be used for deeper excavations, but the uppermost 1 ft is generally replaced with clean topsoil which will host new vegetation. Erosion controls may also be advisable until the site stabilizes.

Mechanical remediation is most often selected for sites with extremely high salt levels; near-surface usable or sensitive groundwater; shallow soils; soils with a difficult to fracture impermeable layer; and where regulatory, lease, or other legal considerations favor mechanical remediation.

Details for mechanical remediation techniques are provided in Appendix H. The following is an overview of mechanical remediation techniques.

Land Spreading

Land spreading has long been a favored mechanical remediation method for smaller spills. Land spreading involves spreading the salt-affected soil evenly over an area large enough to decrease the salts concentration to an acceptable level. As shown in Appendix H, the area of land required depends on the concentration of salts in the spill, the volume of affected soil, and the concentration of salts in the receiving land. Land spreading may be used alone, or in conjunction with *in situ* chemical amendment remediation.

Even if sufficient land is not available to bring salts concentrations to within the remediation goal, the available area may still be sufficient to decrease the salts concentrations to a level which is more readily treatable by chemical methods. The disadvantage to this approach is that the salt-affected surface area may be expanded, although at lower levels.

Depending on the size of the spill-affected area, land-spreading equipment may be large or small. A front-end loader or backhoe can be used for small areas. Other construction equipment (i.e., dozers, trackhoes, etc.) may be necessary for larger spill areas.

<u>Burial</u>

The burial technique involves placement of the salt-affected soil into a hydraulically and chemically isolated position relative to groundwater and runoff water. Therefore, burial is generally not used in areas with a near-surface seasonal high water table. Burial is typically used where the salt concentrations are sufficiently high that all other remediation techniques except offsite disposal have been rejected.

Several potential problems exist with burial technology and the long-term security of the buried material. The presence of plastic sheeting, rocks, and gypsum does not necessarily preclude the long-term effects of animal activity and vegetation. Deep-rooted trees in particular may disrupt the burial vault after several decades.

Design of the burial activity begins by determining the volume of salt-affected soil which must be buried. An ideal burial vault location is one where the bottom is at least 5 ft above the seasonal high water table, and the top of the salt-affected soil is at least 6 ft below the surrounding soil surface.

The salt-affected soil is excavated from the spill site and put into this cavity. An upper capillary barrier of plastic, gravel, or rock is then placed above the affected soil, followed by a layer of sand and a layer of gypsum. Under ideal conditions, the top of the gypsum layer is placed at least 5 ft below the soil surface.

Clean soil with sufficient clay to minimize deep percolation is placed above the gypsum layer. A clean soil layer that is sufficiently mounded above the surrounding soil elevation is more likely to remain mounded after subsidence. Contouring the final side slopes of the mound to less than 3% will usually minimize risk of erosion. At least the upper 1 ft of soil should be fertile topsoil. The soil should be vegetated in a self-sustaining grass adapted to the area and soil used. The mounded top helps minimize deep percolation of water and to direct rainwater and potential runon water away from the site. Fertile topsoil in the upper 1 ft of the mound is important to re-establishing vegetation.

Road Spreading

Road spreading often represents an excellent use for salt-affected soil. Salt-affected soil should be applied in a manner such that salt does not damage the road bed, roadside vegetation, or significantly affect runoff water. State and local regulatory considerations may dictate whether road spreading is a viable option. Regulatory agencies may also prescribe how road spreading must be performed.

Soil Washing

Soil washing may be done *in situ* or at a location removed from the site. Soil washing is essentially chemical remediation with intensive mechanical agitation to speed the reaction and better control the use and final disposition of soil, salts, and water.

In the initial phase of soil washing, freshwater or brackish water may be mixed with the salt-affected soil to decrease salinity if the relationship between EC and SAR is monitored closely to avoid dispersion. When the EC and SAR relationship begins to approach dispersion (low EC and high SAR), then the salty washwater can be drained and disposed. Chemical amendment additions with freshwater can then be applied to displace sodium from cation exchange sites. When the sodium has been displaced sufficiently to meet the remediation goal, the soil water containing the displaced sodium can be removed. When the EC and SAR or ESP goals have been achieved, the soil may require fertilization to replace and balance nutrients.

In addition to rapid and complete remediation, advantages to soil washing include close control of soil chemistry, chemical additions, and water which can result in material cost savings. A disadvantage is that soil washing has been very expensive and may require specialized equipment. For this reason, soil washing contractors are often utilized. If the cost could become more competitive with other remediation technologies, soil washing could become a preferred technique.

Offsite Disposal

Usually considered the option of last resort, offsite disposal often ranks as the most expensive method. Prior to submitting salt-affected soil to a commercial disposal facility, waste receipt criteria should be checked to determine if the salt-affected soil is within criteria for placement in the facility. State or local regulatory authorities may require a manifest to transport these materials. Depending on the landscape configuration, the excavation may require replacement soil and vegetation.

REVIEW OF SECTION 7

Remediating salt-affected soils can be a complex undertaking in which a wide array of physical, chemical, and biotic (both microbial and vegetative) factors are involved. In the event a remediation effort is to be initiated, it is important to provide sufficient planning and execute field activities such that the effort will succeed. Section 7 is summarized as follows:

- Natural remediation is an *in situ* technique which allows nature to progress with little assistance from humans.
- Natural remediation techniques include unassisted recovery, halophytic vegetation, and recognition that some sites do not warrant remediation efforts.
- Where feasible, natural remediation is often the preferred technology, and is becoming increasingly accepted in remediation of salt-affected soils.
- It is wasteful to attempt remediation at sites where tangible environmental restoration or improvement will not be realized or where the environment will be further damaged by the effort.
- Chemical amendment remediation involves the *in situ* displacement of sodium from clay cation exchange sites and permanent removal of produced water salts to a suitable location.
- Chemical amendment remediation can involve improvement of drainage, application of chemical and other soil amendments, erosion controls, irrigation, bioremediation, and revegetation.
- Mechanical remediation techniques involve excavation and physical transport of soil.
- Mechanical remediation techniques include land spreading, burial, road spreading, soil washing, and offsite disposal.

- Mechanical remediation is generally selected if natural or chemical amendment remediation techniques are unsuitable. However, mechanical remediation can be less complex and less costly than other categories of remediation.
- A goal of all remediation technologies is self-sustaining vegetative cover and no offsite migration of produced water salts.

Section 8

POST-REMEDIATION MONITORING AND PROJECT TERMINATION

The remediation effort is concluded when post-remediation monitoring and documentation demonstrate that the remediation effort has been successful, and that further administrative attention to the remediation project is unnecessary.

POST-REMEDIATION MONITORING

For most remediated sites, demonstration of the long-term effectiveness of the remediation effort will require an observation and monitoring period of at least two years. At some sites, follow-up physical treatments or applications of chemical amendment, fertilizer, etc., may be performed beyond the suggested two-year observation and monitoring period as a matter of typical agricultural practice. However, if the area does not appear to be undergoing an acceptable rate of remediation, the remediation effort is not complete and additional measures may be required. In general, if two reasonably wet growing seasons have passed without establishment of adequate sustainable vegetation, then chemical or physical soil problems may remain.

There are several reasons why two years of periodic monitoring are suggested. First, more than one year may be required for soil chemical and physical alterations to stabilize. Vegetative and climatic factors, including plant succession and changes in depth to the water table, will also vary seasonally and among years. Vegetation must demonstrate the ability to survive these fluctuations in order to achieve success. Severe climate and soil factors may dictate a much longer period than two years to achieve adequate revegetation.

The effort required for post-remediation monitoring also depends on closure criteria, regulatory reporting requirements, and lease considerations. Unless otherwise required, successful remediation can be assumed if vegetation is self-sustaining at the affected site, and downgradient effects of the spill are no longer problematic.

Unless remediation criteria require collection of soil samples, it may be possible to document remediation success with photographs and easily performed measurements of vegetation. Seasonal photographs can be used to document site and background conditions for the two-year monitoring period.

In some circumstances, evidence of no decrease in plant yields compared to background may be necessary. This information can be documented by estimating the relative plant abundance, height, and aboveground biomass. Biomass is measured by collecting similar plants from three discreet areas (e.g., three each from 1-square-meter plots) at both the affected site and the background, and weighing them for comparative purposes. If documentation is required that soil salt or petroleum hydrocarbon levels have been achieved, spill site and background soil samples may also need to be collected and analyzed.

Worksheet 5 (Appendix B) is a generic form for post-remediation monitoring. Worksheet 5 can be customized to address site- and operator-specific considerations.

PROJECT TERMINATION

The operator may wish to document that no further attention is warranted for the affected site or downgradient areas. To the extent practical, documentation of project termination can include evidence of regulatory, legal, and internal company recognition that the site is considered successfully remediated.

Monitoring a site can be expensive and time consuming. When selecting a remediation option, long-term costs and future concerns should be considered in addition to more immediate remediation costs—especially when accounting for high priority day-to-day production activities. If such costs are high, a remediation alternative which allows immediate project closure may be preferable to one requiring long-term monitoring.

Project termination is documented at the bottom of Worksheet 5 (Appendix B). Once completed, files pertaining to site remediation can be archived.

REVIEW OF SECTION 8

- Typically, a two-year periodic observation and monitoring period begins immediately following the remediation effort.
- The remediation effort is usually not completed until site vegetation is adequate in coverage and has been self-sustaining for the observation and monitoring period.
- If the remediation technical and cultural goals (i.e., drivers) have been met at the end of the post-remediation observation and monitoring period, the remediation project can be terminated.

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APPENDIX A

Tools for Creating a Field Manual for Remediating Small Areas of Salt-Impacted Soil

SUMMARY

Appendix A contains information to aid remediation decision making for the most common and least complex saltwater release sites (e.g., <1/10 acre, <2 ft in depth, and low to moderate inputs). For pit closures or spills that do not fall into this category, refer to Sections 4 through 7 and Appendix B of this manual.

Tools are provided to: (1) summarize site characteristics, (2) determine the viability of chemical remediation, and (3) estimate amounts of amendments to be applied if chemical remediation is deemed viable. (Note: Appendix B contains more comprehensive forms and worksheets that may be more suitable for many sites.)

Appendix A may be reproduced and combined with material from other appendices in this manual (and useful material from other sources) to create an individualized field or pocket manual.

USE OF APPENDIX A

Sections 5–7 of this manual discuss several remediation options that may be technically feasible at a given site. Often, a combination of technologies is viable. However, company policy, lease requirements, regulatory constraints, landowner considerations, and cost may influence the selection of a remedial approach.

This appendix provides a starting point for the user to create his/her own custom field guide for addressing the most common and least complex saltwater release sites (e.g., areas <1/10 acres, <2 ft depth of penetration into the soil, and low to moderate input requirements).

During the remedial decision-making process, the user may need to refer to other sections of this manual for additional information, data collection forms, and/or worksheets. The table below describes where these materials can be found for a number of activities. The user may wish to reproduce material from these sections to include in their own custom field guide.

Activity	**Refer to Manual**	**Helpful Forms and Worksheets (Appendix B)**
Estimate the horizontal and vertical extent of the salt-affected area	Section 6	Forms 3 and 4 or Form 5
Determine soil texture (coarse, medium, fine, etc.)	Section 6	Form 3
Measure electrical conductivity (EC)	Appendices G and J	-
Determine cation exchange capacity (CEC) and sodium adsorption ratio (SAR)	Appendices G and J	-
Determine the moisture deficit (potential need for and amount of supplemental water)	Appendix I	Worksheet 3
Application of chemical amendments	Appendix K	Worksheet 4
Mulching	Appendix L	-
Revegetation	Appendix F	Worksheet 1

Page A-2 contains a data gathering checklist of important site characteristics that may, at a small, relatively uncomplicated spill site, be substituted for Forms 3, 4, and 5. A checklist to determine the feasibility/desirability of chemical remediation techniques can be found on page A-3. If chemical remediation is selected at a site, the guidelines provided on pages A-4 through A-7 may be used to calculate the quantity of gypsum to apply, or Appendices B or K may be used to select alternative amendments.

The user is cautioned that remediation of salt-affected soils is a complex process dependent upon interpretation of several critical and interrelated variables, and appropriate application of corrective measures. Therefore, the user is advised to refer to other sections of this manual for clarification of any information presented in this appendix.

SUMMARY OF SITE CHARACTERISTICS

For relatively uncomplicated saltwater release sites, this data-gathering checklist may be substituted for Form 5 in Appendix B for summarizing general site characteristics.

Site Name:

Parameter	Value	Refer to Manual	Helpful Forms and Worksheets (Appendix B)
Horizontal and vertical extent of the salt-affected area (in sq ft)		Section 6	Forms 3 and 4
Predominant soil texture (coarse, medium, fine, etc.) to a depth of 6 ft		Section 6	Form 3
Maximum EC value in the salt-affected area		Appendices G and J	-
Maximum CEC and SAR values for the 0–1 ft depth interval		Appendices G and J	-
Maximum CEC and SAR values for the 1–2 ft depth interval		Appendices G and J	-
Net annual moisture condition		Appendix I	Worksheet 3

FEASIBILITY OF CHEMICAL REMEDIATION

For relatively uncomplicated saltwater release sites, this checklist may be useful for determining the feasibility of low to moderate intensity chemical remediation. Sites with more extensive contamination may require more in-depth analysis.

Condition	Yes	No	Implication	Refer to Manual
Is the EC <16 mmhos/cm?			EC >16 mmhos/cm usually indicates heavily affected areas. If immediate remediation is a priority, consider mechanical remediation options. Halophytic revegetation may be used in soils with EC >16, in some circumstances, and usually in conjunction with chemical amendments.	Section 4, Table 4-2 (page 4-11)
Is the water table "deep" (>6–10 ft below ground surface), or if shallow, is lowering the water table feasible?			The objective of chemical remediation is to displace salt so it can leach to an area below the root zone. Therefore, the top of the seasonal high water table should be at least 6 ft below the soil surface. If useable groundwater is subject to contamination either because of its shallow depth or permeable soil or subsoil characteristics, then mechanical techniques may be the most efficient means for protecting groundwater quality.	Section 7, Improvement of Drainage (page 7-3)
Are impermeable layers <u>absent</u> between 0–7 ft below ground surface, or if present, is disrupting of layers feasible?			Salt must exit the root zone (approximately 6 ft below ground surface) for chemical remediation techniques to be permanently effective in most cases. If the salt is trapped within the root zone by an impermeable layer, halophytic revegetation or mechanical remediation may be more cost effective than attempting to improve drainage and applying chemical amendments.	Section 3, Drainage (page 3-8); Appendix E; Appendix F; Appendix H
Is rainfall sufficient for leaching, or if not, is irrigation feasible?			Water, from either precipitation or irrigation, transports salt as it percolates downward through the soil. Unless rainfall is adequate, there will not be sufficient rainfall to leach salts to a safe depth. If the salt does not leach deep enough, it may return to the surface during dry seasons. The speed and effectiveness of chemical remediation will be enhanced by supplemental watering in regions with marginal or inadequate rainfall.	Section 3, Water (page 3-14); Section 6, Supplemental Water (page 6-16); Section 7, Irrigation (page 7-7); Appendix I
Is the potential for erosion minimal, or if needed, are erosion controls feasible?			Erosion is worsened by the loss of vegetative cover and other changes in the soil that may be caused by the effects of salt. Erosion inhibits the reestablishment of vegetation and the retention of chemical additives. If erosion control is not feasible, then mechanical remediation may be the only viable alternative.	Section 3, Slope and Erosion Susceptibility (page 3-7); Section 6, Erosion (page 6-17)
Is the pH <5.5 or >8.5?			Very acidic and very alkaline soils may present additional complications.	Section 3, pH (page 3-11) and Figure 3-7 (page 3-13); Section 4, Relationship of pH to ESP (page 4-9); Section 6, Table 6-1 (page 6-9); Appendix B; Appendix K

If any of the questions were answered "no," the decision maker should refer to the appropriate pages of this manual.

If all of the questions were answered "yes," low to moderate input chemical remediation is a technically viable option and may be further evaluated against other remedial options.

INSTRUCTIONS FOR TABLE A-1—RECLAMATION PRACTICES

For relatively uncomplicated saltwater release sites, Table A-1 may be used to estimate the amounts of amendments to be applied if chemical remediation is found to be a viable remedial option.

HOW TO USE TABLE A-1

1. Determine Moisture Deficit (Sections A, B, or C)
Find the section of Table A-1 that matches the rainfall characteristics for the site [select either adequate rainfall (Section A), marginal rainfall (Section B), or inadequate rainfall (Section C)]. To select the appropriate section, estimate the net annual moisture condition [i.e., precipitation evaporation index (PEI)]. Appendix I contains the information needed to calculate the net annual moisture condition. For the site of interest, obtain the normal annual precipitation and mean annual class A pan evaporation rate from the maps in Appendix I. Calculate the net annual moisture condition as follows:

Annual Precipitation (inches) Minus Annual Evaporation (inches) = Net Annual Moisture Condition

If the Net Annual Moisture Condition is:	Select Table A-1 Section:
Less negative or more positive than -12 inches (e.g., -4 inches or +7 inches)	A, Adequate Rainfall
Between -12 and -28 inches (e.g., -19 inches)	B, Marginal Rainfall
More negative than -28 inches (e.g., -33 inches)	C, Inadequate Rainfall

2. Locate Soil EC (Column 1)
Within the appropriate section of Table A-1, find the EC value in Column 1 that matches the site conditions. If EC levels are <4 mmhos/cm and there is evidence that the salt-affected soil will not support natural vegetation, chemical amendments may be needed to alleviate dispersed soil conditions. At low soil EC values, soil dispersion may occur if ESP >5% in soils with smectite clays or ESP > 15% in soils containing clays other than smectites (e.g., illites).

3. Calculate Chemical Amendment (Gypsum) Requirement
To calculate the amount of chemical amendment (expressed as gypsum) required, use the equation provided in Column 2:

a. Use the values for CEC and ESP from the 0–1 ft depth interval to calculate the gypsum requirement for the 0–1 ft depth interval. (Figure A-1 may be used to convert SAR to ESP.)

b. Repeat the calculation using the CEC and ESP for the 1–2 ft depth interval.

c. Add the results from the two calculations to get the amount of gypsum to treat the upper 2 ft of soil. An additional topdressing of gypsum will help prevent soil crusts from forming at the ground surface.

d. If the pH is <5.5 or >8.5, or chemical amendments other than gypsum are to be applied, consult manual.

EXAMPLE GYPSUM CALCULATION:

A site characterization found that the 0–1 ft depth interval had a CEC = 14 meq/100 g and an SAR = 32. The 1–2 ft depth interval was found to have a CEC = 17 meq/100 g and an SAR = 20. Using Figure A-1, the SAR values of 32 and 20 convert to ESP values of 37% and 26%, respectively. Using the equation in Column 2 (and ignoring the CEC denominator), calculate the pounds of gypsum per 100 sq ft of soil as follows:

0–1 ft depth interval: (14 meq)(37-5)(0.078) = 35 lb gypsum/100 sq ft

1–2 ft depth interval: (17 meq)(20-5)(0.078) = 20 lb gypsum/100 sq ft

To find Total Gypsum Requirement:

(35 lb gypsum/100 sq ft) + (20 lb gypsum/100 sq ft) = 55 lb gypsum/100 sq ft

If a chemical amendment other than gypsum is to be used, consult manual.

About 1 vertical ft of water will be required to dissolve 50 pounds of gypsum per 100 sq ft of salt-affected soil. Therefore, slightly over 1 vertical ft of water will be required to dissolve 55 pounds of gypsum per 100 sq ft of soil in this example.

4. Note Mulch and Fertilizer Application Rates (Columns 3 and 4)
Mulch and fertilizer improve drainage and fertility of soil. Mulch (Column 3) and fertilizer (Column 4) may be applied at the rates indicated.

5. Note Remedial Actions (Column 5)
Remedial actions noted in Column 5 provide additional information and cautions applicable to the spill site circumstances within the same row. The steps provided are in approximate chronological order (there may be some site-specific exceptions).

Table A-1. Reclamation Practices for Adequate, Marginal, and Inadequate Rainfall Areas

Column 1	Column 2	Column 3	Column 4	Column 5
EC (mmhos/cm)	**Calculate Gypsum Application Rate* (lb/100 sq ft)**	**Mulch Rate** (depth in inches before incorporation***)**	**N-P-K Fertilizer Rate** (lb/100 sq ft)**	**Remedial Actions**
Section A, Adequate Rainfall (net annual moisture condition less negative or more positive than -12 inches)				
0–4****	(CEC)(ESP-5)(0.078)= then, 0-1 + 1-2 ft = total	2c, 3m, 4f	3 lb of 13-13-13	Incorporate gypsum (to displace sodium and prevent dispersion) and mulch. Surface apply fertilizer. Plant.
4–8	(CEC)(ESP-5)(0.078)= then, 0-1 + 1-2 ft = total	2c, 3m, 4f	3 lb of 13-13-13	Incorporate gypsum and mulch. Surface apply fertilizer. Plant with semi-salt-tolerant vegetation.
8–16	(CEC)(ESP-5)(0.078)= then, 0-1 + 1-2 ft = total	2c, 3m, 4f	3 lb of 13-13-13	Incorporate gypsum and mulch. Surface apply fertilizer. Plant with salt-tolerant vegetation.
>16	=>	=>	=>	Consult Environmental Specialist.
Section B, Marginal Rainfall (net annual moisture condition between -12 and -28 inches)				
0–4	(CEC)(ESP-5)(0.078)= then, 0-1 + 1-2 ft = total	2c, 3m, 4f	3 lb of 13-13-13	Incorporate gypsum (to displace sodium and prevent dispersion) and mulch. Surface apply fertilizer. Plant. Irrigate, if required.
4–8	(CEC)(ESP-5)(0.078)= then, 0-1 + 1-2 ft = total	2c, 3m, 4f	3 lb of 13-13-13	Incorporate gypsum and mulch. Surface apply fertilizer. Plant with semi-salt-tolerant vegetation. Irrigate, if required.
8–16	(CEC)(ESP-5)(0.078)= then, 0-1 + 1-2 ft = total	2c, 3m, 4f	3 lb of 13-13-13	Incorporate gypsum and mulch. Irrigate, if required. Surface apply fertilizer. Plant with salt-tolerant vegetation. Irrigate again, if required.
>16	=>	=>	=>	Consult Environmental Specialist.
Section C, Inadequate Rainfall (net annual moisture condition more negative than -28 inches)				
0–4	(CEC)(ESP-5)(0.078)= then, 0–1 + 1–2 ft = total	2c, 3m, 4f	2 lb of 13-13-13	Incorporate gypsum (to displace sodium and prevent dispersion) and mulch. Surface apply fertilizer. Plant. Irrigate.
4–8	(CEC)(ESP-5)(0.078)= then, 0–1 + 1–2 ft = total	2c, 3m, 4f	2 lb of 13-13-13	Incorporate gypsum and mulch. Surface apply fertilizer. Plant with semi-salt-tolerant vegetation. Irrigate.
8–16	(CEC)(ESP-5)(0.078)= then, 0–1 + 1–2 ft = total	2c, 3m, 4f	2 lb of 13-13-13	Incorporate gypsum and mulch. Irrigate. Surface apply fertilizer. Plant with salt-tolerant vegetation. Irrigate again.
>16	=>	=>	=>	Consult Environmental Specialist.

* Example Gypsum Calculation: A site characterization found that the 0–1 ft depth interval had a CEC = 14 meq/100 g and an SAR = 32. The 1–2 ft depth interval was found to have a CEC = 17 meq/100 g and an SAR = 20. Using Figure A-1, the SAR values of 32 and 20 convert to ESP values of 37% and 26%, respectively. Using the equation in Column 2 (and ignoring the CEC denominator), calculate the pounds of gypsum per 100 sq ft of soil as follows:
    0–1 ft depth interval: (14 meq)(37-5)(0.078) = 35 lb gypsum/100 sq ft
    1–2 ft depth interval: (17 meq)(20-5)(0.078) = 20 lb gypsum/100 sq ft
  To find Total Gypsum Requirement:
    (35 lb gypsum/100 sq ft) + (20 lb gypsum/100 sq ft) = 55 lb gypsum/100 sq ft
  If a chemical amendment other than gypsum is to be used, consult manual.
  About 1 vertical ft of water will be required to dissolve 50 pounds of gypsum per 100 sq ft of salt-affected soil. Therefore, slightly over 1 vertical ft of water will be required to dissolve 55 pounds of gypsum per 100 sq ft of soil in this example.

** Mulch and fertilizer improve soil drainage and fertility and may speed the remediation process. Consult your company policy or Environmental Specialist regarding the use of these amendments.

*** c = coarse-textured soil, m = medium-textured soil, f = fine-textured soil.

**** See instructions on the use of Table A-1 regarding gypsum application to soils with EC <4 mmhos/cm.

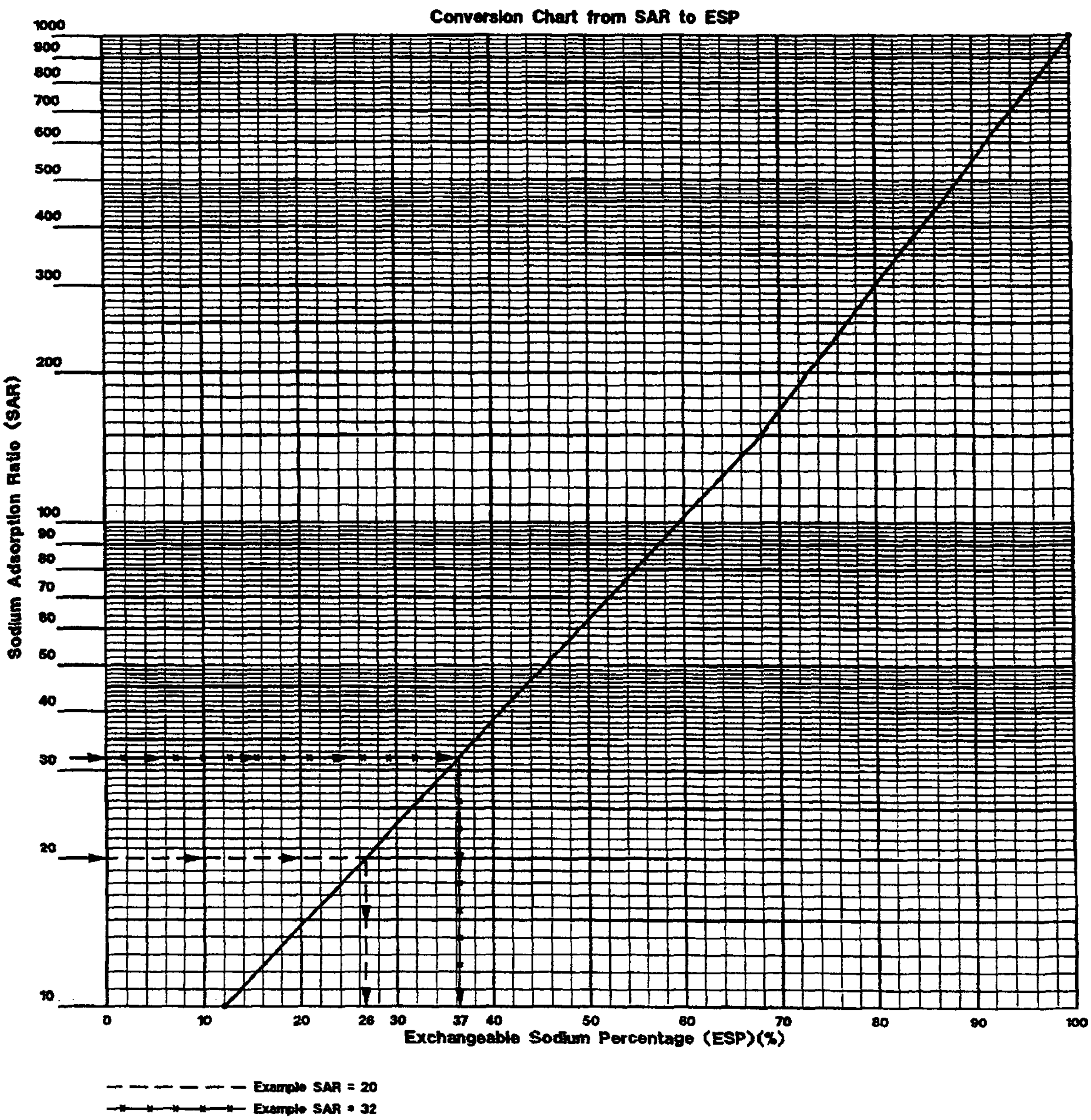

Figure A-1. Correlation of ESP and SAR.

APPENDIX B

Forms, Worksheets, and Instructions

SUMMARY

Appendix B contains the forms and worksheets referred to in the Decision Tree (Section 5) and elsewhere in Sections 6 and 7 of this manual. These forms are provided as examples of ways to organize and archive information on the remedial process. Operators may complete them as they see fit or develop their own strategies for documentation. These data-gathering forms provide spaces where data pertinent to spill and site assessment may be collected and organized. The worksheets allow a step-by-step process for converting data collected into interpretations critical to remediation success. Decision making is facilitated when collected and interpreted data from these forms and worksheets are used in conjunction with the Decision Tree in Section 5 of this manual.

At first glance, these forms appear to request a daunting quantity of data. However, not all information prompted by the forms or worksheets is essential for remediation of produced water spills on soil. Some blanks request information simply for user convenience in recordkeeping, whereas other blanks request information which if not: (a) known, and (b) considered, could result in failure of a remediation effort. In addition, information on the same topic can often be obtained from different sources. Data collected manually during a site visit are usually most dependable, but do not reflect important considerations such as seasonal variations (e.g., rainfall distribution and water table fluctuations). Nevertheless, shortcuts to gathering field data can often be made based on data obtained from other sources (e.g., county Soil Surveys). Therefore, within each oilfield, and in accordance with user preference, certain blanks, forms, and worksheets will be frequently used, whereas others may seldom be used. The most essential data and interpretation requirements for most spills are condensed in Form 5. The user is encouraged to select the most appropriate tools from among those provided in this manual. To assist the user in deciding which forms or worksheets will be helpful, each individual form and worksheet has been listed and summarized in Table B-1. An introductory summary and instructions are provided at the beginning of each form or worksheet. The following forms and worksheets are included in Appendix B:

Form

1. Initial Spill Report
2. Desktop Site Characteristics Review
3. Onsite Surface Evaluation
4. Sample Location Data
5. Condensed Essential Data

Worksheet

1. Halophytic Vegetation
2. Drainage
3. Supplemental Water
4. Chemical Amendments
5. Post-Remediation Monitoring and Project Termination

Table B-1. Summary of Origins, Objectives, and Uses of Data Collected in Forms and Worksheets Contained in Appendix B.

Form/ Objective	Data Origin/ Use
1. Initial Spill Report	**Field Staff, Site Records, and Spill Manager**
Document initial internal reports of spill	Recordkeeping
Record spilled water constituents data	Calculate chemical amendments[a]
Note external spill reports made	Recordkeeping
2. Desktop Site Characteristics Review	**Published and/or Previously Established Information, Soil Survey, and Appendix I**
Obtain previously established information	Record general knowledge base
Obtain county-specific data pertinent to site	Anticipate field circumstances
Obtain precipitation and evaporation data	Calculate moisture availability
Consider initial remediation options	Eliminate unacceptable options
Note regulatory considerations	Conform to regulatory constraints
3. Onsite Surface Evaluation	**Onsite Surface Observations**
Evaluate site surface	Identify equipment, landscape, and cultural limitations
Site sketch	Spatially relate field conditions, prepare sampling plan
4. Sample Location Data	**Observations at Sample Locations**
Collect data at sample locations	Collect samples and record physical and chemical data
5. Condensed Essential Data	**User's Experience, Forms 1–4, and Worksheets 1–5**
Provide optional data collection short form	Condense probable essential data and interpretations
Worksheet	**Purpose**
1. Halophytic Vegetation	Determine feasibility of halophytic vegetation
2. Drainage	Determine potential need for enhanced drainage
3. Supplemental Water	Determine potential need for supplemental water
4. Chemical Amendments	Calculate type and quantity of chemical amendments
5. Post-Remediation Monitoring and Project Termination	Record project completion and monitoring

a Although it is suggested that chemical amendments be calculated based on soil parameters, they can also be calculated based on the volume of produced water spilled and the concentration of salts in it. Chemical amendments are calculated based on volume and concentration of salts in produced water under assumptions noted in Worksheet 4. Results may exceed calculations based on soil data.

FORM 1 - INITIAL SPILL REPORT (INSTRUCTIONS)

SUMMARY

This form is intended to be filled in shortly after the spill is identified. Form 1 initiates administrative tracking of the spill event, and prompts the user to assemble initial spill-related data which may be useful later. Data collection prompted includes composition and volume of material spilled, when and where the spill occurred, and if the spill was reported to a regulatory authority. Using one calculation method described in Appendix K, spilled volume, spilled total dissolved solids (TDS), and sodium concentration data can be used to calculate the quantity of chemical amendment required. This form may be modified to be consistent with operator policy.

Site Name (C): Lease name.

Date (C): Date spill reported.

Spill ID No. (C): A designation that allows differentiation among multiple spills on a lease.

Size (H): Volume of spilled material (saltwater or produced water spilled). Exact estimates are not critical but should be +/- 25%. If the spill is badly underestimated, the remediation plan may not work. If the spill volume is badly overestimated, excessive costs may be incurred.

Oil (H): Percent oil in spilled material. May affect remediation alternative.

TDS (H): Total dissolved solids in spilled material can be used to estimate total salt spilled.

Total Sodium (H): Sodium (Na) concentration in spilled material can be used to estimate total sodium spilled.

Location (I): Sufficiently specific to assist in locating site on Soil Survey, include field, county, and state.

Immediate Spill Response (H): Any actions already taken.

Who Discovered Spill or Affected Area (C): Names may be useful if additional information is needed.

Date Spill or Affected Area Discovered (C): Subsequent weather may have altered the appearance of the site.

Did Spilled Material Enter Surface Waters (I): Fate of salts. Potential rapid migration of salts.

Reports Previously Made (C): Recordkeeping.

Was Spill Covered by Spill Prevention Control and Countermeasures Plan (SPCC) (H): Because SPCC spills are reported to the EPA-NRC, remediation connected with waterways may have special restrictions.

Remediation Project Manager (C): Spill remediation project manager.

Form Completed By (C): Name for future reference.

Date (C): When the form is completed, if different from the date begun.

Notes:	(E) = Essential information	(H) = Helpful information
	(I) = Important information	(C) = Convenient information

FORM 1 - INITIAL SPILL REPORT

Site Name (C): ____________________ **Date (C):** ____________

Spill ID No. (C): ____________ **Size (H):** ________ (bbl) **Oil (H):** ______ (%)

TDS (H): ______________ (ppm) **Total Sodium (H):** ____________ (ppm)

Location (I): ____

Field (H): ____________ **County (I):** ____________ **State (I):** ________

Immediate Spill Response (H): ______________________________

____

____

____

____

Who Discovered Spill or Affected Area (C): ______________________

Date Spill or Affected Area Discovered (C): ______________________

Did Spilled Material Enter Surface Waters (I): ______________________

Reports Previously Made (C):

State (C): Who __________ Organization ______________ Date ________

Fed (C): Who __________ Organization ______________ Date ________

Supervisor __________ Env. Specialist __________ Landowner ________

Other (Native American nation, local government, other government, etc.) (C):

Who ____________ Organization ______________ Date ________

Was Spill Covered by Spill Prevention Control and Countermeasures Plan (SPCC) (H):Y/N

Remediation Project Manager (C): ______________________________

Form Completed By (C): ____________________ **Date (C):** ____________

Notes:

(E) = Essential information

(I) = Important information

(H) = Helpful information

(C) = Convenient information

FORM 2 - DESKTOP SITE CHARACTERISTICS REVIEW (INSTRUCTIONS)

SUMMARY

Form 2 prompts the user to gather information already known about the spill site. This information alerts the user about site characteristics important to remediation planning during the onsite assessment. An aerial photograph shows landscape feature relationships which are not always clear during site visits. Soil and meteorological data characteristics, as well as regulatory considerations and locally acceptable remediation options are also prompted in Form 2. This form may be modified to be consistent with operator policy.

Site Name (C): Lease name from Form 1.

Date (C): Date this form is prepared.

Spill ID No. (C): From Form 1.

SOIL SURVEY INFORMATION

Obtain a Soil Survey of county where spill site is located. If the requested information is not available from the Soil Survey, or the Soil Survey has not yet been published, then it may be obtained by calling the U.S. Department of Agriculture-Natural Resource Conservation Service (USDA-NRCS) [formerly the Soil Conservation Service (USDA-SCS)]. Generic data from the Soil Survey can indicate typical potentially serious soil and landscape limitations to remediation, such as impermeable layers, flooding, high water table, etc. USDA-NRCS staff can assist in completing this form if the Soil Survey is difficult to obtain.

Soil Survey Name (county, state) (H): Reference for future.

Date Published (H): Some counties have more than one survey publication date.

Aerial Photo Sheet No., Soil Series (name), Map Unit Designation (I): Specifying the maps in the Soil Survey allows rapid reference if any of the information needs to be rechecked. Each aerial photograph is numbered and usually dated along the inside margin. An example soil series name is Coweta silt loam. An example map designation is Cab. Aerial photographs show spatial relationships not always clear to the onsite observer.

Slope (I): Readily available from the Soil Survey; normally expressed as a range in percent. Slopes can change substantially over time on erodible or accretional soils.

Soil Type (E): Soil Survey will note if soil is organic or mineral. The vast majority of soils are mineral soils.

TYPICAL SOIL HORIZON CHARACTERISTICS FROM SOIL SURVEY

Soil Horizon, Texture, pH, Permeability, Carbonates, Gypsum, Salinity, Shrink-Swell, Sodium Adsoprtion Ratio (SAR), Erosion Factor, Cation Exchange Capacity (CEC), Drainage, Impermeable Layer, Bedrock, Hydrologic Group, Flooding, High Water Table, Land Capability (E,I): Generic data readily available from the Soil Survey. Multiple forms may be required if there are very different soil horizons in the top 6 ft of depth. Not all of these data categories are included in all Soil Surveys. These data preview conditions which can be anticipated during onsite evaluations, and help guide the field evaluation effort. Substantial variability can occur within individual mapping units. As a result, field verification is advisable.

PRECIPITATION EVAPORATION INDEX (PEI)

From Worksheet 3 (page B-23) and Appendix I.

Precipitation (E): See maps in Appendix I.

Evaporation (E): See maps in Appendix I.

PEI (E): Precipitation less evaporation; usually a negative number in dry western states.

Regulatory Issues (E): Any special regulatory issues should be noted. Unusual regulatory constraints [e.g., tribal restrictions or Bureau of Land Management (BLM) reporting] can be noted at the bottom of the form.

Remediation Options (E): A number of general remediation options are listed. Each site, oilfield, or state may have special conditions, or there may be lease constraints which make certain options inappropriate. Early elimination of these options may reduce the amount of data and the level of effort required to develop a remediation plan.

Notes:
(E) = Essential information
(I) = Important information
(H) = Helpful information
(C) = Convenient information

FORM 2 - DESKTOP SITE CHARACTERISTICS REVIEW

Site Name (C): ______________________ **Date (C):** ______________

Spill ID No. (C): ____________

SOIL SURVEY INFORMATION

Soil Survey Name (county, state) (H): __________ **Date Published (H):** ________

Aerial Photo Sheet No. (I): __________ **Soil Series (name) (I):** __________

Map Unit Designation (I): __________________

Slope (I):(circle one) <1 / 1–3 / 3–6 / >6 (%) **Soil Type (E):**(circle one) organic/mineral

TYPICAL SOIL HORIZON CHARACTERISTICS FROM SOIL SURVEY

Soil Horizon (I): ____________ (desig.) **Texture (I):** ____________ (name)

pH (I): ________ **Permeability (E):** _____ (in/hr) **Carbonates (I):**Y/N

Gypsum (I): Y/N **Salinity (I):**_____ (mmhos/cm)**Shrink-Swell (I):**(circle one) High/Med/Low

SAR (I): __________ (ratio) **Erosion Factor (I):** ____________ (K)

CEC (I): ______________________ (meq/100g) **Drainage (E):** ______ (class)

Impermeable Layer (< 0.2 in/hr) (depth) (E):_____ (ft) **Bedrock (depth) (E):** ______(ft)

Hydrologic Group (E): ______________ (class designation) **Flooding (E):** Y/N

High Water Table (E): Y/N **(depth) (E):** ____________________(ft)

Land Capability (I): ____________ (class) **(description) (I):**______________

PEI (from Worksheet 3, page B-23)

Precipitation (E): ______(in) **Evaporation (E):** ________ (in) **PEI (E):**_______ (in)

Regulatory Issues (E):

Enforced Criteria: pH_____ EC________ (mmhos/cm) SAR _______ (ratio)

ESP __________________ (%) Cl ____________________ (mg/L)

Enforced Reporting: ________Federal __________State __________ Other

Other Regulatory Constraints (e.g., endangered species or delineated wetland area)________

____

____

____

____

Remediation Options (E): (circle viable alternatives)

Unassisted Remediation	Halophytic Plants	Road Spread
Land Spread	Offsite Disposal	Remed. w/Drainage
Remed. w/Irrigation	*In Situ* w/Chemical Amendment	Soil Washing
Deep Burial		

Notes:
(E) = Essential information
(I) = Important information
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(C) = Convenient information

FORM 3 - ONSITE SURFACE EVALUATION (INSTRUCTIONS)

SUMMARY

Form 3 prompts the user to record general site characteristics observable from the site surface, and to note them on a site sketch. During the field evaluation, specific attention should be devoted to verification or contradiction of important considerations noted in Forms 1 and 2. There is often great variation in soil and landscape properties within mapping units shown and described in the Soil Survey. The site visit may also reveal important new factors not previously noted. Examples are property boundaries, recent site alterations, surface and subsurface impediments to field equipment, and the observable breadth and intensity of spill impacts. Based on all of the above information, the user is prompted to select representative locations for collecting soil samples and record these locations on the site sketch. This form may be modified to be consistent with operator policy.

Site Name (C): Lease name from Forms 1 and 2.

Date (C): Date form is prepared.

Form Prepared By (C): Who prepared site sketch.

Spill ID No. (C): From Forms 1 and 2.

Landscape (E): Topographic relationships important regarding the fate of salts.
- **Upland** - Normally dry
- **Riparian** - Associated with a watercourse
- **Wetland** - Normally wet (note if formally delineated)
- **Seep** - Moist or wet near bottom or side of slope - often saline

Land Use (E): Of special interest is any limit to remediation options (e.g., parkland, drainage-way, pecan groves, etc.).

Slope of Affected Area (E): Pertains primarily to erodibility and fate of runoff.
- **Flat:** <1%
- **Slight:** 1% to 3%
- **Moderate:** 3% to 8%
- **Steep:** >8%
- **Basin:** Concave depression

Typical Vegetation (E): Categories of vegetation (e.g., healthy grassland, sparse woodland, brushland, overgrazed pastureland, etc.).

Physical Hazards and Equipment Limitations (E): Note any constraints regarding equipment to be used in remediation, application of chemical amendments, or anything that would prevent mechanical removal of soil (e.g., soft loose soil, excessive wetness, boulders, rock outcrops, ditches, trees, stumps, fences, pond, steep slope, severe erosion, buried pipe, electric lines, buildings, roads, etc.).

Other Issues (E): Any unusual issues should be noted (such as location of wells or any special animal habitat, etc.). Note anything which may present other constraints (e.g., potential for off-site migration, lease requirements, BLM rules, etc.).

Observable Spill Area (E): Rough calculation of spill-affected area.

Observable Spill Depth (I): If easily determined. This information may require use of soil samples and laboratory data.

Scale (I): Approximate scale in ft per grid square.

Site Sketch (E): Prepare a sketch and portray the following information:

❑ Site Boundary	❑ Spill Origin	❑ Apparent Spill Area
❑ Immovable Physical Features	❑ Onsite Roads	❑ Evidence of Erosion
❑ Proximity to Surface Water	❑ Landscape Position	❑ Vegetative Coverage
❑ Suitable Background Sample Area	❑ Vegetation (types)	❑ Slope (directions)
❑ Background Sample (locations)	❑ Date of Sketch	❑ Standing Saltwater (Y/N)
❑ Scale (ft/grid square)	❑ Land Contours	❑ Vegetative Health
❑ Background Vegetation (types)	❑ Sample (locations)	❑ Background Sample (ID)
❑ Wetland Delineation Boundary	❑ Slope (gradients)	❑ Oily Appearance
❑ Standing Saltwater (approx. bbl)	❑ North Arrow	❑ Legend
❑ Subsurface Equipment Present (list)	❑ Sample (ID)	❑ Affected Property Line(s)

Notes:
(E) = Essential information
(I) = Important information
(H) = Helpful information
(C) = Convenient information

FORM 3 - ONSITE SURFACE EVALUATION

Site Name (C): ______________________ **Date (C):** ______________

Form Prepared By (C): ____________ **Spill ID No. (C):** ____________

Landscape (E): ________________ **Land Use (E):** ______________

Slope of Affected Area (E): ________ **Typical Vegetation (E):** ____________

Physical Hazards and Equipment Limitations (E): ______________________

Other Issues (E): ____

Observable Spill Area (E): ________ (sq ft) **Observable Spill Depth (I):** ________ (ft)

Scale (I): ________________

Site Sketch (E):

	A	B	C	D	E	F	G	H	I	J
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Notes:
(E) = Essential information
(I) = Important information
(H) = Helpful information
(C) = Convenient information

FORM 4 - SAMPLE LOCATION DATA (INSTRUCTIONS)

SUMMARY

Form 4 is filled out at the time samples are collected. In some spill scenarios, data from various sample collection locations will be relatively uniform, whereas substantial variation may occur at other sites. The user should use good judgment based on all the above information to determine the number and locations of samples required to characterize the area to be remediated. Collection of background samples is often warranted in order to determine the extent of impact, but may have little value in other spill circumstances. Observations recorded when samples are collected also help to correlate field observations with analytical data. Samples collected should be representative of the area to be remediated. This form may be modified to be consistent with operator policy.

Site Name (C): Lease name from Forms 1, 2, and 3.

Date (E): Date samples collected. Seasonal variation causes this to be an essential datum with regard to location of salt and moisture relationships.

Spill ID No. (C): From Forms 1, 2, and 3.

FIELD INFORMATION TO BE COLLECTED WHILE SAMPLING

In locations where soil samples will be collected, information in the table of Form 4 should be collected while sampling.

Sample No. (E): Sample identification. Chosen by user.

Horizon Designation (H): Horizon designations are O for organic, A for mineral topsoil, E for bleached zone in mineral subsoil, B for nonbleached upper subsoil in mineral soil, C for deep subsoil, and R for rock.

Sample Depth (E): Sample depth is the depth from the soil surface to the top and bottom of the sample (e.g., 0–1 ft or 1–2 ft). Although samples can be collected in 1-ft increments, samples correlate best if depth intervals are associated with horizon breaks.

TPH (I): Pertains to extent of migration and possible need for the laboratory to analyze soil samples for oil and grease (O&G) or total petroleum hydrocarbons (TPH). If a portable hydrocarbon detection instrument is available (e.g., PID), the sample excavation can be checked for TPH (ppm). Same day instrument calibration data should also be entered into the record, but may be important only if there are >1% hydrocarbons in the spilled material.

EC (E): Field soil EC measurements for each depth interval sampled can be obtained from a field-prepared saturated paste extract. A small amount of soil from the bottom of the sample excavation can be used to determine the level of salts occurring at that depth. If the EC of this sample is high at the bottom of the last sample collected, then deeper samples should be collected to a maximum depth of 4 ft. During evaporative conditions, white particles of solidified salt called efflorescences may be visible at the soil surface. Compare EC in spill area to background to delineate spill boundary.

Roots/Rocks (I): The presence of roots and rocks of gravel size or larger provide information about the ability of water to move through soil. The more rocks and roots, the more quickly water typically moves through the soil. An approximation of volume percent of soil occupied by rocks and roots (e.g., "few," "common," or "abundant") is the appropriate response. The abrupt diminishing of roots with depth can also indicate a restrictive layer, or a soil chemical problem such as excess acidity.

CO_3 (I): Soil carbonates are opaque white earthy materials in soils. They can occur in various sizes from fist-sized chunks to powder. A drop of dilute (3N, about a 1:10 dilution from concentrate) hydrochloric acid on calcium carbonate will result in effervescence. Dolomite, a calcium and magnesium carbonate, reacts only slightly if heated, but this is usually not attempted in the field. The intensity of effervescence is dependent on the particle size of the carbonates as well as mineralogy and soil texture. It is sometimes difficult to see effervescence in sandy soils. Otherwise, the relative effervescence of this field test generally relates to the relative concentration of carbonates. Responses should be "none," "moderate," or "abundant." It is very important to know at what depth the carbonates occur. This procedure can be performed in the field or analytical laboratory.

Texture (E): Soil texture can be obtained by appearance and feel for each depth increment sampled. Under most circumstances, water can move most easily in coarse-textured soils, and is most restricted in fine-textured soils. "Coarse" or sandy soils consist predominantly of grains which can be can easily be seen, tend to fall apart when moist, and feel gritty. "Fine" or clayey textured soils are sticky and waxy to the touch and tend to not fall apart when moist. "Medium" or loamy textured soils feel spongy, gritty, and waxy at the same time.

Topsoil Thickness (E): Topsoil thickness provides information about erosion and soil fertility. The topsoil has the most organic matter and roots. The topsoil thickness should be indicated in inches from the soil surface (e.g., 0–4 inches).

Impermeable Layer (E): The depth and thickness of an apparent impermeable layer should be recorded if encountered during sampling. An impermeable layer can be a tight, heavy clay layer with few roots, if any, or a hard and brittle layer of coarse, medium, or fine texture. In order to allow the salts to move out of the soil, this layer must be broken physically or chemically.

Permeability (E): Approximate permeability is an assessment of how quickly water can move through the soil. A response of "rapid," "moderate," "slow," or "very slow" should be recorded for each layer. Indicators are how easily the soil comes apart when putting it into the sample collection container, the relative abundance of roots, and the relative extent of pore space inside chunks of soil. Soil texture is also an indicator. Coarse soils usually have a much higher permeability compared to fine-textured soils. For large-scale or sensitive projects, where permeability may be restricted, a field permeability test may be performed.

Oily (E): If the soil has an oily appearance or odor, an approximation of the hydrocarbon content should be recorded. Responses are "very," "some," and "none." A squeeze test can also be used, but the interpretations vary for soil types. In general, when soil is squeezed, if liquid oil runs or drips out of the soil, there is >10% oil in the soil sample. If after squeezing, an oily stain appears all over the hand, there is from 5% to 10% oil in the soil; or if staining of the hand is spotty, then there is 1% to 5%. There is <1% oil if there is an odor but no oily stain. Some natural soil clays will also leave a stain, but are not oily in appearance or odor. Leaching may not be advisable prior to bioremediation if oil can be leached into groundwater.

Wetness (E): The degree of wetness describes the soil moisture content at the time of sampling. Responses are "saturated," "moist," or "dry." If a soil is very dry just a few days after a heavy rain, then it may hold little water indicating a susceptibility to potential drought stress. A sample which is wet a week or so after a slight rain may have a high water table or very low permeability. A sample which is dripping wet may indicate the presence of a high water table.

The information collected on this form will help determine the capability of the soil to be remediated.

Notes:
(E) = Essential information
(I) = Important information
(H) = Helpful information
(C) = Convenient information

FORM 4 - SAMPLE LOCATION DATA

Site Name (C): ______________________ **Date (E):** ______________

Spill ID No. (C): ______________

FIELD INFORMATION TO BE COLLECTED WHILE SAMPLING

Samp. No. (E)	Horiz. Desig. (H)	Sample Depth (ft) (E)	TPH (ppm) (I)	EC (mmhos/ cm) (E)	Roots/ Rocks (class) (I)	CO_3 (Y/N) (I)	Texture (class) (E)	Topsoil Thick. (in) (E)	Imperm Layer (Y/N) (E)	Perm. (class) (E)	Oily (Y/N) (E)	Wet. (degree) (E)

Notes:
(E) = Essential information
(I) = Important information
(H) = Helpful information
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FORM 5 - CONDENSED ESSENTIAL DATA (INSTRUCTIONS)

SUMMARY

This form combines the most essential information and interpretations provided in Forms 1–4 and Worksheets 1–4. This form may be modified to be consistent with operator policy.

ADMINISTRATIVE

For recordkeeping convenience. Details on other forms.

CHARACTERISTICS FROM SOIL SURVEY OR OTHER AVAILABLE SOURCES

Important information which should be available as published or commonly available information, and which may not be readily observable in the field. Information requested here will help guide the field investigation and data-collection effort. Potential site limitations visible from aerial photographs and generalized soil, water, and landscape relationships may alert the user to potential problems. Details are on other forms.

SITE OBSERVATIONS AND ANALYTICAL DATA

Essential data obtained during site visits, sample collection, and from analytical results. This information describes the areal and vertical extent of the affected area, areas which could become impacted by runoff or subsurface migration, miscellaneous observable remediation limitations, and ability of the soil to respond to treatment. Titratables refer to the quantity of acid or base required to reach a suitable pH during the remediation effort. A corresponding site sketch is recommended.

IMPORTANT INTERPRETATIONS

Interpretive endpoints are based on above data and logic and calculations from Worksheets 1–4. Many of these are major decision-making crossroads found in the Decision Tree (Section 5).

FORM 5 - CONDENSED ESSENTIAL DATA

ADMINISTRATIVE

Site Name ____________ Date Spill Reported __________ Spill ID No. ________

Regulatory Jurisdiction ______________________________

Regulatory Constraints ______________________________

Locally Acceptable Remediation Options ______________________________

CHARACTERISTICS FROM SOIL SURVEY OR OTHER AVAILABLE SOURCES

Aerial Photo Sheet No. ______________ Soil Series (name) ______________

Map Unit Designation ______________ Drainage ______________ (class)

Impermeable Layer/Bedrock ____________ (depth)

Seasonal High Water Table Depth ____________ (ft) Season(s) ____________ (months)

Groundwater Quality (good/poor/unusable) Migration Rate _____ (ft/yr) Flood Prone Site (Y/N)

Organic Soil (Y/N) Any Portion of Affected Site Delineated as Wetland (Y/N)

Typical Soil Horizon Data to 6 ft as Follows:

Depth (ft)	Texture (C, M, F)	pH (s.u.)	CEC (meq/100g)	Permeability (in/hr)	Shrink-Swell (H, M, L)	Erodibility (K)	Carbonates (%)

SITE OBSERVATIONS AND ANALYTICAL DATA (site sketch recommended - note the following)

Affected Onsite Area ______ (sq ft) Onsite Open Water Affected (Y/N, describe) ______

____

____

Affected Offsite Area _______ (sq ft) Offsite Open Water Affected (Y/N, describe) ______

____

____

Landscape Position (top, side, bottom, depression)

Potential Groundwater Impact (Y/N) Depth ________ (ft)

Slope Type (H, M, L, basin)________________ Direction (down toward N,S,E,W)

Potential Open Water Impact (Y/N) Distance ____________ (ft from affected area)
Vegetation Remaining (type) __________________ Remaining Coverage ________ (%)
Erosion Visible (H, M, L) Remaining Topsoil Thickness _______________________ (ft)
Surface Impediments to Equipment _________ Buried Impediments (e.g., pipes) (Y/N)
Sample Collection (draw locations with sample numbers on Form 4)

Typical Soil Horizon Data to 2 ft as Follows:

Samp. No.	Depth (ft)	Texture (C, M, F)	pH (s.u.)	EC (mmhos/cm)	SAR (ratio)	CEC (meq/100g)	ESP (%)	Titratables (meq/100g)

IMPORTANT INTERPRETATIONS

Groundwater Accessible by Migrating Salts (Y/N) Interception Feasible (Y/N)
Internal Soil Drainage Enhancement Required (Worksheet 2) (Y/N) Feasible (Y/N)
Supplemental Water Indicated (Worksheet 3) (Y/N) Feasible (Y/N)
Chemical Amendments Required (Worksheet 4) (Y/N) Feasible (Y/N)
Chemical Amendments to Depth _________ (ft) Type(s) ____________________
Chemical Amendments Application Rate _____________ (lb/1,000 sq ft) Feasible (Y/N)
Erosion Control Enhancements Recommended (Y/N) Feasible (Y/N)
Remediation Equipment Limitations ___________________ Land reshaping required (Y/N)
Revegetation Planting Recommended (Y/N) Feasible (Y/N)
Halophytic Revegetation Planting Recommended (Worksheet 1) (Y/N) Feasible (Y/N)
Other Considerations ____

____

____

____

____

WORKSHEET 1 - HALOPHYTIC VEGETATION (INSTRUCTIONS)

SUMMARY

The possibility of utilizing halophytic vegetation is considered in this worksheet. This worksheet uses site data collected on data-gathering forms to show or anticipate conditions to which remediation vegetation would be exposed. A list of halophytic vegetation candidates tolerant to these physical and chemical conditions is then generated. The list is further refined by regulatory or other considerations. This worksheet may be modified to be consistent with operator policy.

Pertinent Site Conditions: Data regarding anticipated soil salinity, wetness, pH, annual rainfall, and the size of the area to be revegetated are entered here. Actual site values are used unless efforts to alter soil salinity, moisture content, or pH, or to irrigate or utilize other chemical or physical techniques in addition to halophytic vegetation are anticipated. After the anticipated EC, moisture category, pH, and annual rainfall are determined, this information is used in Appendix F to identify candidate halophytic vegetation. There may be several candidates. The common names are then entered into Worksheet 1. This list is compared with any local regulatory or other considerations which may eliminate any of these plants.

Selection of Halophyte Candidate Plant and Technology: Each remaining candidate plant is considered and a determination made regarding whether an effort would be made to revegetate with this plant on the affected site. If the answer is "yes," and no other chemical or physical remediation actions are required, then the remediation option chosen can simply be establishment of this halophytic vegetation. If this is the choice, then time and effort spent investigating other options may not be warranted. If the answer is "no," or that other options will also be performed in addition to establishment of halophytic vegetation, then follow the Decision Tree (Section 5) to the next step.

WORKSHEET 1 - HALOPHYTIC VEGETATION

Pertinent Site Conditions:

EC (mmhos/cm) 0–1 ft ______________________________

Wetness (saturated, moist, dry, seasonal) ______________________________

pH 0–1 ft ______________________________

Annual Rainfall (inches) ______________________________

Area to Revegetate (acres) ______________________________

Selection of Halophyte Candidate Plant and Technology:

Common Names of Available Halophytes	Locally Accepted (Y/N)

Notes:
Pertinent Site Conditions: Complete with site information.
Selection of Halophyte Candidate Plant and Technology: Complete with information from either the USDA-NRCS or a plant vendor.

WORKSHEET 2 - DRAINAGE (INSTRUCTIONS)

SUMMARY

The potential need for enhanced soil drainage is evaluated in this worksheet. One of the most critical aspects of remediating salt-affected soil is assuring that the subsoil provides a sufficiently permeable route to allow salts to move out of the upper 6 ft of soil. Most failures of *in situ* chemical amendment remediation efforts in areas of adequate and possibly marginal rainfall are due to omission of this one consideration from remediation planning. This worksheet may be modified to be consistent with operator policy.

Data: Worksheet 2 has been prepared to provide a determination about whether the spill-affected soil is capable of allowing salts to move beyond 6 ft via leaching. Data required include depth to the high water table, determination of wetlands classification, landscape position, depth to an impermeable layer, hydraulic conductivity, and shrink-swell potential.

The Soil Survey and local community knowledge will provide most of the data for a "generic" soil of this type. However, influences by humans can alter many of these properties, and the precision of large-scale mapping sometimes misrepresents soil conditions at a specific location. For best results, determine these characteristics first-hand by examining the soil to be remediated.

Criteria: Data gathered in previous steps are interpreted as follows. If any of the following are true, then this soil is at great risk of not being able to allow the salts to move out of the upper 6 ft of soil:

- If the depth to the top of the seasonal high water table or perched water is less than 6 ft from the soil surface
- If the site is in a wet or delineated wetlands area (or at low elevation and close to one)
- If the landscape position is basin (or sometimes toe-slope)
- If the saturated hydraulic conductivity (or permeability) of ANY layer (no matter how thin) is <0.2 in/hr
- If the shrink-swell potential is high

Interpretation: A determination based on all of this information is then made. If the soil is determined to have a drainage problem, then chemical remediation alone (without appropriate drainage enhancement) does not have a high probability of success.

Determination: A determination is then made regarding whether drainage improvement efforts will be made. If drainage improvement efforts will be made, continue with the next step in the Decision Tree (Section 5) leading to *in situ* chemical remediation efforts. If drainage will not be improved, then consider the natural remediation or mechanical remediation section of the Decision Tree.

WORKSHEET 2 - DRAINAGE

	Decision-Making Parameter	Data: Site Condition (record)	Criteria: Potential Drainage Problem If:	Interpretation: Drainage Problem? (Y/N)
1	Depth to seasonal high water table (groundwater or perched) (ft)	______	<6 ft	______
2	Site often wet or in a delineated wetlands (Y/N)	______	Y	______
3	Depth to impermeable layer, restrictive layer, or bedrock from 0–6 ft (ft)	______	<6 ft	______
4	Hydraulic conductivity of most restrictive layer from 0–6 ft (in/hr)	______	<0.2 in/hr	______
5	Shrink-swell potential (low/moderate/high)	______	High	______
6	Cumulative determination based on all evidence	NA	Any of above	______

Determination: If cumulative evaluation is that the site has a drainage problem, then *in situ* chemical remediation will probably result in long-term failure without concurrent improvement of drainage.

Notes: Determine responses for lines 1–5 from field, Soil Survey, USDA-NRCS, or community knowledge.

WORKSHEET 3 - SUPPLEMENTAL WATER (INSTRUCTIONS)

SUMMARY

The potential need for supplemental water (irrigation) is evaluated in this worksheet. When *in situ* chemical amendment remediation will be used, sufficient leaching water is required to move salts permanently below the root zone. Worksheet 3 is provided to determine if sufficient water is naturally available in the form of rainfall to remediate the soil chemically, and if not, the amount of supplemental water indicated. This worksheet may be modified to be consistent with operator policy.

Data: The important data to be collected are soil texture group, annual PEI, and the percent of salts in the soil which must be removed to reach a target level.

Soil texture group should be determined in the field, but the Soil Survey and local community knowledge may provide information. The soil texture group to enter in this table is the finest texture which occurs in a cumulative 2 ft of soil in the upper 6 ft. The response will be coarse (sandy), medium (loamy), or fine (clayey).

The PEI, or net annual moisture condition, is determined from weather maps in Appendix I. The location of the spill is found on each map. By interpolation, note the annual normal precipitation in inches and the annual pan evaporation in inches. Subtract the annual pan evaporation in inches from the annual normal precipitation in inches. The mathematical result is the PEI, and it is recorded in Worksheet 3. In general, a north-south line which follows the eastern edge of Oklahoma separates a positive PEI to the east, from a negative PEI to the west. PEI values more or less become more negative until near the Pacific Coast. The more negative the PEI, the more supplemental water may be required to provide enough water to move the salts below 6 ft. Where the PEI is positive, rainfall alone is usually enough to provide this amount of water. Depending on soil texture, a slightly negative PEI may not indicate the need for supplemental water.

Determination of Quantity of Supplemental Water Indicated: Approximately 1 ft of water is required to remove 80% of salts from 1 ft of soil (Abrol, *et al.*, 1988). This and a number of other factors have been combined to provide a supplemental water indication matrix in Worksheet 3. Diligent application of supplemental water using pulse flooding (flooding with several inches of water followed by several days of drying, and repeating this process until all supplemental water has been applied) may reduce the total quantity of supplemental water required for leaching by as much as 50% of the volume shown in the Worksheet 3 matrix.

Use of this matrix requires calculation of the amount of salt which must be removed from the soil. This value is calculated from the following information:

- The highest soil EC in mmhos/cm in either the 0–1 or 1–2 ft soil layer; this is measured in a saturated paste extract
- The target EC in mmhos/cm; for most agricultural crops this will be 4 mmhos/cm; higher ECs (based on background soil or the tolerance level of halophytic plants) can be used in many cases

The desired percent decrease in EC = [1-(Target EC/Current EC)][100].

Example: The following example shows how to determine the amount of water that is indicated.

Assume the finest soil texture is medium, the annual precipitation is 16 inches, the annual pan evaporation is 38 inches, the target EC is 4 mmhos/cm, and the highest soil EC is 28 mmhos/cm.

The PEI is then 16 inches precipitation - 38 inches evaporation = -22 inches.

The desired percent decrease in EC = [1-(4/28][100] = 85.7%. This percent decrease falls within a percent decrease range of 80% to 96% EC.

The above information is converted into inches of supplemental water using the matrix in Worksheet 3. In a medium-textured soil where the EC should be decreased between 80% and 96%, and having a PEI of -22 inches, the amount of supplemental water indicated to remove this much salt beyond 6 ft is about 42 inches. In this example, if supplemental water is diligently applied in successional pulse flooding events, then as little as one-half this much water (21 inches) may be sufficient to leach salts.

Interpretation: Based on this information, the cost and potential problems associated with supplying this much water are considered. A decision is then made whether this amount of water will be supplied. If this much water WILL NOT be supplied, consider natural remediation or mechanical remediation. If this much water WILL be supplied, the supplemental water problem is solved, and the next step is to consider the potential for soil erosion.

WORKSHEET 3 - SUPPLEMENTAL WATER

Data:
Soil texture group* (finest texture in any layer >2 ft thick) (coarse, medium, fine) ____________

Annual PEI** (rainfall less evaporation) ________________________________ (inches)

Percent EC decrease required to reach target EC*** ____________________________ (%)

Determination of Quantity of Supplemental Water Indicated:

	To Decrease EC by 0%–64%		
If Annual PEI is	**>-12**	**-12 to -28**	**<-28**
Texture Group:	**Supplemental Water Indication (in)**		
Coarse	0	8	18
Medium	0	10	21
Fine	0	12	24

	To Decrease EC by 64%–80%		
If Annual PEI is	**>-12**	**-12 to -28**	**<-28**
Texture Group:	**Supplemental Water Indication (in)**		
Coarse	0	18	36
Medium	0	21	42
Fine	0	24	48

	To Decrease EC by 80%–96%			
If Annual PEI is	**<-4**	**-4 to -12**	**-12 to -28**	**<-28**
Texture Group:	**Supplemental Water Indication (in)**			
Coarse	0	18	36	72
Medium	0	21	42	84
Fine	0	24	48	96

If supplemental water indicated is >0 inches, the application of supplemental water should be considered.

As little as one-half the supplemental water indication shown may suffice with diligent pulse flooding.

Interpretation: If the cumulative determination is that supplemental water is indicated, then *in situ* chemical remediation will probably exhibit long-term failure without application of the quantity of supplemental water indicated.

Notes:

* Obtain information from field, Soil Survey, or community knowledge.

** Obtain precipitation and evaporation data from Appendix I.

*** Percent EC decrease required = [1 - (target EC/current EC)][100].
Calculate for either 0–1 or 1–2 ft layer (whichever has highest current EC)
Example: Current EC in 0–1 ft = 18 mmhos/cm
Current EC in 1–2 ft = 28 mmhos/cm
Target EC = 4 mmhos/cm
Percent EC decrease required = [1 - (4/28)][100] = 85.7%

WORKSHEET 4 - CHEMICAL AMENDMENTS (INSTRUCTIONS)

SUMMARY

Chemical amendments can be used to displace sodium from soil cation exchange sites. Worksheet 4 provides a step-by-step process whereby soil or spilled produced water analytical data are used to calculate the quantity and type of chemical amendment required to remediate the spill-affected soil. This worksheet may be modified to be consistent with operator policy.

Step 1: The quantity of chemical amendment to apply may be calculated based on soil measurements (Step 2A) or measurements from the spilled material (Step 2B). The first step is to decide which of these two methods will be used. Using the calculations based on spilled material (Step 2B) has the following inherent disadvantages:

- Assumes the entire spill is contained in the upper 2 ft of soil
- Assumes all sodium is retained on clay cation exchange sites
- Assumes uniform distribution of spilled material over the entire spill-affected area
- Does not address soil responses to salt over time

As a result, this option should be used only when soil data cannot be obtained and only if the spill occurred within the previous 6 months. Use of the calculations based on soil measurements (Step 2A) is always acceptable, regardless of the age of the spill. Therefore, Step 1 guides the user into either Step 2A for calculations based on soil measurement or into Step 2B for calculations based on spilled material.

Step 2A: Following the soil measurement option, Step 2A involves collection of the data shown. Soil pH, CEC, and ESP are determined separately at the analytical laboratory for the 0–1 and 1–2 ft depth increments. The 0–1 and 1–2 ft depth intervals can be substantially different in physical and chemical properties which are important to chemical amendment selection. The spill area is also determined.

Step 3A: In Step 3A, the comprehensive gypsum requirement is calculated. Gypsum is used as a reference material to determine how much calcium should be applied to displace sodium to an endpoint ESP of 5%. An ESP of 5% accounts for smectite, which is especially sensitive to exchangeable sodium, and sampling and analytical inefficiencies.[1] The final calculation in this step is the total calculated pounds of pure gypsum required to displace sodium in the affected area. However, due to sodium displacement inefficiencies with gypsum, it is generally recommended to apply about 1.25 times the amount of gypsum calculated in Step 3A. Thus, if gypsum is the material selected for application, then 1.25 times that amount should be applied and incorporated into the spill area. If the pH is between 5.5 and 8.5, and neither calcium nitrate nor calcium chloride are to be applied, then this is the actual amount of gypsum to apply. The principal disadvantage of gypsum is that 1 ft of water is required to dissolve gypsum applied at a rate of 10 tons/acre under optimal dissolution conditions (high EC and high ESP).

Step 4A (neutral pH soil): The corresponding alternative amount of calcium chloride or calcium nitrate to apply when the pH is between 5.5 and 8.5 is given in Step 4A (neutral pH soil). Although the equivalent weight of calcium chloride and calcium nitrate is less than that of gypsum, these two materials are usually much more expensive than gypsum. They also have potential disadvantages associated with the addition of nitrates or yet more chlorides. However, with these disadvantages understood, both of these amendments are fast acting and require less water to dissolve compared to gypsum.

---

[1] Higher ESP endpoints (ESP = 6 – 15%) may be appropriate if smectite clays are known to be absent and there is a high degree of confidence in the characterization and analysis of ESP of the affected soil.

High or Low pH Amendments: If the pH is less than 5.5, as an option, it may be advisable to apply lime as a chemical amendment unless plant pH preference is lower than 5.5. Calcium and magnesium from lime dissolving in acid soil will displace sodium in acid soils, and it will raise the pH to a level more suitable to the growth of many plants. If the pH is more than 8.5, an acidifying amendment may be used to displace sodium in soils with carbonates. Acidifying amendments can decrease the soil pH to a level more suitable to the growth of most plants, but over time, gypsum will also tend to lower pH. The acidifying amendments usually work best in topsoil and when the soil contains carbonates because calcium and magnesium are released when the carbonates dissolve in the acid. However, it may be better to use gypsum, calcium chloride, or calcium nitrate if the pH is above 8.5 or if the soil has insufficient carbonates to buffer the pH change. Any adjustments made in soil pH should be consistent with the pH preference or tolerance range of the vegetation present.

Step 4A (acid soil): Data required to calculate the amount of lime to apply for an acid soil are calculated in Step 4A (acid soil). If the soil analytical results show that the soil pH is less than 5.5 and the deliberate liming option is chosen, the analytical laboratory should be asked to provide a lime requirement to raise the pH to 7.0 as indicated in Appendix J. The laboratory should perform a titration procedure and report the results in pounds of calcium carbonate ($CaCO_3$) required to raise the pH of the soil to 7.0 in 1,000 pounds of soil. This should be done separately for the 0–1 and 1–2 ft depth intervals. The total amount of calcium carbonate to apply is calculated at the bottom of Step 4A (acid soil).

Step 5A (acid soil): The lime requirement to raise the pH to 7.0 may not supply enough calcium to displace the amount of sodium necessary. Lime applied in excess of the pH 7.0 endpoint does not dissolve and therefore, supplies little calcium or magnesium at a pH level above 7.0. Therefore, in Step 5A (acid soil), the lime requirement value is converted into a gypsum equivalent value. In Step 6A (acid soil), the remaining sodium displacement required is calculated so that it can be supplied by gypsum.

Step 6A (acid soil): In Step 6A (acid soil), the gypsum equivalent value of lime from Step 5A (acid soil) is subtracted from the total comprehensive gypsum value required to displace sodium calculated in Step 3A. The result is the amount of gypsum which should be co-applied with the calcium carbonate to provide the total amount of calcium required to displace sodium. For more rapid response, strong and very soluble liming agents, such as calcium oxide (CaO) and calcium hydroxide [$Ca(OH)_2$], can be used but they are both dangerous to handle and they could have a cementing effect on the soil. In contrast, it is always acceptable to apply limestone or dolomite to raise pH. Unlike calcium oxide and calcium hydroxide, limestone and dolomite will not cause chemical burns or raise the soil pH above 8.5. In addition, limestone and dolomite are usually readily available, inexpensive, and relatively easy to handle. Their reaction rate in soil can be accelerated by applying in small grain sizes.

Step 4A (alkali soil): Data required to determine the amount of acidifying amendment to apply to an alkali soil are shown in Step 4A (alkali soil). If this option is chosen, the laboratory is asked to provide a sulfur (S) requirement in pounds of sulfur per 1,000 pounds of soil to decrease the pH to 8.3. The total amount of sulfur to apply is calculated at the bottom of Step 4A (alkali soil).

Step 5A (alkali soil): In Step 5A (alkali soil), the gypsum equivalent of the sulfur is calculated.

Step 6A (alkali soil): The amount of gypsum to co-apply with sulfur to supply the total amount of calcium required is calculated in Step 6A (alkali soil).

Step 7A (alkali soil): Acidifying alternatives to sulfur are given in Step 7A (alkali soil). These include aluminum sulfate [$Al_2(SO_4)_3$]:$18H_2O$; iron (II or ferrous) sulfate ($FeSO_4$:$7H_2O$); and sulfuric acid (H_2SO_4). Sulfuric acid is dangerous to handle and is applied as a liquid. Use of elemental sulfur should be restricted to sites which have topsoil remaining because the oxidation of sulfur to sulfate requires the presence of a soil-borne bacterium which will usually be more abundant and amid more growth support factors in topsoil in contrast to surface exposed subsoil. To avoid undesired results, it is important to apply no more of these acidifying chemicals than is calculated here.

Step 2B: Data required to calculate the chemical amendment equivalent and requirement based entirely on the concentration and quantity of spilled material are listed in Step 2B. These data include the volume spilled (in barrels) and the sodium concentration (in mg/L) in the spilled material. The sodium concentration is typically between 20% to 35% of the TDS (in mg/L) in produced waters, and the TDS data are requested as a check function. The spill area is also recorded here as a matter of convenience.

Step 3B: The gypsum equivalent and requirement based on the concentration and quantity of spilled material are calculated in Step 3B. The amount of gypsum to apply to the spill area is the last calculation in Step 3B. Calculating the gypsum requirement in this manner does not address potentially high or low soil pH conditions. For reasons listed in Step 1 of this worksheet, calculation of the chemical amendment requirement based on soil data is preferred over calculations based on the concentration and quantity of spilled material.

Worksheet 4
Chemical Amendments Worksheet

Chemical amendment for displacing sodium and adjusting pH is calculated for upper 2 ft of spill-affected soil*

Step 1

Is volume and sodium concentration of spilled material known and <6 months old?

YES → Optional: Go to Step 2B (page B-32)

YES or NO ↓

Chemical amendment calculations will be based on soil parameters

Step 2A

Collect Data

Spill Area	=		sq ft
pH (0-1 ft)	=		s.u.
pH (1-2 ft)	=		s.u.
CEC (0-1 ft)	=		meq/100 g
CEC (1-2 ft)	=		meq/100 g
ESP (0-1 ft)	=		%
ESP (1-2 ft)	=		%

Step 3A

Calculate Comprehensive Gypsum Requirement
Calculate separately for 0-1 and 1-2 ft

For 0-1 ft
Gypsum requirement = [ESP-5] x [CEC] x [0.00078] = [ ] lbs gypsum/sq ft

[ ] lbs gypsum/sq ft x [ ] sq ft spill area = [ ] Total lbs gypsum

For 1-2 ft
Gypsum requirement = [ESP-5] x [CEC] x [0.00078] = [ ] lbs gypsum/sq ft

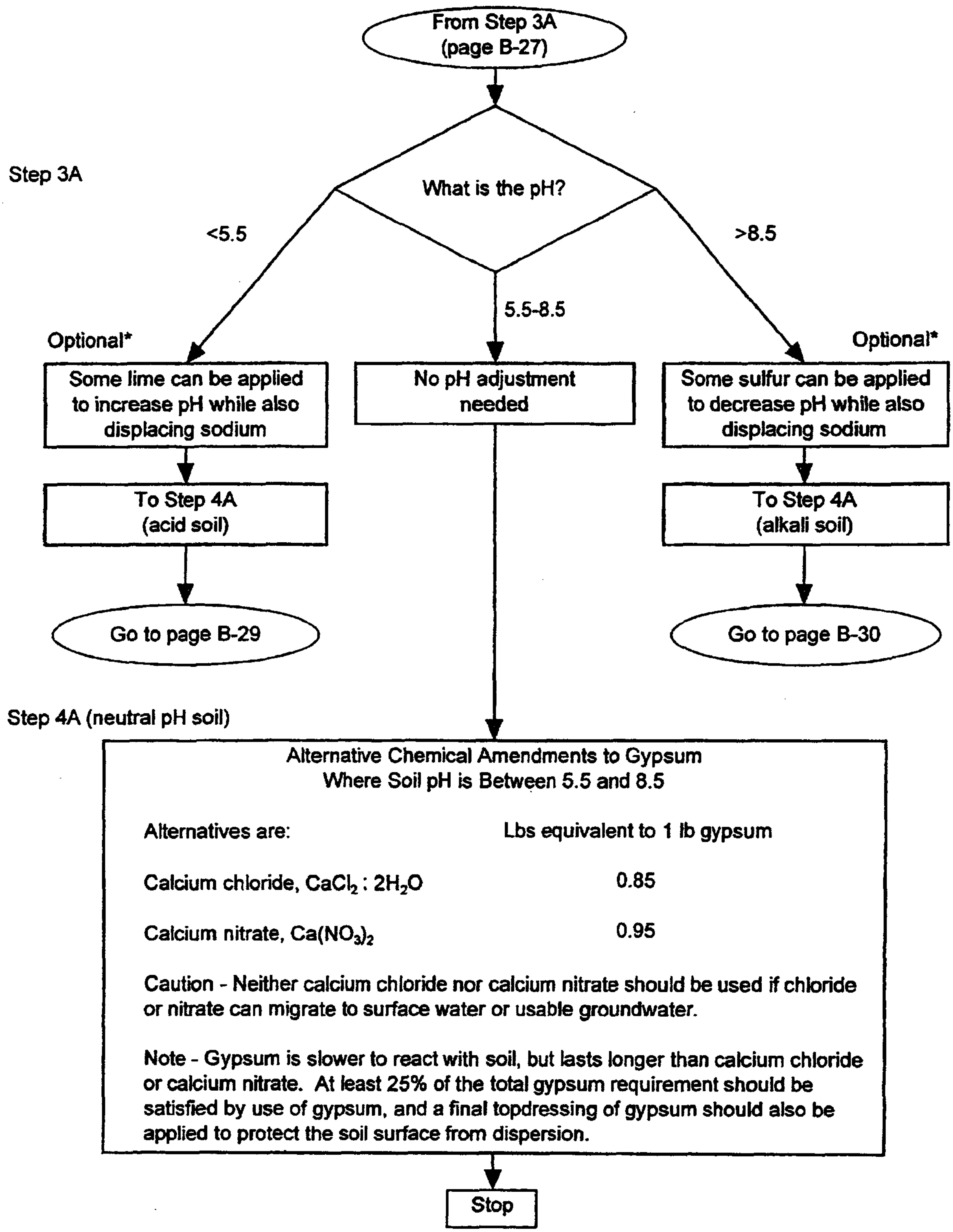
[ ] lbs gypsum/sq ft x [ ] sq ft spill area = [ ] Total lbs gypsum

For combined 0-2 ft

0-1 ft [ ] total lbs gypsum + 1-2 ft [ ] total lbs gypsum = 0-2 ft [ ] Total lbs gypsum to apply

Go to page B-28

* Calculations are performed using only numbers in boxes [i.e., numbers in denominators (e.g., per 100 g in CEC expression) are for identification only and have already been considered in the constants provided (e.g., for 0-1 ft of a soil with ESP = [45] % and CEC = [13] meq/100 g, the first line calculation would be: [45-5] x [13] x [0.00078] = [0.4056] lbs gypsum/sq ft)].



* Most plants prefer pH 5.5-8.5. pH should be adjusted to within 5.5 to 8.5 as part of salt remediation of most soils, but there may be exceptions in certain locations and agricultural situations. Applications of pH-neutral amendments will usually improve yields in both strongly acid and strongly alkaline soils.

From Step 3A (page B-28)

(To increase pH while displacing sodium)

Step 4A (acid soil)

Collect Data

Have laboratory titrate acidity up to pH 7.0 and provide a lime requirement in lbs $CaCO_3$ /1,000 lbs soil

Determine 0-1 and 1-2 ft separately

From 0-1 ft [ ] lbs $CaCO_3$ /1,000 lbs soil

\+

From 1-2 ft [ ] lbs $CaCO_3$ /1,000 lbs soil

=

Total 0-2 ft [ ] lbs $CaCO_3$ /2,000 lbs soil

0-2 ft

([ ] lbs $CaCO_3$ /2,000 lbs soil) x [0.092] x ([ ] sq ft soil) = [ ] Total lbs $CaCO_3$ to apply

Step 5A (acid soil)

Calculate Gypsum Equivalent

For 0-1 ft

([ ] lbs $CaCO_3$ /1,000 lbs soil) x [0.158] x ([ ] sq ft soil) = [ ] Total lbs gypsum equivalent

For 1-2 ft

([ ] lbs $CaCO_3$ /1,000 lbs soil) x [0.158] x ([ ] sq ft soil) = [ ] Total lbs gypsum equivalent

For combined 0-2 ft

0-1 ft [ ] lbs gypsum equivalent + 1-2 ft [ ] lbs gypsum equivalent = 0-2 ft [ ] Total lbs gypsum equivalent

Step 6A (acid soil)

Calculate Gypsum to Co-Apply with Calcium Carbonate ($CaCO_3$)

From Step 3A — From Step 5A (acid soil)

(0-2 ft [ ] total lbs comprehensive gypsum required) - (0-2 ft [ ] total lbs gypsum equivalent) = [ ] Total lbs gypsum to co-apply

Stop

From Step 3A (page B-28)

(To decrease pH while displacing sodium)

Step 4A (alkali soil)

Collect Data

Have laboratory titrate alkalinity to pH 8.3 and provide an acid requirement in lbs S/1,000 lbs soil

Determine 0-1 and 1-2 ft separately

From 0-1 ft [ ] lbs S/1,000 lbs soil

\+

From 1-2 ft [ ] lbs S/1,000 lbs soil

=

Total 0-2 ft [ ] lbs S/2,000 lbs soil

0-2 ft

([ ] lbs S/2,000 lbs soil) x [0.092] x ([ ] sq ft soil) = [ ] Total lbs S to apply

Step 5A (alkali soil)

Calculate Gypsum Equivalent

For 0-1 ft

([ ] lbs S/1,000 lbs soil) x [0.495] x ([ ] sq ft soil) = [ ] Total lbs gypsum equivalent

For 1-2 ft

([ ] lbs S/1,000 lbs soil) x [0.495] x ([ ] sq ft soil) = [ ] Total lbs gypsum equivalent

For combined 0-2 ft

0-1 ft [ ] lbs gypsum equivalent + 1-2 ft [ ] lbs gypsum equivalent = 0-2 ft [ ] Total lbs gypsum equivalent

Step 6A (alkali soil)

Calculate Gypsum to Co-Apply with Sulfur (S)

From Step 3A: (0-2 ft [ ] total lbs comprehensive gypsum required) - From Step 5A (alkali soil): (0-2 ft [ ] total lbs gypsum equivalent) = [ ] Total lbs gypsum to co-apply

Go to page B-31

From Step 6A (alkali soil) (page B-30)

Step 7A (alkali soil)

Alternative Chemical Amendments to Sulfur (S) Where pH is > 8.5

Alternatives are:	Lbs equivalent to 1 lb sulfur
Aluminum sulfate (alum), $Al_2(SO_4)_3 : 18\ H_2O$	6.94
Iron sulfate, $FeSO_4 : 7\ H_2O$	8.69
Sulfuric acid, H_2SO_4	3.06

Caution - These acid-forming amendments including elemental sulfur (S) are typically recommended only if carbonates are present in the soil. Sulfuric acid can cause burns and must be used with care. Use of elemental sulfur also requires the presence of topsoil.

Stop

From Step 1
(page B-27)

Chemical amendment will be based on spilled material parameters*

Step 2B

Collect Data

Spill Area = ______ sq ft

Volume Spilled = ______ bbls

Total Dissolved Solids = ______ mg/L

Sodium Concentration = ______ mg/L

Sodium in mg/L is typically about 20%-35% of TDS in mg/L

Step 3B

Calculate Gypsum Equivalent and Requirement

(______ sodium in mg/L) x 6.94 x (______ bbl spilled) = ______ meq Na spilled

The gypsum requirement in meq is equal to the meq Na spilled

(______ meq Na spilled) x 0.00019 x = ______ Total lbs gypsum to apply to spill area

Stop

* *This option should be selected only after noting assumptions made in the instructions for Worksheet 4 (Steps 1 and 3B).*

WORKSHEET 5 - POST-REMEDIATION MONITORING AND PROJECT TERMINATION (INSTRUCTIONS)

SUMMARY

Verification of successful remediation and project termination of the spill event and subsequent remediation project are documented here. This worksheet may be modified to be consistent with operator policy.

Administrative Information: The site name, spill ID number, and date spill initially reported are taken from Form 1.

Date Remediation Completed: The last date that remediation work was completed at the site. All tasks performed after this date would be considered monitoring or administrative.

Date Project Termination Anticipated: For most remediation efforts, project termination can be anticipated as early as two years after the date that the remediation effort was completed. This two-year duration is used to provide monitoring data to verify that the remediated area has successfully withstood two years of seasonal changes.

Category of Remediation Used: The category of remediation used is one (or a combination) of the categories listed at the bottom of Form 2.

Criteria for Soil Monitoring and Completion of Remediation: If any regulatory, lease, legal, or other criteria are required to be met, or any reports are required to be written, such information is entered in this section. Dates regarding when information is due and when it is actually sent out are recorded here. Space is provided to list data pertaining to the spill site and background for seasonal comparison. A space for noting whether the criteria have been met is also provided.

Comparative Plant Yield Documentation: Information regarding the viability of plant growth on the remediated spill site is entered in this segment. Similar to the above segment, if any regulatory, lease, or other criteria pertaining to vegetation are required to be met, or any reports are required to be written, this information is entered in this section. Space is also provided to record dates information is due and the actual dates the information is sent out. The specific plant type(s) in the spill site and background areas are listed, as is height and biomass. An approximation of these values is all that is needed, and the same methodology should be used for the same types of plants in both the spill site and background areas. If halophytic vegetation which is not present in the background area has been used, then it should be noted that different plants were measured in the spill and background areas. Plant height (or other characteristics) can be measured quickly from the ground surface. Plant biomass can be obtained by cutting all plants in a 1-square-meter area about 1 inch above the ground surface, and weighing the total mass of plants. Variations on these procedures can be adapted as appropriate. This information should be collected on one of the dates in which photographs are taken, as indicated below. A space for noting whether the comparative data appear to be acceptable is also provided.

Photographs of Site and Background: A physical object may be used to denote scale in each photograph. The object used could be a shovel, yardstick, or other object which the viewer could associate with an approximate length. Space is provided to note the date the photograph was taken in each quarter.

Project Termination: When it is determined that remediation has been successful, or that the spill site is otherwise eligible for project termination, the appropriate information should be entered in this segment. If remediation or some other form of project termination is to be reported, that information can also be recorded here.

WORKSHEET 5 - POST-REMEDIATION MONITORING AND PROJECT TERMINATION

Site Name: ____________________ **Spill ID No.:** ____________________

Date Initially Reported: ______________ **Date Remediation Completed:** __________

Date Termination Anticipated (2 yr from date remed. complete): ____________________

Category of Remediation Used: ______________________________

Criteria for Soil Monitoring and Completion of Remediation (list below):

Report to	Date		Criteria	Result		Acceptable (Y/N)
	Due	Sent		Spill Site	Background	

Comparative Plant Yield Documentation:

Report to	Date		Plant Type	Plant				Acceptable (Y/N)
				Height		Biomass		
	Due	Sent		Site	Bkgd.	Site	Bkgd.	

Photographs of Site and Background:

Year	Winter Date Taken	Spring Date Taken	Fall Date Taken
0–1			
1–2			

Project Termination:

Interest Group	Declared to	Declared Date
Regulatory		
Legal		
Corporate		

APPENDIX C

State Regulatory References

SUMMARY

Appendix C contains a list of regulatory agencies (Table C-1) that govern salt-affected soil remediation in each state. Some states have no agency that actually governs remediation of salt-affected soils. In these cases, the state agency that can be consulted for information (if any) is listed. In some states local remediation regulatory bodies exist. States having no exploration or production are not listed.

Table C-1. State Regulatory References (current as of March 31, 1997).

State	Agency	Telephone	Notes
Alaska	Department of Environmental Conservation - *Division of Spill Prevention and Response*	Anchorage - 907-269-7500 Fairbanks - 907-451-2121 Juneau - 907-465-5340 24-hr 800-478-9300	
Alabama	Oil and Gas Board or Department of Environmental Management	205-349-2852 334-271-7700	
Arizona	Oil and Gas Conservation Commission	520-770-3500	
Arkansas	Department of *Pollution Control and Ecology*	800-322-4012	
California	*Department of Conservation* Oil and Gas Division	805-322-4031 916-323-1781	
Colorado	Oil and Gas Conservation Commission	303-894-2100	
Delaware	Department of Natural Resources	Out of state - 302-739-5072 In state - 800-662-8802	
Florida	Department of Natural Resources - Oil and Gas Division	904-488-2974	
Georgia	Environmental Protection Agency	800-241-4113	
Illinois	Department of Natural Resources Oil and Gas Division	*Counties divided into divisions:* Calmi - 618-382-3150 Centralia - 618-533-8979 Newton - 618-783-3699 Springfield - 217-524-1673	
Indiana	Department of Natural Resources	317-232-4200	
Kansas	Corporation Commission	Counties divided into divisions: Div. 1 - 316-225-6760 Div. 2 - 316-337-6231 Div. 3 - 316-431-6946 Div. 4 - 913-628-1200	
Kentucky	Division of Water	800-928-2380 502-564-2380	
Louisiana	Department of Natural Resources or Department of Environmental Quality	504-765-0671 2-hr emergency 504-342-1234 Non-emergency 504-763-3908	
Michigan	Department of Environmental Quality	517-373-9837 (cleanup criteria) Emergency Spill Response 517-373-7660	
Mississippi	Department of Natural Resources - Oil and Gas Board	601-354-7142	
Missouri	Department of Natural Resources	Emergency Response 573-634-2436	

Table C-1. Continued.

State	Agency	Telephone	Notes
Montana	Board of Oil and Gas	406-656-0040	
Nebraska	Department of Environmental Quality	Emergency Response 573-634-2436	
Nevada	Division of Environmental Protection	Emergency Response 702-687-4670 ext. 3022 2-hr response 702-687-3202	
New Jersey	Department of Environmental Protection	609-292-7172 609-292-1073 (cleanup criteria)	
New Mexico	Oil Conservation Division	Counties divided into districts: Dist. 1 - Hobbs - 505-393-6161 Dist. 2 - Artesia - 505-748-1283 Dist. 3 - Aztec - 505-334-6178 Dist. 4 - Santa Fe - 505-827-7131	
New York	Department of Environmental Conservation Division of Mineral Resources	Avon Office 716-226-2466 Olean Office 716-372-0645 Central Office 518-457-7480	
North Dakota	North Dakota Industrial Commission - Oil and Gas Division	701-328-9900	
Ohio	Department of Natural Resources - Oil and Gas Division	614-265-6437	
Oklahoma	Corporation Commission Oil and Gas Conservation Division	Counties divided into divisions: Div. 1 NE 918-367-3391 Div. 2 NW 405-375-5570 Div. 3 SW 405-255-0103 Div. 4 SE 405-332-3441 After 5 p.m. 405-521-2240	
Oregon	Department of Environmental Quality	503-229-5630 800-452-4011	
Pennsylvania	Bureau of Oil and Gas Management	412-442-4000	
South Dakota	Department of Environmental Natural Resources	605-394-2229	
Tennessee	Department of Geology	615-532-0166	
Texas	Texas Railroad Commission	512-463-6765	
Utah	Oil, Gas and Mining	801-538-5340	
Virginia	Department of Minerals and Resources - Oil and Gas Division	703-676-5423	
Washington	Washington Department of Emergency Management Department of Ecology (clean up criteria)	800-258-5990 (24-hr emergency response) 360-407-6300 (cleanup criteria)	
West Virginia	Division of Environmental Protection - Office of Oil and Gas	800-642-3074	
Wyoming	Oil and Gas Conservation Commission	307-261-7520	

Note: Other regulatory agencies or departments may have jurisdiction as well.

APPENDIX D

Glossary

SUMMARY

Appendix D is a glossary containing a list of terms and acronyms to provide the user with a clearer reference and definition of the concepts in this manual. The glossary also contains terms which are not used in the manual, but are commonly used in salt-affected soil remediation references. Be aware that regulatory agencies may define terms differently in the context of their own rules, regulations, or requirements.

AASHO: American Association of State Highway Officials.

Abney level: A small hand level for leveling or measuring slope in percent or degrees.

Acid soil: A soil with a preponderance of hydrogen ions, and probably aluminum, in proportion to hydroxyl ions. Specifically, soil with a pH value of less than 7.0; for most practical purposes, a soil with a pH value of less than 6.6.

Adsorption: The attachment of compounds or ionic parts of salts to a surface or another phase. Nutrients in solution (ions) carrying a positive charge become attached to (adsorbed by) negatively charged soil particles.

Aeration, soil: The process by which air in the soil is replaced by air from the atmosphere. In a well-aerated soil, the soil air is very similar in composition to the atmosphere above the soil. Poorly aerated soils usually contain a much higher percentage of carbon dioxide and a correspondingly lower percentage of oxygen than the atmosphere above the soil. The rate of aeration depends largely on the volume and continuity of pores within the soil.

Aerobic: (1) Having molecular oxygen as a part of environment. (2) Growing only in the presence of molecular oxygen, as aerobic organisms. (3) Occurring only in the presence of molecular oxygen (said of certain chemical or biochemical processes, such as aerobic decomposition).

Aggregate, soil: Many fine particles held in a single mass or cluster. Natural soil aggregates, such as granules, blocks, or prisms, are called peds. Clods are aggregates produced by tillage.

Air porosity: The proportion of the bulk volume of soil that is filled with air at any given time or under a given condition, such as specified moisture tension. Usually the large pores, that is, those drained by a tension of less than approximately 100 cm of water.

Alkali soil: (1) A soil with a high degree of alkalinity (pH of 8.5 or higher) or with a high exchangeable sodium content (15% or more of the exchange capacity), or both. (2) A soil that contains sufficient alkali (sodium) to interfere with the growth of most crop plants.

Alkaline soil: Any soil whose pH is greater than 7.0.

Allophane: A somewhat amorphous clay mineral associated with soils which develop from volcanic ash deposits. They have a high and very pH dependent cation exchange capacity, and very high surface area to weight ratio.

Aluminum oxides: See gibbsite.

Anaerobic: (1) The absence of molecular oxygen. (2) Growing in the absence of molecular oxygen (an anaerobic bacteria). (3) Occurring in the absence of molecular oxygen (as a biochemical process).

Anion: A negatively charged ion; for example chloride (Cl) and sulfate (SO_4).

Anion exchange capacity: The sum total of exchangeable anions that a soil can adsorb. In addition to predominantly negative charge sites which attract soil cations, all soil clays and organic matter simultaneously have a relatively small number of positive charge sites which retain anions in dynamic equilibrium with the soil solution. The number of anion negative charges retained by 100 grams of soil is called the anion exchange capacity. Expressed as milliequivalents per 100 grams of soil (or of other adsorbing material, such as clay).

Aquifer: A geologic formation that holds and yields usable amounts of water.

Available water capacity (available moisture capacity): The capacity of soils to hold water available for use by most plants. It is commonly defined as the difference between the amount of soil-pore water at field moisture capacity and the amount at wilting point. It is commonly expressed as inches of water per inch of soil. The capacity (in inches) in a 60-inch profile or to a limiting layer is expressed as:

Very low	0 to 3 inches
Low	3 to 6 inches
Moderate	6 to 9 inches
High	9 to 12 inches
Very high	more than 12 inches

Base saturation: The degree to which material having cation-exchange properties is saturated with exchangeable bases (sum of Ca, Mg, Na, and K), expressed as a percentage of the total cation exchange capacity.

Bedrock: The solid rock that underlies the soil and other unconsolidated material or that is exposed at the surface.

BLM: Bureau of Land Management.

Brackish water: Water having a dissolved material content in the range of 1,000 to 3,000 mg/L, but not necessarily corresponding to ocean water with respect to ionic ratios.

Brine: Water having more than 30,000 mg/L dissolved material, but not necessarily corresponding to ocean water with respect to ionic ratios.

Bulk density, soil: The mass of dry soil per unit bulk volume. The bulk volume is determined before drying to constant weight at 105°C.

Calcareous soil: Soil containing sufficient calcium carbonate (often with magnesium carbonate) to effervesce (fizz) visibly when treated with cold, 0.1N hydrochloric acid.

Caliche: (1) A layer near the surface, more or less cemented by secondary carbonates of calcium or magnesium precipitated from the soil solution. It may occur as a soft, thin soil horizon; as a hard, thick bed just beneath the solum; or as a surface layer exposed by erosion. Not a geologic deposit. (2) Alluvium cemented with sodium nitrate, chloride, and/or other soluble salts in the nitrate deposits of Chile and Peru.

Capillary fringe: A zone just above the water table (zero gauge pressure) that remains almost saturated. (The extent and the degree of the capillary fringe depends upon the size distribution of pores.)

Capillary water: The water held in the capillary, or small pores, of a soil, usually with a tension greater than 60 cm of water.

Carbon:nitrogen ratio: The ratio of the weight of organic carbon to the weight of total nitrogen in a soil or in organic material. It is obtained by dividing the percentage of organic carbon (C) by the percentage of total nitrogen (N).

Cation: An ion carrying a positive charge of electricity. The common soil cations are calcium, potassium, magnesium, sodium, and hydrogen.

Cation exchange capacity (CEC): The total amount of exchangeable cations that can be held by the soil, expressed in terms of milliequivalents per 100 grams of soil at neutrality (pH 7.0) or at some other stated pH value. Soil clays and organic matter have a relatively large number of negative charge sites which retain cations in dynamic equilibrium with the soil solution. The number of cation positive charges retained by 100 grams of soil is called the cation exchange capacity.

CEC: See cation exchange capacity.

Chisel: A tillage implement with one or more cultivator-type feet to which are attached strong knifelike units used to shatter or loosen hard, compact layers, usually in the subsoil, to depths below normal plow depth.

Chlorosis: A condition in plants resulting from the failure of chlorophyll to develop, usually because of a deficiency in an essential nutrient. Leaves of chlorotic plants range from light green through yellow to almost white.

Clay: As a soil separate, the mineral soil particles less than 0.002 mm in diameter. As a soil textural class, soil material that is 40% or more clay, less than 45% sand, and less than 40% silt.

Coarse fragments: Rock or mineral particles greater than 2.0 mm in diameter.

Coarse texture: The texture exhibited by sands, loamy sands, and sandy loams—except very fine, sandy loam. A soil containing large quantities of these textural classes.

COE: U.S. Army Corps of Engineers.

Colloid soil: "Colloid" refers to organic or inorganic matter with very small particle size and a correspondingly large surface area per unit of mass. Most colloidal particles are too small to be seen with the ordinary compound microscope. Soil colloids do not go into true solution as sugar or salt do, but they may be dispersed into a relatively stable suspension, and thus, be carried in moving water. By treatment with salts and other chemicals, colloids may be flocculated, or aggregated, into small crumbs or granules that settle out of water. (Such small crumbs of aggregated colloids can be moved by rapidly moving water or air just as other particles can be.) Many mineral soil colloids are really tiny crystals, and the minerals can be identified with X-rays and in other ways.

Confined aquifer: (1) An aquifer bounded above and below by impermeable beds, such as clay or unfractured shale, or by beds of distinctly lower permeability than that of the aquifer itself. (2) An aquifer containing confined groundwater.

Conservation practice factor: The ratio of soil loss for contouring, strip cropping, or terracing, to that for up and down the slope farming, as used in the soil-loss equation.

Consistence, soil: The feel of the soil and the ease with which a lump can be crushed by the fingers. Terms commonly used to describe consistence are:

> *Loose*: Noncoherent when dry or moist; does not hold together in a mass.
>
> *Friable*: When moist, crushes easily under gentle pressure between thumb and forefinger and can be pressed together into a lump.
>
> *Firm*: When moist, crushes under moderate pressure between thumb and forefinger, but resistance is distinctly noticeable.
>
> *Plastic*: When wet, readily deformed by moderate pressure but can be pressed into a lump; will form a "wire" when rolled between thumb and forefinger.

Sticky: When wet, adheres to other material and tends to stretch somewhat and pull apart rather than to pull free from other material.

Hard: When dry, moderately resistant to pressure; can be broken with difficulty between thumb and forefinger.

Soft: When dry, breaks into powder or individual grains under very slight pressure.

Cemented: Hard; little affected by moistening.

Crust: A thin, brittle layer of hard soil that forms on the surface of many soils when they are dry. An exposed, hard layer of materials cemented by calcium carbonate, gypsum, or other binding agents. Most desert crusts are formed by the exposure of such layers through removal of the upper soil by wind or running water and their subsequent hardening.

Desalination: Removal of salts from saline soil, usually by leaching.

deciSiemens/meter (dS/m): This is the internationally accepted unit of specific conductance (or electrical conductivity) which is numerically equal to mmhos/cm.

Disperse: (1) To break up compound particles, such as aggregates, into the individual component particles. (2) To distribute or suspend fine particles, such as clay, in or throughout a dispersion medium, such as water. Dispersion is an electro-chemically induced process which results in physical movement of clay particles. Dispersion in soil is the reverse process to aggregation. When freshwater is applied after a saltwater spill, it dilutes and leaches the total salt concentration in the soil solution leaving mostly sodium cations to balance electrically the cation exchange sites. This condition of dilute total salts consisting of predominantly sodium cations causes clay particles to repel from each other and migrate into pore spaces thereby clogging pores.

Dispersed soil: Soil in which the clay has dispersed. A dispersed soil consists of discrete soil particles which are not segregated into aggregates or structural peds. The soil macropores become clogged with soil particles and greatly restrict water and air movement into and through the soil.

Dissolved material: All material which passes through a filter having a pore size of 0.45 μm.

Dissolved solids: A term that expresses the quantity of dissolved material in a sample of water, either the residue on evaporation, dried at 180°C, or, for many waters that contain more than about 1,000 ppm, the sum of determined constituents, generally reported in mg/L.

Diversion: A channel or dam constructed across the slope for intercepting and diverting surface runoff to a safe or convenient discharge point.

Drainage class (natural): Refers to the frequency and duration of periods of saturation or partial saturation during soil formation, as opposed to altered drainage, which is commonly the result of artificial drainage or irrigation but may be caused by the sudden deepening of channels or the blocking of drainage outlets. The following seven classes of natural soil drainage are recognized:

Excessively drained: Water is removed from the soil very rapidly. Excessively drained soils are commonly very coarse textured, rocky, or shallow; some are steep. All are free of the mottling related to wetness.

Somewhat excessively drained: Water is removed from the soil rapidly. Many somewhat excessively drained soils are sandy and rapidly pervious; some are shallow. Some are so steep that much of the water they receive is lost as runoff. All are free of the mottling related to wetness.

Well drained: Water is removed from the soil readily, but not rapidly. It is available to plants throughout most of the growing season, and wetness does not inhibit growth of roots for significant periods during most growing seasons. Well drained soils are commonly medium texture. They are mainly free of mottling.

Moderately well drained: Water is removed from the soil somewhat slowly during some periods. Moderately well drained soils are wet for only a short time during the growing season, but periodically they are wet long enough that most mesophytic crops are affected. They commonly have a slowly pervious layer within or directly below the solum or periodically receive high rainfall, or both.

Somewhat poorly drained: Water is removed slowly enough that the soil is wet for significant periods during the growing season. Wetness markedly restricts the growth of mesophytic crops unless artificial drainage is provided. Somewhat poorly drained soils commonly have a slowly pervious layer, a high water table, additional water from seepage, nearly continuous rainfall, or a combination of these.

Poorly drained: Water is removed so slowly that the soil is saturated periodically during the growing season or remains wet for long periods. Free water is commonly at or near the surface for long enough during the growing season that most mesophytic crops cannot be grown unless the soil is artificially drained. The soil is not continuously saturated in layers directly below plow depth. Poor drainage results from a high water table, a slowly pervious layer within the profile, seepage, nearly continuous rainfall, or a combination of these.

Very poorly drained: Water is removed from the soil so slowly that free water remains at or on the surface during most of the growing season. Unless the soil is artificially drained, most mesophytic crops cannot be grown. Very poorly drained soils are commonly level or depressed and are frequently ponded. Yet, where rainfall is high and nearly continuous, they can have moderate or high slope gradients.

Dry-weight percentage: The ratio of the weight of any constituent of a soil to the oven-dry weight of the soil (constant weight at 105°C).

dS/m: See deciSiemens/meter

E&P: Exploration and production - primarily drilling for and recovery of subsurface petroleum.

EC: See electrical conductivity.

ECP: See exchangeable cation percentage.

Effective porosity: The amount of interconnected pore space available for fluid transmission.

Effective precipitation: That portion of the total precipitation which becomes available for plant growth.

Electrical conductivity (EC): Conductivity measured directly in reciprocal units of resistance and reported in mmhos/cm. EC is an indirect measure of total dissolved solids (TDS).

Electromagnetic imaging (EM) devices: Field instruments which sense the ability of the local surroundings, including soil, to conduct electricity by detecting resistance to induced electromagnetic radiation. Used to sense variations in soil EC within a field, but also responds to soil water content, porosity, type and amount of clay, electric power lines, and buried pipes.

EM: See electromagnetic-imaging devices.

EPA: U.S. Environmental Protection Agency.

EPA-NRC: U.S. Environmental Protection Agency - National Response Center.

Ephemeral stream: A stream which flows only in direct response to precipitation in the immediate watershed or in response to the melting of a cover of snow and ice, and which has a channel bottom that is always above the local water table.

Equivalent per million: An equivalent weight of an ion or salt per 1 million grams of solution or soil. For solutions, equivalents per million (e.p.m.) and milliequivalents per liter (meq/L) are numerically identical if the specific gravity of the solution is 1.0 as it is for freshwater at 20°C.

Equivalent; equivalent weight: The weight in grams of an ion or compound that combines with or replaces 1 gram of hydrogen. The atomic weight or formula weight divided by the valence of the cations or anions which would form upon dissolution. This measure indicates how many grams of an ion or compound will supply one mole of positive or negative charges when dissolved. The mass of the dissolved cations and anions is of no consequence to the actual electrical interactions, but it is important for calculating the mass of materials participating in these reactions. The equivalent weight of a substance is the mass of the substance which will supply a standard number of positive or negative electrical charges when dissolved. For example the formula weight of anhydrous calcium chloride ($CaCl_2$) is about 111 grams. Since calcium is divalent and there are two monovalent chloride ions, there would be two moles of positive and two moles of negative charges supplied by 111 grams of calcium chloride. Therefore 55 grams of calcium chloride is the equivalent weigh because 55 grams of calcium chloride would supply one mole of positive or negative charges when dissolved in water. The amount of chemical amendment required by a soil is based on the number of electrical charges of sodium which must be displaced and an equal number of electrical charges from the chemical amendment used to displace the sodium.

Erodible: Susceptible to erosion.

Erosion: The wearing away of the land surface by water, wind, ice, or other geologic agents and by such processes as gravitational creep.

> *Erosion* (*geologic*): Erosion caused by geologic processes acting over long geologic periods and resulting in the wearing away of mountains and the building up of such landscape features as floodplains and coastal plains. Synonym: natural erosion.
>
> *Erosion* (*accelerated*): Erosion much more rapid than geologic erosion, mainly as a result of human or animal activities or of a catastrophe in nature, such as fire, that exposes the surface.

ESP: See exchangeable sodium percentage.

Evapotranspiration: The loss of water from a soil by evaporation and plant transpiration.

Exchange acidity: The titratable hydrogen and aluminum that can be replaced from the adsorption complex by a neutral salt solution. Usually expressed as milliequivalents per 100 grams of soil. Acidity in a soil is primarily the result of hydrogen ions (H^+), aluminum ions (Al^{+3}), and aluminum mono- and di-hydroxide ions [$Al(OH)^{+2}$ and $Al(OH)_2{}^{+1}$, respectively]. Because they have a positive electrical charge these ions participate in cation exchange reactions, and because they cause soil acidity they are called exchangeable acids. Exchangeable acidity is therefore the number of meq/100 grams of soil which consist of hydrogen, aluminum, and aluminum mono- and di-hydroxide ions. The remainder of the cation change capacity would consist of exchangeable bases such as sodium, potassium, calcium, and magnesium. The role of aluminum ions in acidity is described in the definition of reserve acidity.

Exchange capacity: The total charge of the adsorption complex active in the adsorption of ions.

Exchangeable anions: Anions on anion exchange sites or in the soil solution that can participate in the anion exchange process in soil. The most common exchangeable anions in the soils are chloride, sulfate, bicarbonate, and carbonate. Exchangeable anions are in dynamic equilibrium between the soil solution and adsorption on anion exchange sites.

Exchangeable cation percentage (ECP): The extent to which the adsorption complex of a soil is occupied by a particular cation. The proportion (in percent) of the total cation exchange capacity of a soil (at a given pH) which is satisfied by a given species of cation at a given point in time. The exchangeable cations are determined by displacing them with a concentrated solution consisting of a different type of cation. The type and quantity of displaced cations are collected and measured in the laboratory. The resulting data give both the cation exchange capacity and the relative cation percentages. For example, if 8 meq calcium, 4 meq potassium, 4 meq sodium, 1 meq aluminum, 1 meq magnesium, 1 meq ammonium, and 1 meq of other miscellaneous cations were displaced by cation exchange from 100 grams of soil, then the cation exchange capacity would be 20 milliequivalents per 100 grams of soil, and relative exchangeable cation percentages would be 40, 20, 20, 5, 5, 5, and 5, respectively. It is expressed as follows:

$$ECP = \frac{\text{Exchangeable cation (meq/100g soil)}}{\text{Cation exchange capacity (meq/100g soil)}} \times 100$$

Exchangeable cations: Cations on cation exchange sites or in the soil solution that can participate in the cation exchange process in soil. The most common exchangeable cations in soils are calcium, magnesium, sodium, potassium, aluminum, and hydrogen. Other exchangeable cations include ammonium, iron, manganese, copper, zinc, and other positively charged dissolved ions in the soil. Exchangeable cations are in dynamic equilibrium between the soil solution and adsorption on cation exchange sites.

Exchangeable sodium percentage (ESP): The extent to which the adsorption complex of a soil is occupied by sodium. Amount of exchangeable sodium expressed as a percentage of total exchangeable cations. Refer to discussion under exchangeable cation percentage. It is expressed as follows:

$$ESP = \frac{\text{Exchangeable sodium (meq/100g soil)}}{\text{Cation exchange capacity (meq/100g soil)}} \times 100$$

Field capacity: Water content of a soil after it has been saturated and allowed to drain freely, usually expressed as a percentage of its oven-dry weight or volume.

Fine texture: The texture exhibited by clay, sandy clay, silty clay, clay loam, and silty clay loam soils. A soil containing large quantities of these textural classes.

Flocculate: To aggregate or clump together individual tiny soil particles, especially fine clay, into small groups or granules. The opposite of deflocculate or disperse.

Fragipan: A natural subsurface horizon with high bulk density relative to the solum above, seemingly cemented when dry but, when moist, showing a moderate to weak brittleness.

Freshwater: Water having less than 1,000 mg/L dissolved material.

Friable: A consistency term pertaining to the ease of crumbling of soils.

Geographic information system (GIS): A computer database management system, which includes remote sensing, mapping, cartography, and photogrammetry for conducting spatial searches and making map overlays.

Gibbsite: Gibbsite [$Al(OH)_3$] is the most common soil oxide of aluminum. It forms in weathered soils, primarily in the temperate and especially in tropical regions. Gibbsite is relatively stable once formed and contributes to soil aggregate stability. Gibbsite strongly adsorbs anions and its anion exchange capacity increases with decreasing pH.

GIS: See geographic information system.

Gleyed soil: Soil that formed under poor drainage, resulting in the reduction of iron and other elements in the profile and in gray colors and mottles.

Granular structure: Soil structure on which the individual grains are grouped into spherical aggregates with indistinct sides. Highly porous granules are commonly called crumbs. A well-granulated soil has the best structure for most ordinary crop plants.

Gravitational water: Water that moves into, through, or out of the soil under the influence of gravity.

Groundwater: Subsurface water that fills available openings in rock or soil materials to the extent that they are considered water saturated.

Gully: A channel resulting from erosion and caused by the concentrated but intermittent flow of water, usually during and immediately following heavy rains. Deep enough to interface with, and not be obliterated by, normal tillage operations.

Halophyte: A type of plant indigenous to, or which can adapt to very saline soils.

Hardness: A property of water that causes formation of an insoluble residue when the water is used with soap and a scale in vessels which water has been allowed to evaporate. It is primarily due to the presence of ions of calcium and magnesium, but also to ions of other alkali metals, other metals (such as iron), and even hydrogen. Hardness of water is generally expressed as ppm of $CaCO_3$ (40 ppm Ca produces a hardness of 100 ppm as $CaCO_3$), also as mg/L, and as the combination of carbonate hardness and noncarbonate hardness.

Hardpan: A hardened or cemented soil layer in the B or lower A soil horizon.

Horizon, soil: See soil horizon.

Humification: The processes involved in the decomposition of organic matter and leading to the formation of humus.

Humus: The well decomposed, more or less stable part of the organic matter in mineral soils.

Hydraulic conductivity: The rate at which water will move through soil under a unit hydraulic gradient.

Hydraulic gradient: Change in the hydraulic head per unit distance.

Hydrologic soil groups: Refers to soils grouped according to their runoff-producing characteristics. The chief consideration is the inherent capacity of soil devoid of vegetation to permit infiltration. The slope and the kind of plant cover are not considered but are separate factors in predicting runoff. Soils are assigned to four groups. In group A are soils having a high infiltration rate when thoroughly wet and having a low runoff potential. They are mainly deep, well drained, and sandy or gravelly. In group D, at the other extreme, are soils having a very slow infiltration rate, and thus, a high runoff potential. They have (a) a claypan or clay layer at or near the surface, (b) have a permanent high water table, or (c) are shallow over nearly impervious bedrock or other material. A soil is assigned to two hydrologic groups if part of the acreage is artificially drained and part is undrained.

Hydromorphic soils: Soil formed under conditions of poor drainage in marshes, swamps, seepage areas, or flats.

Impervious soil: A soil through which water, air, or roots penetrate slowly or not at all. No soil is absolutely impervious to air and water all the time.

Indurated: A condition of a rock or soil hardened or consolidated by pressure, cementation, or heat.

Infiltration: The downward entry of water into the soil.

Infiltration rate: A soil characteristic determining or describing the maximum rate at which water can enter the soil under specified conditions, including the presence of excess water.

Intake rate: The average rate of water entering the soil under irrigation. Most soils have a fast initial rate; the rate decreases with application time. Therefore, intake rate for design purposes is not constant but is a variable depending on the net irrigation application. The rate of water intake (in inches per hour) is expressed as follows:

Very low	Less than 0.2 in/hr
Low	0.2 to 0.4 in/hr
Moderately low	0.4 to 0.75 in/hr
Moderate	0.75 to 1.25 in/hr
Moderately high	1.25 to 1.75 in/hr
High	1.75 to 2.5 in/hr
Very high	More than 2.5 in/hr

Intermittent stream: (1) A stream or reach of stream that drains a watershed of at least one square mile. (2) A stream or reach of stream that is below the local water table for at least some part of the year, and obtains its flow from both surface runoff and groundwater discharge.

Irrigation methods: The manner in which water is artificially applied to an area. The methods and the manner of applying the water are as follows:

Border-strip: The water is applied at the upper end of a strip with earthen borders confining the water to the strip.

Flooding: The water is released from the field ditches and allowed to flood over the land.

Furrow: The water is applied to row crops in ditches made by tillage implements.

Sprinkler: The water is sprayed over the soil surface through nozzles from a pressure system.

Iron oxides: Principally goethite (FeOOH) and hematite (Fe_2O_3) in soils. A very small amount of goethite gives soil a yellow color and a very small amount of hematite gives soil a red color. These minerals are common in most soils and are abundant in highly weathered soils in the tropics. Both goethite and hematite have pH dependent charges. At high pH they have a negative charge and a cation exchange capacity. At low pH they have a positive charge and an anion exchange capacity. In most soils, iron oxides help to stabilize soil aggregates. Red soils are indicative of a high degree of oxidation. Yellow soils are also oxidized but less intensively than red soils. Red and yellow mottles (spots) in a soil are often indicative of a fluctuating water table. In water logged soils the iron in goethite and hematite has become soluble and leached out of the soil leaving a chalky gray color. If these soils are drained, any remaining iron rapidly oxidizes and forms oxides exhibited by new yellow or red coloring.

Iron pan: An indurated soil horizon in which iron oxide is the principle cementing agent.

Kaolinite: A commonly occurring layered alumino-silicate clay mineral. The layers of a kaolinite mineral are not expandable. The cation exchange capacity and specific surface are in the low range compared to most other common clay minerals. The cation exchange capacity of kaolinite is very pH dependent.

Land capability classification: The designation of soil units for showing their suitability for specific uses, such as cropping, grazing, woodland, wildlife, or others, usually divided into eight classes. The classes range from Group I for soils which are very productive, easy to work with, and have few if any limitations for most uses to Group VIII for soils or land conditions which are minimally productive, extremely difficult to work, with and have very severe limitations. Lower case letters represent subclasses such as "e" for highly erodible; "w" for excess wetness; "s" for droughty, or stoney; and "c" for prolonged coldness.

Land spreading/land treatment: A process in which contaminated soils or waste are spread over a treatment area and tilled with native soil. Nutrients and/or water may be added to enhance biodegradation.

Leachate: A solution obtained by leaching, such as water that has percolated through soil containing soluble substances and which contains certain amounts of these substances in the solution.

Leaching: The removal of materials in solution from the soil.

Lime, agricultural: A soil amendment consisting principally of calcium carbonate, but including magnesium carbonate; used to furnish calcium and magnesium and to neutralize soil acidity.

Loamy: Intermediate in texture and properties between fine-textured and coarse-textured soils. Includes all textural classes with the words loam or loamy as a part of the class name, such as clay loam or loamy sand.

Loess: Material transported and deposited by wind and consisting of predominantly silt-sized particles.

Macronutrient: A chemical element necessary in large amounts (usually greater than 1 ppm in the plant) for the growth of plants and usually applied artificially in fertilizer or limiting materials. (Macro refers to quantity and not to the essentiality of the element.)

Medium texture: The texture exhibited by loam, silt loam, silt, and sandy clay loam soils. A soil containing large quantities of these textural classes.

meq: See milliequivalent.

Micromho: The unit used in reporting specific conductance of water per centimeter at 25°C.

Micronutrient: A chemical element necessary in only extremely small amounts (less than 1 ppm in the plant) for the growth of plants. Examples are B, Cl, Cu, Fe, Mn, and Zn. (Micro refers to the amount used and not to the essentiality of the element.)

Milliequivalent: One thousandth of an equivalent. Refer to discussion in equivalent.

Millimhos per centimeter (mmhos/cm): The basic unit of measure of electrical conductivity in soil, and the inverse of electrical transmissivity through a solution. Refer to discussion in specific conductance.

Mineral soil: A soil consisting predominately of, and having its properties determined predominately by, mineral matter. Usually contains less than 20% organic matter, but may contain an organic surface layer up to 30 cm thick.

mmhos/cm: see millimhos per centimeter.

Moderately coarse-textured soil: Coarse sandy loam, sandy loam, or fine sandy loam.

Moderately fine-textured soil: Clay loam, sandy clay loam, or silty clay loam.

Moisture tension (or pressure): The equivalent negative pressure in soil water. It is equal to the pressure applied to soil water to achieve hydraulic equilibrium, through a porous permeable wall or membrane, with a pool of water of the same composition. The pressures used and the corresponding percentages most commonly determined are as follows:

> *Fifteen-atmosphere percentage:* The percentage of water contained in a saturated soil subjected to an applied pressure of 15 atmospheres until it is in equilibrium.
>
> *One-third-atmosphere percentage*: The percentage of water contained in a saturated soil subjected to an applied pressure of 1/3 atmospheres until it is in equilibrium.

Montmorillonite: An alumino-silicate clay mineral with a 2:1 expanding crystal lattice: two silicon tetrahedral layers enclosing an aluminum octahedral layer. Considerable expansion may be caused along the "C" axis by water moving between silica layers of contiguous units (interlayer water absorption).

Morphology, soil: The composition of the soil, including texture, structure, consistence, color, and other physical, chemical, and biological properties of the various soil horizons that make up the soil profile.

Mottling, soil: Irregular spots of different colors that vary in number and size. Mottling generally indicates poor aeration and impeded drainage. Descriptive terms are as follows: abundance - *few, common,* and *many*; size - *fine, medium,* and *coarse*; and contract - *faint, distinct,* and *prominent.* The size measurements are of the diameter along the greatest dimension. *Fine* indicates less than 5 mm (about 0.2 inch); *medium*, from 5 to 15 mm (about 0.2 to 0.6 inch); and *coarse*, more than 15 mm (about 0.6 inch).

Munsell color system: A color-designation system that specifies the relative degrees of the three simple variables of color: hue, value, and chroma. For example: 10 YR 6/4 is a color (of soil) in which hue = 10 YR, value = 6, and chroma = 4. These notations can be translated into several different systems of color names as desired.

Mycorrhiza: The association, usually symbiotic, of fungi with the roots of seed plants.

Naturally occurring radioactive material (NORM): Radioactive material occurring naturally in the environment including material brought to the surface during oil exploration and production.

NORM: See naturally occurring radioactive material.

O&G: Oil and grease. A measure of hydrocarbon content in soils and water. Usually used in reference to petroleum hydrocarbons.

Osmotic: A type of pressure exerted in living bodies as a result of unequal concentration of salts in both sides of a cell wall or membrane. Water will move from the area that has the lesser salt concentration through the membrane into the area that has the greater salt concentration; it therefore, exerts additional pressure on its side of the membrane.

Oven-dry soil: Soil dried at 105°C until it reaches constant weight.

Pans: Horizons or layers in the soils that are strongly compacted, indurated, or very high in clay content.

Parent material: The unconsolidated organic and mineral material in which soil forms.

Particle density: The mass per unit volume of soil particles.

Particle-size distribution: The amounts of the various soil separates in a soil sample, usually expressed as weight percentages.

Ped: A unit of soil structure, such as an aggregate, crumb, prism, block, or granule, formed by natural processes (in contrast to a clod, which is formed artificially).

PEI: See precipitation evaporation index.

Perched groundwater: Unconfined groundwater that is separated from an underlying body of groundwater by an unsaturated zone and a confining bed. The perched zone of saturation may be either permanent, where recharge is frequent enough to maintain a saturated zone, or temporary, where recharge is insufficient.

Percolation: The downward movement of water through the soil.

Perennial stream: A stream, or part of stream, that flows continuously during the year as a result of groundwater discharge or surface runoff.

Permeability: The quality of the soil that enables water to move through the profile. Permeability is measured as the number of inches per hour that water moves through the saturated soil. Terms describing permeability are as follows:

Very slow	less than 0.06 in/hr
Slow	0.06 to 0.2 in/hr
Moderately slow	0.2 to 0.6 in/hr
Moderate	0.6 to 2.0 in/hr
Moderately rapid	2.0 to 6.0 in/hr
Rapid	6.0 to 20 in/hr
Very rapid	more than 20 in/hr

pH, soil: The negative logarithm of the hydrogen-ion activity of a soil. The degree of acidity (or alkalinity) of a soil as determined by means of a glass electrode or indicator at a specified moisture content of soil-water ratio and expressed in terms of the pH scale (see reaction, soil).

Photoionization detector (PID): A field instrument capable of detecting certain petroleum hydrocarbon vapors at low concentrations.

Phreatophyte: A nonbeneficial, water-loving plant that derives its water from subsurface sources.

PID: See photoionization detector.

Plowpan: A compacted layer formed in the soil directly below the plowed layer.

Pore space: The total space not occupied by soil particles in a bulk volume of soil.

Porosity: The volume percentage of the total bulk not occupied by solid particles.

ppm: Part(s) per million. A measure of concentration of a substance in a solid, liquid, or gas. In solids ppm equates to milligrams per kilogram (mg/kg) and in liquids to milligrams per liter (mg/L).

Precipitation evaporation index (PEI): A measure in vertical inches of the average annual abundance of rainfall for a given location. The mean annual class A pan evaporation in inches is subtracted from the normal annual total precipitation in inches to give the precipitation evaporation index. The PEI is calculated to determine if supplemental water will be required to leach salts from a salt-affected soil.

Produced water: Water extracted from the ground during oil production processes. Produced water is often, but not always high in salts and usually contains some hydrocarbons.

Profile, soil: A vertical section of the soil extending through all its horizons and into the parent material.

QA/QC: See quality assurance/quality control.

Quality assurance/quality control (QA/QC): A system of procedures, checks, audits and corrective actions used to ensure the quality of work performed. QA/QC protocols can be utilized during any phase of a project from planning through field work and laboratory analysis to remediation planning, execution, verification, monitoring, and administrative closure. Quality controls and assurance protocols can be adapted to a given project from established literature and practices.

Reaction, soil: A measure of the acidity or alkalinity of a soil expressed in pH values. A soil that tests to pH 7.0 is described as precisely neutral in reaction because it is neither acid nor alkaline. The degrees of acidity and alkalinity (expressed as pH values) are as follows:

Extremely acid	below 4.5 s.u.
Very strongly acid	4.5 to 5.0 s.u.
Strongly acid	5.1 to 5.5 s.u.
Medium acid	5.6 to 6.0 s.u.
Slightly acid	6.1 to 6.5 s.u.
Neutral	6.6 to 7.3 s.u.
Mildly alkaline	7.4 to 7.8 s.u.
Moderately alkaline	7.9 to 8.4 s.u.
Strongly alkaline	8.5 to 9.0 s.u.
Very strongly alkaline	9.1 s.u. and higher

Regolith: A general term for the layer or mantle of fragmental and unconsolidated rock material, whether residual or transported and of highly varied character, that nearly everywhere forms the surface of the land and overlies or covers the bedrock.

Reserve acidity: The pH of a soil solution is a measure of the active acidity [concentration of dissolved free hydrogen ions (H^+)] in the soil solution. A low pH indicates an excess of hydrogen ions compared to hydroxyl ions (OH^-). The lower the pH the greater the acidity in the soil, and the scale is logarithmic. In very acid soils (pH < 5), trivalent aluminum (Al^{+3}) which is a component of numerous clay minerals becomes increasingly soluble. When dissolved, each aluminum ion is strong enough to split three water molecules (by three stages of hydrolysis) in order to bond with the three hydroxyl ions thus released. This releases three hydrogen ions to the soil solution, and further increases the acidity. When chemical amendments are added to neutralize an acid soil, the amount of chemical amendment applied (lime) must be sufficient to neutralize both the free hydrogen ions (H^+) and the three species of free aluminum ions [Al^{+3}, $Al(OH)^{+2}$, and $Al(OH)_2{}^{+1}$] which are still capable of causing further hydrolysis and acidification. Because of the complex reactions involved, the amount of lime required to balance the pH is determined by titrating a known mass of soil with a base representing lime. When the titration stabilizes at an appropriate endpoint (e.g., pH = 7.0), the amount of base used correlates with the amount of lime which must be added to neutralize the hydrogen ions and aluminum ions. Reserve acidity is the combined acid potential of H^+, Al^{+3}, $Al\ (OH)^{+2}$, and $Al\ (OH)_2{}^{+1}$ ions adsorbed on clay colloids, whereas active acidity is free H^+ in the soil solution (not adsorbed).

Rill: A steep-sided channel resulting from accelerated erosion. A rill is generally a few inches deep and not wide enough to be an obstacle to farm machinery.

Rock fragments: Rock or mineral fragments having a diameter of 2 mm or more (e.g., pebbles, cobbles, stones, and boulders).

Saline-sodic: (1) A soil containing sufficient exchangeable sodium to interfere with the growth of most crop plants and also containing appreciable quantities of soluble salts. (2) A soil in which the exchangeable sodium percentage (ESP) is greater than 15% and the conductivity of the saturation extract (EC) is greater than 4 mmhos/cm.

Saline soil: A nonsodic soil containing sufficient soluble salts to impair its productivity. The conductivity of the saturation extract is greater than 4 mmhos/cm (at 25°C) and the pH is usually less than 8.3.

Salinity: A term describing water solutions containing dissolved mineral solids. The U.S. Geological Survey has assigned terms for degrees of salinity for waters with the following dissolved-solids concentration ranges:

Slightly saline	1,000 to 3,000 mg/L
Moderately saline	3,000 to 10,000 mg/L
Very saline	0,000 to 35,000 mg/L
Briny	over 35,000 mg/L

Sand: (1) A soil particle between 0.05 and 2.0 mm in diameter. (2) Any one of five soil separates, namely: very coarse sand, coarse sand, medium sand, fine sand, and very fine sand. (3) A soil textural class.

SAR: See sodium adsorption ratio.

Saturated Paste: The mixture of soil and water which occurs when all soil pores are just filled with water. In undersaturated soil, deionized water is added to a soil sample with minimal mixing until all soil pores are filled with water and there is negligible air in the pores. Mixing is minimized to retain natural pore size distribution as much as possible and to minimize expansion of expandable clay minerals such as smectite and vermiculite. The percent of soil-pore water weight to dry soil weight at this precise moisture content is called the saturation percentage, and this is unique for each different soil due to different types, sizes, and shapes of solid constituents. The saturated paste moisture content is useful as a reference because it represents the actual concentrations and ratios of dissolved constituents which are available for uptake by plant roots.

Saturated Paste Extract: Soil-pore water containing dissolved constituents which has been removed from a saturated paste for analysis.

Series, soil: See soil series.

Sheet erosion: The removal of a fairly uniform layer of soil material from the land surface by the action of rainfall and surface runoff.

Shrink-swell: The shrinking of soil when dry and the swelling when wet. Shrinking and swelling can damage roads, dams, building foundations, and other structures. It can also damage plant roots.

Silica: An important soil constituent composed of silicon and oxygen. The essential material of the mineral quartz.

Silt: As a soil separate, individual mineral particles that range in diameter from the upper limit of clay (0.002 mm) to the lower limit of very fine sand (0.05 mm). As a soil textural class, soil that is 80% or more silt and less than 12% clay.

Slick spots: Small areas in a field that are slick when wet, as a result of a high content of alkali or of exchangeable sodium.

Slope length factor: A relative number for evaluating the length of slope in the soil-loss equation.

Slope steepness factor: A relative number for evaluating the land slope in the soil-loss equation.

Sodic soil: A soil that contains an exchangeable sodium percentage (ESP) of 15% or more.

Sodium adsorption ratio (SAR): The empirical mathematical expression developed as an index of the sodium hazard in soils. The concentrations of sodium, calcium, and magnesium are expressed in meq/L:

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

Soil: The unconsolidated mineral material on the immediate surface of the earth serving as natural medium for the growth of land plants.

Soil air: (1) The soil atmosphere. (2) The gaseous phase of the soil. (3) It is that volume not occupied by solid or liquid.

Soil association: A group of defined and named taxonomic soil units which typically occur together in a characteristic pattern over a geographic region.

Soil complex: A mapping unit used in detailed Soil Surveys where two or more defined taxonomic units are so intimately intermixed geographically that it is undesirable or impractical, because of the scale being used, to separate them. A more intimate mixing of smaller areas of individual taxonomic units than that described under soil association.

Soil erodibility factor: A numerical value by soil type for estimating the tendency of a soil to be eroded in the soil-loss equation.

Soil extract: The solution separated from a soil suspension or from a soil filtration, centrifugation, suction, or pressure. (May or may not be heated before separation.)

Soil formation factors: The variable, usually interrelated, natural agencies that are active in and responsible for the formation of soil. The factors are usually grouped into five major categories: parent rock, climate, organisms, topography, and time.

Soil horizon: A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics such as color, structure, texture, consistency, kinds and numbers of organisms present, degree of acidity or alkalinity, etc. The following table lists the designations and properties of the major soil horizons. Very few soils, if any, have all of these horizons well developed, but every soil has some of them.

Horizon Designation	Description
0	Organic horizons of mineral soils.
01	Organic horizons in which essentially the original form of most vegetative matter is visible to the naked eye.
02	Organic horizons in which the original form of most plant or animal matter can not be recognized with the naked eye.
A	Mineral horizons consisting of (1) horizons of organic-matter accumulation formed or forming at or adjacent to the surface; (2) horizons that have lost clay, iron, or aluminum, with the resultant concentration of quartz or other resistant minerals of sand or silt size; or (3) horizons dominated by (1) or (2) above, but transitional to an underlying B or C.
Ap	The plowed portion of the A horizon.
A1	Mineral horizons, formed or forming at or adjacent to the surface.
A2 or E	Mineral horizons in which the feature emphasized is loss of clay.
A3	A transitional horizon between A and B and dominated by properties characteristic of an overlying A1 or A2, but that has some subordinate properties of an underlying B.
AB	A transitional horizon between A and B and dominated by properties of B in which the two parts cannot be conveniently separated into A and B.
A and B	Horizons that would qualify for A2 except for included parts that constitute less than 50% of the volume that would qualify as B.
AC	A horizon transitional between A and C that has subordinate properties of both A and C but that is not dominated by properties characteristic of either A or C.
B and A	Any horizon qualifying as B in greater than 50% of its volume, including parts that qualify as A2.
B	Soil horizon beneath A horizon. Clay and nutrients, etc., have accumulated in this horizon.

Horizon Designation	Description
B1	A transitional horizon between B and A1 or between B and A2 in which the horizon is dominated by properties of an underlying B2 but has some subordinate properties of an overlying A1 or A2.
B2	That part of the B horizon where the properties on which the B is based are without clearly expressed subordinate characteristics, indicating that the horizon is transitional to an adjacent overlying A or an adjacent overlying C or R.
B3	A transitional horizon between B and C or R in which the properties diagnostic of an overlying B2 are clearly expressed but are also associated with clearly expressed properties characteristic of C or R.
C	A mineral horizon or layer, excluding bedrock, that is either like or unlike the material form which the solum is presumed to have formed, relatively unaffected by pedogenic processes, and lacking properties diagnostic of A or B.
R	Underlying consolidated bedrock such as granite, sandstone, or limestone.

Soil map: A map showing the distribution of soil types or other soil-mapping units in relation to the prominent physical and cultural features of the earth's surface.

Soil permeability (hydraulic conductivity): A soil characteristic indicating the rate water moves through the soil.

Soil pores: That part of the bulk volume of soil not occupied by soil particles.

Soil separates: Mineral particles less than 2 mm in equivalent diameter and ranging between specified size limits. The names and sizes (in mm) of separates recognized in the U.S. are as follows:

Very coarse sand	2.0 to 1.0 mm
Coarse sand.	1.0 to 0.5 mm
Medium sand.	0.5 to 0.25 mm
Fine sand	0.25 to 0.10 mm
Very fine sand	0.10 to 0.05 mm
Silt	0.05 to 0.002 mm
Clay	less than 0.002 mm

Soil series: A group of soils that have profiles that are almost alike, except for differences in texture of the surface layer or of the underlying material. All the soils of a series have horizons that are similar in composition, thickness, and arrangement.

Soil solution: The aqueous liquid phase of the soil and its solutes that consists of ions dissociated from the surface of the soil particles and of other materials.

Soil Survey: The systematic examination, description, classification, and mapping of soils in an area. Soil Surveys are classified according to the kind and intensity of field examination.

Solum: The upper part of a soil profile, above the C horizon, in which the processes of soil formation are active. The solum in soil consists of the A, E, and B horizons. Generally, the characteristics of the material in these horizons are unlike those of the underlying material. The living roots and plant and animal activities are largely confined to the solum.

Specific conductance: A measure of the ability of water to conduct an electrical current. It is the reciprocal of the electrical resistance in ohms measured between opposite faces of a centimeter cube of an aqueous solution at a specific temperature. The standard measurement is expressed in microSiemens per centimeter at 25°C, abbreviated µS/cm. The old units were micromhos per centimeter at 25°C, abbreviated µmhos/cm at 25°C. Specific conductance is related to the type and concentration of ions in solution and can be used to approximate the dissolved-solids concentration in water. Estimates of the dissolved-solids concentration (in mg/L) range from 60% to 85% of the specific-conductance value in µS/cm at 25°C. For sulfate-type waters, the estimated range of dissolved solids concentration in mg/L is from 90% to 100% of the specific-conductance value.

Static water level: The water level in a well which is in equilibrium with the groundwater flow conditions of the aquifer at the well; that is, when no water is being, or recently has been, taken from the aquifer either by pumping or by free flow. It is generally expressed as the distance from the ground surface (or from measuring a point near the ground surface) to the water level in the well; also, static head.

Stones: Rock fragments greater than 10 inches in diameter, if rounded, and 15 inches along the greater axis, if flat.

Structure, soil: The arrangement of primary soil particles into compound particles or aggregates. The principal forms of soil structure are as follows: *platy* (laminated), *prismatic* (vertical axis of aggregates longer than horizontal), *columnar* (prisms with rounded tops), *blocky* (angular or subangular), and *granular*. *Structureless* soils are either *single grained* (each grain by itself, as in dune sand) or *massive* (the particles adhering without any regular cleavage, as in many hardpans).

Subsoil: Technically, the B horizon; roughly, the part of the solum below plow depth.

Subsoiling: Breaking of compact subsoils, without inverting them, with a special knifelike instrument (chisel) that is pulled through the soil at depths usually of 12 to 24 inches with spacings usually of 2 to 5 ft.

Subsurface tillage: Tillage with a special sweeplike plow or blade that is drawn beneath the surface at depths of several inches that cuts plant roots and loosens the soil without inverting it and without incorporating the surface cover.

Surface soil: The uppermost part of the soil, ordinarily moved tillage, or its equivalent in uncultivated soils; it ranges in depth from 3 to 4 inches to 8 or 10 inches. Frequently designated as the plow layer, the Ap layer, or the Ap horizon.

TDS: See total dissolved solids.

Terrace: An embankment or ridge constructed on the contour or at a slight angle to the contour across sloping soils. The terrace intercepts surface runoff so that water soaks into the soil or flows slowly to a prepared outlet.

Texture, soil: The relative proportions of sand, silt, and clay particles in a mass of soil. The basic textural classes, in order of increasing proportion of fine particles, are *sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay*, and *clay*. The sand, loamy sand, and sandy loam classes may be further divided by specifying "coarse," "fine," or "very fine."

Tile drain: Concrete, plastic, or ceramic pipe placed at suitable depths and spacings in the soil or subsoil to provide water outlets from the soil.

Till: (1) Unstratified glacial drift deposited directly by the ice and consisting of clay, sand, gravel, and boulders intermingled in any proportion. (2) To plow and prepare for seeding; to seed or cultivate the soil.

Tilth, soil: The physical condition of the soil as related to tillage, seedbed preparation, seedling emergence, and root penetration.

Total dissolved solids (TDS): Mineral material suspended or dissolved in solution which passes a standard glass filter and 0.45 µm filter and does not evaporate below 180° C. TDS is generally used as a gross indicator of the mass of dissolved salts in a solution, but the analytical method is subject to interferences from colloidal material.

Total petroleum hydrocarbons (TPH): A measure of hydrocarbons similar to oil and grease, but measured by any one of several different procedures. See oil and grease.

TPH: See total petroleum hydrocarbons.

Transpiration: Loss of water vapor from the leaves and stems of living plants to the atmosphere.

Unconfined groundwater: Groundwater that has a free water table and is not overlain by a confining bed.

Unsaturated flow: The movement of water in a soil that is not filled to capacity with water.

Unsaturated zone: The thickness of material between the land surface and the water table.

USDA-SCS: U.S. Department of Agriculture, Soil Conservation Service, currently known as Natural Resources Conservation Service (USDA-NRCS).

USDA-NRCS: U.S. Department of Agriculture, Natural Resources Conservation Service, formerly known as Soil Conservation Service (USDA-SCS)

Valence: The combining capacity or electrical charge of atoms or groups of atoms. Sodium (Na^+) and bicarbonate (HCO_3^-) are monovalent, while calcium (Ca^{++}) and sulfate (SO_4^{-2}) are divalent.

Volatilization: The evaporation or changing of a substance from liquid to vapor.

Water harvesting: Any practice that increases runoff, such as covering the surface with plastic, applying sealants, paving, etc.

Water table: The upper surface of a zone of saturation, where the body of groundwater is not confined by an overlying impermeable zone.

Water-holding capacity: See available water capacity.

Weathering: All physical and chemical changes produced by atmospheric agents in rocks or other deposits at or near the earth's surface. These changes result in disintegration and decomposition of the material.

Wetland(s): (1) Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and other similar areas [40CFR Sec 230.3(f)]. (2) Wetlands are usually identified and delineated during a formal onsite evaluation of vegetation, soils, and hydrology by a qualified delineator. (3) There are a number of federal and often state regulations pertaining to wetlands which must be considered regarding remediation activities in wetlands.

Wilting point: (More correctly called permanent wilting percentage or permanent wilting point.) The soil moisture level at which plants wilt and cannot be revived by placing them in a saturated atmosphere, that is, soil moisture levels at which plants wilt and die.

Xerophytes: Plants that grow in or on extremely dry soils or soil materials.

APPENDIX E

Drainage

SUMMARY

Proper soil drainage is critical to the necessary migration of water through the soil when a chemical amendment remediation approach is used. Appendix E contains a discussion of differing hydrologic soil groups and provides synopses of mechanisms which can be used to improve drainage including:

- Chemical Amendment
- Plant Growth
- Mulching
- Deep Plowing
- Subsurface Drains
- Intensive-Water-Demand Plants

DRAINAGE

Many spill circumstances will require some amount of attention to internal soil drainage. Unattended poor internal soil drainage may be the most common reason for failure of remediation projects. Soil drainage factors can be combined into hydrologic soil groups, as shown in Table E-1.

Table E-1. Hydrologic Soil Groups.

Hydrologic Soil Groups	Definition
A	Soils having a high infiltration rate even when thoroughly wetted and consisting chiefly of deep, well to excessively drained sands or gravels (low runoff potential). These soils have a high rate of water transmission.
B	Soils having a moderate infiltration rate when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse texture. These soils have a moderate rate of water transmission.
C	Soils having a slow infiltration rate when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
D	Soils having a very slow infiltration rate when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

Source: USDA, Soil Survey Division Staff, 1993; USDA-SCS, 1979.

In order to remediate a salt-affected soil chemically, salts must have a pathway through which they can migrate out of the root zone during leaching. Impediments to salt migration out of the root zone include bedrock, an impermeable layer, a water table, or a very slowly permeable soil within 6 ft of the soil surface. Unless these conditions are altered, chemically displaced salts will be unable to migrate out of the root zone.

There are six basic ways to create a path for soil-pore water to migrate below the root zone. They are:

- Chemical amendment
- Plant growth
- Mulching
- Deep plowing
- Installing subsurface drains
- Establishment of intensive-water-demand plants around the spill-affected area to lower the water table

In most spill circumstances which require attention to improved drainage, several or all of these methods may be utilized simultaneously.

CHEMICAL AMENDMENT

Application of appropriate chemical amendments causes the soil to aggregate. A period of years may be required for slowly soluble amendments, such as gypsum, to aggregate soil sufficiently to create macropores, whereas typically a few weeks or months may be required for very soluble amendments, such as calcium nitrate or calcium chloride. These reactions are dependent on soil moisture conditions.

In order to aggregate the soil, the chemical amendment must come into contact with the salt-affected soil. If the soil has already dispersed, the chemical amendment requires a mechanical method to place it in the salt-affected areas. This can be done with plowing to shallow depths, or by hydraulic injection as a slurry or solution for deeper depths.

All forms of chemical amendment should be incorporated into the soil. A final topdressing of gypsum may protect the surface from dispersion. Various chemical amendments and their application are discussed in Appendix K.

PLANT GROWTH

During remediation, the roots of any vegetation present will help physically to move soil particles. If the soil chemistry has been adjusted with an effective chemical amendment, the soil particles will aggregate. If the salt concentration is high (EC >8–12 mmhos/cm) at the outset of remediation, establishment of interim, salt-tolerant vegetation will help generate macropores. If the water table is also high, then wetlands plants may be advisable. Vegetation also occurs in conjunction with other soil biota, such as invertebrate animals, fungi, and microbes, all of which will help aggregate soil. If required, addition of fertilizer will stimulate these organisms, and the soil will be remediated more quickly. Attributes of various types of vegetation are given in Appendix F.

MULCHING

The use of mulch greatly assists the soil in aggregation, improves aeration, and minimizes evaporation and erosion. Mulch should be incorporated into the soil as deeply as possible. Chemical amendments (previously discussed) should be applied at least as deep as the mulch is placed. Mulch and chemical amendments can be incorporated with a variety of plows and rototillers. Mulch has been shown to accelerate the rate of remediation substantially, and improve the effectiveness of chemical amendments.

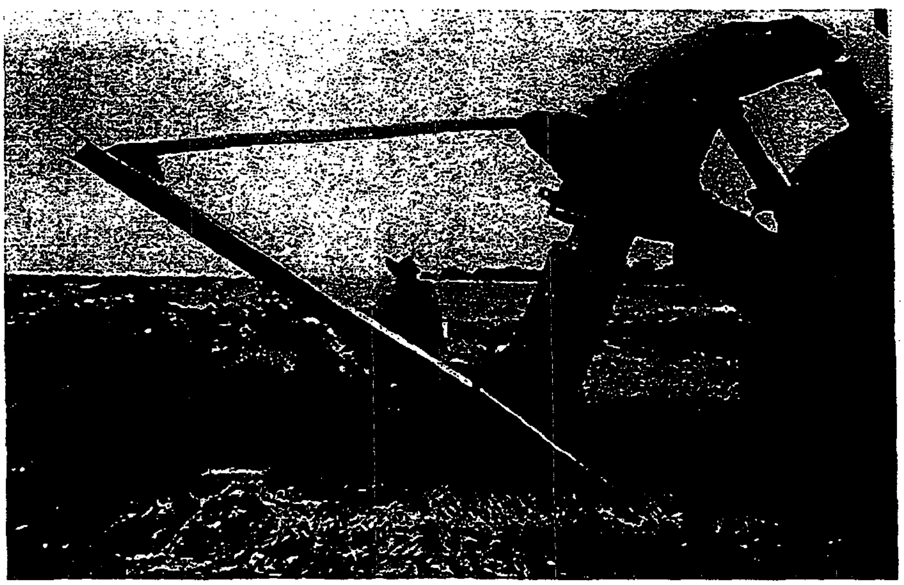
The interface between the mulch and the soil usually acts as a water channel or macropore. Then, as the mulch decomposes, larger macropores are left where the mulch had been. If the chemical amendment has had time to promote soil aggregation, these pores will remain open for some time. If the chemical amendment has not reacted by the time the mulch decomposes, then the clay particles may disperse again and refill the macropores. Mulch with high C:N ratios will decompose slowly, and mulch with low C:N ratios will decompose quickly. Mulches are discussed in more detail in Appendix L.

DEEP PLOWING

Impermeable layers can be broken up by heavy-duty deep plows, or by hydraulic fracturing. Breaking up this layer will promote internal soil drainage and removal of soluble salts. Deep plows are mechanical implements pulled by a tractor or tracked vehicle and are functional to a depth of about 3 ft. Pictures of two types of deep plows are shown in Figures E-1 and E-2. Deep plows are usually pulled in a cross pattern.

These ripper shanks are pulled through the soil to break cemented pans. The person is about 2m tall.

Figure E-1. Ripper Shanks (Singer/Munns, 1992).
(SOILS, AN INTRODUCTION by Singer/Munns, © 1992. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ)



This giant slip-plow mixes soil horizons as it is pulled through the soil. Soil is lifted up the inclined blade to the top where it falls back into the slit made by the plow. This is an effective tool for destroying stratification.

Figure E-2. Giant Slip-Plow (Singer/Munns, 1992).
(SOILS, AN INTRODUCTION by Singer/Munns, © 1992. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ)

Impermeable layers can be fractured (but not mixed) by high pressure hydraulic injection. As noted above, chemical amendments can be the material injected during this process. Hydraulic injection can go to a depth of 10 ft or more.

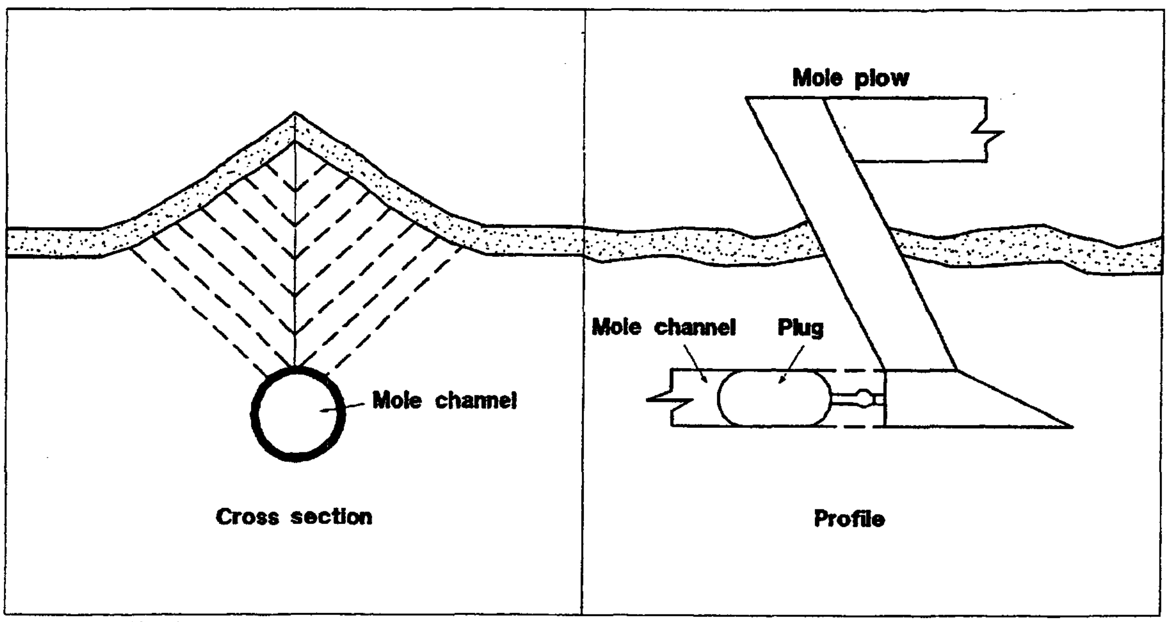
SUBSURFACE DRAINS

Subsurface drains can be used to lower the water table and/or intercept downward-migrating salts if the receiving groundwater is sensitive to salts. Consultation with a drainage expert is recommended if subsurface drains are contemplated.

For very small plots, one or two open trenches may suffice. Trench drains may be most effective for a coarse soil over a finer-textured subsoil where the water table is higher than the finer-textured subsoil. The trench is dug slightly lower than the top of the fine-textured subsoil, and "perched" water runs into it. The salty water is collected in the trench for transfer to a processing or disposal unit. The trench drain would not be appropriate for intercepting salts to prevent migration into groundwater if there is no barrier layer between the topsoil and the groundwater.

In larger areas, or if a greater intensity of drain spacing is required, a temporary mole drain, or more permanent drain tubing can be installed. These subsurface drains can be used both to lower the water table and intercept salts. Both mole drains and subsurface tubing drains terminate in a sump. Saltwater collected in the sump is disposed in an approved manner.

Mole drains involve pulling a 4-inch-diameter, bullet-shaped implement through the subsoil. This drain is temporary and will usually close and seal off within a couple of years as the soil settles. Figure E-3 portrays a mole drainage system.



Plug is pulled through the soil, leaving a channel through which drainage water can move.

Figure E-3. Diagrams Showing How an Underground Mole Drainage System is Put in Place (Hughes, H. A. 1980).
(Reproduced by permission of Deere & Company, © 1980. Deere & Company. All rights reserved).

To install subsurface drain tubing, a trench approximately 8 inches wide is dug. Sand may be placed in the bottom of the trench in addition to 4-inch-diameter perforated plastic drain tubing. The drain tube should be surrounded with a filter sock to minimize clogging the drain interior with soil particles. The lengths of 4-inch lateral tubing snap together, and also snap into the main, which can be 4 or 6 inches in diameter. A diagram depicting lateral and main configurations is shown in Figure E-4.

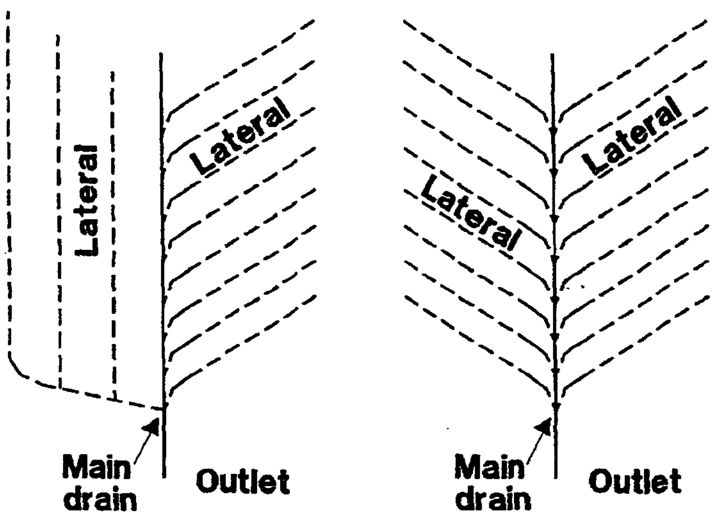


Figure E-4. Example Layer of Subsurface Laterals and Main (adapted from Brady, 1984).

Subsurface drain tubing is placed at the depths and lateral spacings shown in Table E-2. However, laterals should not be placed more than twice as deep as the surface layer of a stratified soil. Drains should also be placed above a transmissive subsoil layer if this layer is within the saturated zone and underlies a finer texture. The reason is to avoid collecting water primarily from the surrounding area instead of from the salt-affected soil above.

Table E-2. Approximate Depth and Spacing of Subsurface Drain Lines.

Soil Texture (group)	Drain Depth (ft)	Lateral Spacing (ft)
Coarse	3	30
Coarse	6	60
Medium	3	20
Medium	6	40
Fine	3	10
Fine	6	20

Extreme caution should be used in working with trenches associated with soil drainage. Shoring should be used to stabilize trench walls if workers will be in them. Check OSHA requirements for working in confined spaces or trenches.

INTENSIVE-WATER-DEMAND PLANTS

Where circumstances permit, high-water-demand plants adjacent to the spill area can be used to lower the water table beneath the salt-affected area. As an example, alfalfa, a deep-rooted, high-water-demand plant can lower a water table in the surrounding area by several feet.

APPENDIX F

Revegetation Materials and Procedures

SUMMARY

Appendix F contains reproductions of different readily available references of plant applications in salt-affected soils for varying areas and land uses. Included in this appendix are articles and tables covering the following:

- Seeding Rangeland
- Salt Tolerance of Agricultural Crops
- Relative Tolerance of Crop Plants to Salt
- Crop Salt-Tolerance Levels for Different Crops
- List of Seed and/or Planting Stock Sources for the Texas-Oklahoma Area
- Divisions for Classifying Crop Tolerance to Salinity
- Salt Tolerance of Herbaceous Crops—Fiber, Grain and Special Crops
- Salt Tolerance of Herbaceous Crops—Grasses and Forage Crops
- Salt Tolerance of Herbaceous Crops—Vegetables and Fruit Crops
- Salt Tolerance of Woody Crops
- General Guide to Selected Grasses and Forbs

SEEDING RANGELAND

Tommy G. Welch and Marshall R. Haferkamp*

Most Texas rangeland produces below its potential. Although production on some of this land may be improved by grazing management alone, much of it requires grazing management, brush control and/or seeding to restore production to the site's potential. This publication is a guide to seeding rangelands.

The most common objective of rangeland seeding is to alter vegetative composition. This usually is done because more higher-quality forage is desired. Occasionally a better seasonal balance of forage supply is needed. Other objectives met by altering vegetative composition through rangeland seeding include soil stabilization and improved wildlife habitats.

WHEN TO SEED

Since seeding rangeland is expensive and the risk of failure is always present, carefully consider seeding or allowing natural revegetation. When the management objective is to improve range condition, evaluate the quantity and distribution of current desirable plants. If desirable plants make up less than 10 to 15 percent of the vegetation, seeding probably is necessary. If desirable plants are uniformly distributed and make up more than 10 to 15 percent of the vegetation, use grazing management to improve range condition.

Often, however, another management decision dictates the necessity for seeding. For example, seeding usually is necessary following a brush control method, such as rootplowing, that destroys the existing turf. Also, when a better seasonal balance of forage supply is desired, seeding usually is required because the species needed to extend the period of green forage are not present. These plants often are introduced species and are seeded in pure stands.

In addition, seeding usually is the most effective way to establish desirable vegetation on abandoned cropland, since natural revegetation processes may take 50 to 100 years on land barren from farming. On other bare areas, such as newly constructed dams and newly laid pipelines, seeding to establish a plant cover often is necessary to prevent wind and water erosion.

WHERE TO SEED

Seed only those sites having sufficient potential to insure reasonable chances of success. First, survey the area to determine if there is a mixture of range sites or if one predominates; then, decide whether the sites are suitable for seeding. If the area is a mixture of sites, expend the most effort on ones with the best chance for success. Select seeding sites so the area can be incorporated into the overall ranch management.

Sites with sufficient soil depth for adequate root development and water storage or sites that can be modified mechanically to accomplish a greater effective soil depth usually are suitable. However, avoid barren, rocky sites, which have greater temperature extremes at the soil surface and are more droughty than sites with some soil and litter on the surface. Low soil moisture and wide temperature extremes can kill plant seedlings.

Although the amount of precipitation received on an area cannot be controlled, select sites that receive runoff water, thereby increasing the amount of moisture available. However, do not disturb steep, potentially erosive areas.

*Extension range brush and weed control specialist and assistant professor, Texas Agricultural Experiment Station, The Texas A&M University System.

WHAT TO SEED

Plants selected for seeding depend on management objectives. For example, plants to improve range condition are different from those selected to stabilize a disturbed area or to extend the grazing season. However, regardless of management objective, select only species of plants that are adapted to the soil, climate and topography of the area to be seeded. If possible, choose plants that: (1) establish easily, (2) are palatable to animals that will graze the seeded area, (3) are relatively productive, (4) withstand invasion by undesirable plants, (5) withstand moderate grazing, (6) prevent erosion under moderate grazing and (7) are available at a moderate price.

Usually, plants best adapted to an area are native ones growing in the area, so it is important to determine the original source of seeds of native species. When available, use certified named varieties. Generally, seed of native species should originate from local sources or from within 200 miles north or south and 100 miles east or west of the area to be seeded. Recommended species and varieties for the various resource areas and soil groups are shown in table 1. Consult local Soil Conservation Service personnel for information on seeding specific range sites, because some species are adapted to only certain range sites within a resource area.

Often, mixtures of native and/or introduced species are seeded on rangeland, partly as an attempt to simulate natural conditions. Using a mixture is helpful because all areas have variations in soil, moisture and slope, and each species in the mixture is adapted better than other species to certain site characteristics. For instance, variation in rooting habits of species in the mixture allows for more efficient use of moisture and nutrients from the various soil depths. Also, the mixture usually extends the grazing season because each species varies slightly in its period of lush growth and dormancy. Finally, a mixture provides a varied diet that often is more desirable to animals.

Under certain conditions, a pure stand of a single species is more desirable. Species low in palatability and needing special management, or species requiring intensive management, should be planted alone. In addition, many introduced species are easier to manage when planted in a pure stand.

Use seed of known quality. Know the germination and purity of the seed, since seeding rates are based on pure live seed.

HOW TO SEED

Seedbed Preparation

An ideal seedbed is firm below seeding depth, free from live, resident plant competition and has moderate amounts of mulch or plant residue on the soil surface. A major purpose of seedbed preparation is to reduce existing plant competition.

Plowing is the most common method of preparing a seedbed. A variety of plowing methods is available. The method selected depends on the type of vegetation to be controlled and the level of financial resources available. On abandoned cropland use a moldboard, offset disk or one-way. On a brush infested area, consider rootplowing.

Herbicides also may be used to control existing vegetation. After applying the herbicide, drill seeds of desired plants directly into the dead vegetative cover. Although this method of seedbed preparation seldom is used, it offers possibilities where wind erosion occurs.

In areas where wind or excessive heat is a problem, protect clean-tilled soil with a cover crop or dead litter crop. Sorghums make an excellent dead litter mulch. To prevent seed production in sorghum, plant it late in the growing season or harvest it, leaving the stubble for mulch. Small grains also may be used as a cover crop. After establishing the cover crop, drill or broadcast seeds of desired species into the stubble or mulch.

In some areas seedbeds have been successfully prepared by burning. For example, prescribed burning may reduce competition from certain perennial plants, allowing subsequently seeded species to establish more easily. Following a wildfire, seeding may be necessary to restore the area's productivity.

On abandoned cropland, an ideal seedbed may be prepared without undue expense, but on rangeland, the ideal seedbed is a goal seldom attained because expenses exceed expected returns. Even though preparing an ideal seedbed may not be economically feasible, prepare the best seedbed that available resources allow. On some brush-infested rangeland, rootplowing, followed by roller chopping, raking or chaining, is an acceptable method of seedbed preparation. Roller chopping usually is conducted before seeding. On potentially productive sites the expense of rootplowing, raking and plowing with an offset disk may be justified. In addition, smooth seedbeds allow for harvesting seed, and the income from seed sales could pay for seedbed preparation costs.

Timing

Choosing the correct time to seed is very important. Try to seed at the beginning of a period that will provide the best growing conditions (favorable temperatures and good soil moisture). In most cases, achieve the greatest success by seeding just before the season of expected high rainfall. Most parts of Texas receive significant rainfall in early to mid-spring; in those areas, warm season plants may be seeded successfully during late winter to early spring. The Trans-Pecos region usually receives its precipitation during mid to late summer, so seeding in midsummer may be best. In the more southern areas of the state where a rainfall peak occurs in the fall, seeding in late summer or early fall may allow seedlings time to become established before the winter season. In terms of temperature, many cool season plants may be seeded either in the spring or early fall, though late summer or fall normally is best because young seedlings may not tolerate hot, dry summers. On the other hand, warm season plants grow best if seeded in the spring.

Seeding Methods

The two most common methods of seeding rangeland are drill and broadcast. Drill methods place the seed in the soil; broadcast methods place the seed on the soil's surface.

Drilling is a superior method because the drill places the seed in the soil, thus improving the probability of seedling establishment. Use drills on old fields and on areas where a smooth seedbed has been prepared. A good drill has the following:

- Double disk opener to provide a trench with minimum soil movement.
- Depth bands for proper depth control.
- Packing mechanism to place seed more firmly in contact with soil.
- Seed boxes with agitators to keep seed mixed and prevent fluffy seed from lodging in box, separate boxes for large and small seed, divided or partitioned boxes to keep seed feeding to individual metering devices and a good metering device to control the amount of seed to be planted.

Since most drills are not sturdy enough to be used on rough rangeland, broadcast seeding often is used instead. However, broadcast seeding has limitations because seed are poorly covered with soil and stand establishment often is slower.

Broadcast the seed by aerial or ground application. Ground application includes broadcasting by hand, rotary spreader, with airstream or exhaust or seeder boxes of the fertilizer-spreader type. Aerial application is popular because it is faster. Aircraft must be equipped with a spreader and a positive, power-driven seed metering device.

Broadcast seeding seldom is effective without some soil disturbance before the seeding operation. Be sure to distribute seed uniformly. Small, slick seed lend themselves to broadcast seeding much better than large fluffy seed, since small seed are easier to broadcast and are covered by natural sloughing of the soil.

Broadcast seeding is more successful if the seed are broadcast on loose, rough soil, where natural sloughing and settling will cover the seed, or when seeding is followed by harrowing, chaining or cultipacking. If the seedbed consists of large clods of soil, seed may be buried too deeply.

Seeding Rate

The quantity of seed to apply per acre depends upon the species, method of seeding and potential site productivity. Seeding rates usually are based on pounds of pure live seed (PLS) per acre. PLS is the percentage of the bulk seed material that is live seed. This is determined by multiplying percentage germination by percentage purity of the lot of seed. When hard seed are involved, PLS = (percent germination + percent hard seed) × percent purity.

Recommended seeding rates usually call for 20 live seed per square foot. The number of seed per pound varies with species. Table 1 gives the number of seed per pound and recommended seeding rates for species used in Texas.

Seeding Depth

Optimum seeding depth is roughly proportional to seed size. Since smaller seeds have a smaller quantity of stored energy, do not seed them as deeply as larger seed. As a rule, plant seed at a depth four to seven times the diameter of the seed. When using a mixture of small and large seed, determine the planting depth by the diameter of smallest seed. In most rangeland seedings, plant the seed about ¼ to ½ inch deep but not deeper than ¾ inch. Plantings can be deeper in light, sandy soils than in heavier, clay soils.

MANAGEMENT AFTER SEEDING

Protect a newly seeded area from grazing until plants are established. Some species establish sooner than others, but in general plants should be well-rooted before grazing to prevent pulling up the seedlings. Length of deferment from grazing varies. In exceptionally good growing conditions, deferment through one growing season may be sufficient. During periods of harsh growing conditions, however, 2 or 3 years of deferment may be necessary. Grazing during dormant periods may help improve the stand by scattering and trampling seed into the soil. After plants are established, practice good grazing management to maintain the seeded stand.

Because seeded areas usually receive some type of soil disturbance, weeds or weedy species often become abundant during the growing season following seeding. Weed control measures such as mowing, shredding or use of herbicides may be necessary during the first growing season to allow seeded species to become established. Most grass seedlings can tolerate a herbicide application after the seedlings have reached the fourth leaf stage.

Table 1. Seed characteristics, seeding rates and adaptations of species used for seeding Texas rangeland.

Name	Variety[1]	Seeds per lb	Seeding rate[2] lb PLS per acre: Normal rows (40 in)	Seeding rate[2] lb PLS per acre: Drill (20 in or less) or broadcast	Ratings of adaptation[3] Tolerance: Drought	Tolerance: Cold	Tolerance: Salt	Soil: Sandy	Soil: Loam	Soil: Clay	Native or introduced	Season of growth[4]	Regional adaptation[5]: Coast Saline Prairie	Coast Prairie	East Texas Timberlands	Claypan Area	Blackland Prairie	East Cross Timbers	West Cross Timbers	Grand Prairie	North Central Prairies	Central Basin	Edwards Plateau	Northern Rio Grande Plain	Western Rio Grande Plain	Central Rio Grande Plain	Lower Rio Grande Valley	Rolling Plains	High Plains	Trans-Pecos	Minimum rainfall (inches)[4]
Alkali sacaton (*Sporobolus airoides*)		1,750,000	0.4	1.0	2	1	1	3	2	1	N	W											X	X	X	X	X	X	X	X	10
Angleton bluestem (*Dichanthium aristatum*)		500,000	0.4	1.0	2	3	2	3	3	1	I	W		X																	30
Big bluestem[7] (*Andropogon gerardii*)		130,000	2.0	6.0	2	1	2	2	1	2	N	W	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	25
Black grama (*Bouteloua eriopoda*)	Nogal	1,335,000	0.5	1.5	1	2	3	1	1	3	N	W																	X	X	10
Blue grama (*Bouteloua gracilis*)		711,000 (spikelet)	0.5	1.5	1	1	2	2	1	1	N	W																X	X	X	10
	Lovington				1	1	2	2	1	1	N	W																X	X	X	10
	Hachita				1	1	2	2	1	1	N	W																X	X	X	10
Blue panicgrass (*Panicum antidotale*)		657,000	0.8	2.0	2	3	2	2	1	1	I	W									X	X	X	X	X	X	X	X	X	X	20
Boer lovegrass (*Eragrostis chloromelas*)		2,922,000	0.8	2.0	1	2	2	1	1	1	I	W																		X	10
	Catalina				1	2	2	1	1	1	I	W																		X	10
Buffelgrass (*Cenchrus ciliare*)	Common	225,000 bur or 867,000 grain	1.2	3.0	1	3	3	2	1	2	I	W												X	X	X	X				16
	Higgins[8]		0.5	1.5	1	3	3	2	1	2	I	W												X	X	X	X				16
	Nueces				1	3	3	2	1	2	I	W												X	X	X	X				16
	Llano				1	3	3	2	1	2	I	W												X	X	X	X				16
Buffalograss (*Buchloe dactyloides*)		42,000 bur or 275,000 grain	5.0	16.0	1	1	2	3	1	1	N	W					X	X	X	X	X	X	X					X	X		15
	Texoka		...	3.0	1	1	2	3	1	1	N	W					X	X	X	X	X	X	X					X	X		15
California cottontop (*Digitaria californica*)		1,092,000	0.4	1.2	2	2	2	2	1	2	N	W									X		X	X	X	X	X	X	X	X	15
Caucasian bluestem (*Bothriochloa caucasica*)		860,000	0.5	1.2	2	2	2	2	1	1	I	W				X	X	X	X	X	X	X	X					X	X		18
Common reed[9] (*Phragmites australis*)	Shoreline	Rhizomes 12 to 18 in long	1 to 1½ rhizomes per foot of row		3	1	2	1	1	1	N	W	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	30
[illegible]do bluestem ([illegible]anthium aristatum)		500,000	0.5	1.2	2	2	2	3	2	1	I	W		X			X							X		X	X				25
Green sprangletop (*Leptochloa dubia*)		538,000	0.7	1.7	1	1	2	1	1	2	N	W						X	X	X	X	X	X	X	X	X	X	X	X	X	10

Indiangrass (*Sorghastrum nutans*)		170,000	1.5	4.5	3	1	2	1	1	2	N	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		16
	Cheyenne				3	1	2	1	1	2	N	W						X	X	X	X							X	X		16
	Lometa				3	1	2	1	1	2	N	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			22
Ranch bluestem (*Bothriochloa ischaemum* var. *songarica*)		835,000	0.5	1.2	1	1	2	3	1	1	I	W		X		X	X	X	X	X	X	X	X	X	X	X	X	X			20
Kleberg bluestem (*Dichanthium annulatum*)		800,000	0.5	1.2	1	2	2	2	1	1	I	W		X		X	X			X		X	X	X	X	X	X				20
Kleingrass (*Panicum coloratum*)	Selection 75	500,000	0.8	2.0	2	3	2	2	1	1	I	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		20
Lehmann lovegrass (*Eragrostis lehmanniana*)		4,245,000	0.8	2.0	1	3	2	1	1	2	I	W											X	X	X	X	X		X	X	10
(*E. lehmanniana* × *E. trichophora*)	Cochise				1	3	2	1	1	2	I	W											X	X	X	X	X		X	X	10
Little bluestem (*Schizachyrium scoparium*)		255,000	1.2	3.4	2	1	3	1	1	1	N	W		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	20
	Pastura				2	1	3	1	1	1	N	W																	X		16
	Cimarron				2	1	3	1	1	1	N	W																X	X		16
Maximilian sunflower (*Helianthus maximiliana*)	Aztec	320,000	...	0.25-1.0[10]	2	1	3	1	1	1	N	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		18
Medio bluestem (*Dichanthium aristatum*)		500,000	0.4	1.0	2	3	2	3	3	1	I	W	X				X							X	X	X	X				25
Old World bluestem (*Dichanthium* spp - *Bothriochloa* spp blend)	T-587	854,000	0.5	1.2	1	2	2	2	1	1	I	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	14
Plains bristlegrass (*Setaria leucopila*)		293,000	1.0	3.0	1	1	2	1	1	1	N	W				X					X	X	X	X	X	X	X	X	X	X	12
Rhodesgrass (*Chloris gayana*)	Bell	1,405,000 (spikelet)	0.4	1.0	2	3	1	2	1	1	I	W	X	X										X	X	X	X				20
Sand bluestem (*Andropogon gerardii* var. *paucipilus*)		125,000	2.0	6.0	2	1	3	1	2	3	N	W						X	X	X	X							X	X		18
	Woodward				2	1	3	1	2	3	N	W						X	X	X	X							X	X		18
	Elida				2	1	3	1	2	3	N	W																X	X		14
Sand lovegrass (*Eragrostis trichodes*)		1,300,000	0.8	2.0	1	1	3	1	2	3	N	W						X	X	X	X							X	X		18
	Mason	2,000,000	0.8	2.0	1	2	3	1	2	3	N	W						X	X	X	X	X	X	X	X			X	X		18

[1] Named varieties are adapted to regions checked. If a named variety is not listed, seed used should have a local origin or be from within 200 miles north or south and 100 miles east or west of site to be seeded. This is particularly important for widely adapted species.

[2] PLS = pure live seed = (percent germination + hard seed) × percent purity.

[3] Symbols for adaptation: 1 = good, 2 = fair, 3 = poor.

[4] Symbols: W = warm season, C = cool season.

[5] Land resource areas are shown in figure 1. Consult local Soil Conservation Service personnel for information for seeding specific range sites because some species are adapted to only part of a resource area and/or to only certain range sites within a resource area.

[6] Extra moisture from runoff may substitute for rainfall. Figure 2 shows the average annual precipitation in Texas.

[7] These tallgrass species occur in resource areas listed. However, seed only on sites with high soil moisture potential such as bottomland range sites in the lower rainfall areas of the state.

[8] Higgins is better adapted to clay soil than other varieties. Nueces and Llano are more cold tolerant than Common and Higgins.

[9] Common reed is used at waterline on farm ponds and watershed dams for stabilization. When used at waterline, use anywhere in the state regardless of quantity of rainfall.

[10] Low rate for range seedings. High rate for wildlife block seedings.

Table 1. Seed characteristics, seeding rates and adaptations of species used for seeding Texas rangeland (concluded).

Name	Variety[1]	Seeds per lb	Seeding rate[2] lb PLS per acre: Normal rows (40 in)	Seeding rate[2] lb PLS per acre: Drill (20 in or less) or broadcast	Ratings of adaptation[3] Tolerance: Drought	Tolerance: Cold	Tolerance: Salt	Soil: Sandy	Soil: Loam	Soil: Clay	Native or Introduced	[4] Season of growth	Regional adaptation[5]: Coast Saline Prairie	Coast Prairie	East Texas Timberlands	Claypan Area	Blackland Prairie	East Cross Timbers	West Cross Timbers	Grand Prairie	North Central Prairies	Central Basin	Edwards Plateau	Northern Rio Grande Plain	Western Rio Grande Plain	Central Rio Grande Plain	Lower Rio Grande Valley	Rolling Plains	High Plains	Trans-Pecos	[6] Minimum rainfall (inches)
Sideoats grama (*Bouteloua curtipendula*)		143,000 (spikelet)	2.0	5.5	2	1	2	2	1	1	N	W				X	X	X	X	X	X	X	X	X	X	X		X	X	X	14
	Premier				2	1	2	2	1	1	N	W											X					X	X	X	14
	El Reno				2	1	2	2	1	1	N	W						X	X	X	X		X					X	X		14
	Vaughn				2	1	2	2	1	1	N	W																	X		14
	Uvalde				2	1	2	2	1	1	N	W										X	X	X	X						18
Sorghum almum (*Sorghum almum*)		90,000	---	2.0 15.0[11]	2	2	2	2	1	1	I	W		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	18
Switchgrass[7] (*Panicum virgatum*)		389,000	1.2	3.5	2	1	2	1	1	1	N	W		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	20
	Alamo	427,365	0.5	2.0	2	1	2	1	1	1	N	W		X	X	X	X	X	X	X	X	X		X				X			25
	Blackwell	389,000	1.2	3.5	2	1	2	1	1	2	N	W					X	X	X	X	X							X	X		20
	Caddo	389,000	1.2	3.5	2	1	2	1	1	2	N	W					X	X	X	X	X							X	X		20
	Greenville	389,000	1.2	3.5	2	1	2	1	1	2	N	W																X	X		20
	Kanlow[12]	389,000	1.2	3.5	3	1	2	1	1	1	N	W					X	X	X	X	X							X	X		25
Weeping lovegrass (*Eragrostis curvula*)		1,500,000	0.8	2.0	2	2	2	1	1	1	I	W			X	X	X	X	X	X	X			X				X	X		16
	Ermelo				2	2	2	1	1	1	I	W			X	X	X	X	X	X	X			X				X	X		16
	Morpa				2	2	2	1	1	1	I	W			X	X	X	X	X	X	X			X				X	X		16
	Renner				2	2	2	1	1	1	I	W			X	X	X	X	X	X	X			X				X	X		16
Western wheatgrass (*Agropyron smithii*)		110,000	2.4	7.0	2	1	1	3	1	1	N	C																X	X		16
	Arriba				2	1	1	3	1	1	N	C																	X		16
	Barton				2	1	1	3	1	1	N	C																	X		16
Wilman lovegrass (*Eragrostis superba*)	Palar	1,103,000	0.8	2.0	1	3	2	1	1	2	I	W										X	X	X	X	X				X	10
Yellow bluestem (*Bothriochloa ischaemum* var. *ischaemum*)	Plains	830,000	0.5	1.2	2	1	2	2	1	2	I	W			X	X	X	X	X	X	X							X	X		18

[11] Low rate for seeding with rangeland mixture

[12] Adapted to lowlands receiving extra moisture from runoff

APPENDIX

SALT TOLERANCE OF AGRICULTURAL CROPS (EC_e)

These data serve only as guidelines to relative tolerances among crops. Absolute tolerances very, depending on climate, soil conditions, and cultural practics.

SENSITIVE CROPS

	dS/m	% per dS/m		dS/m	% per dS/m
Bean	1.0	19	Boysenberry	1.5	22
Carrot	1.0	14	Plum; prune †	1.5	18
Strawberry	1.0	33	Apricot †	1.6	24
Onion	1.2	16	Orange	1.7	16
Almond †	1.5	19	Peach	1.7	21
Blackberry	1.5	22	Grapefruit †	1.8	16

MODERATELY SENSITIVE CROPS

	dS/m	% per dS/m		dS/m	% per dS/m
Turnip	0.9	9.0	Flax	1.7	12
Radish	1.2	13	Potato	1.7	12
Lettuce	1.3	13	Sugarcane	1.7	5.9
Clover, berseem	1.5	5.7	Cabbage	1.8	9.7
Clover, strawberry	1.5	12	Celery	1.8	6.2
Clover, red	1.5	12	Corn (forage)	1.8	7.4
Clover, alsike	1.5	12	Alfalfa	2.0	7.3
Clover, ladino	1.5	12	Spinach	2.0	7.6
Foxtail, meadow	1.5	9.6	Trefoil, big	2.3	19
Grape †	1.5	9.6	Cowpea (forage)	2.5	11
Orchardgrass	1.5	6.2	Cucumber	2.5	13
Pepper	1.5	14	Tomato	2.5	9.9
Sweet Potato	1.5	11	Broccoli	2.8	9.2
Broadbean	1.6	9.6	Vetch, common	3.0	11
Corn	1.7	12	Rice, paddy †	3.0 ††	12 ††
			Squash, scallop	3.2	16

MODERATELY TOLERANT CROPS

	dS/m	% per dS/m		dS/m	% per dS/m
Wildrye, beardless	2.7	6.0	Cowpea	4.9	12
Sudangrass	2.8	4.3	Soybean	5.0	20
Wheatgrass, std. crested	3.5	4.0	Trefoil, birdsfoot	5.0	10
Fescue, tall	3.9	5.3	Ryegrass, perennial	5.6	7.6
Beet, red †	4.0	9.0	Wheat, durum	5.7	5.4
Hardinggrass	4.6	7.6	Barley (forage) †	6.0	7.1
Squash, zucchini	4.7	9.4	Wheat †	6.0	7.1
			Sorghum	6.8	16

TOLERANT CROPS

	dS/m	% per dS/m		dS/m	% per dS/m
Date palm	4.0	3.6	Wheatgrass, fairway crested	7.5	6.9
Bermudagrass	6.9	6.4	Wheatgrass, tall	7.5	4.2
Sugarbeet †	7.0	5.9	Cotton	7.7	5.2
			Barley †	8.0	5.0

1 dS/m = approximately 640 mg/L salt.
† Tolerance is based on growth rather than yield.
††Values for paddy rice refer to the electrical conductivity of the soil water during the flooded growing conditions.

Maas, E.V., (1984). Crop Tolerance. California Agriculture. Vol. 38 - No. 10 (University of California) pp.20-21.

Relative Tolerance of Crop Plants to Salt.

Vegetable Crops

$EC_4 \times 10^3 = 12$	$EC_4 \times 10^3 = 10$		$EC_4 \times 10^3 = 4$
Garden beets	Tomato	Sweet corn	Radish
Kale	Broccoli	Potatoes (White Rose)	Celery
Asparagus	Cabbage	Carrot	Green beans
Spinach	Bell pepper	Onion	
	Cauliflower	Peas	
	Lettuce	Squaab	
		Cucumber	
$EC_4 \times 10^3 = 10$	$EC_4 \times 10^3 = 4$		$EC_4 \times 10^3 = 3$

Forage Crops

$EC_4 \times 10^3 = 18$	$EC_4 \times 10^3 = 12$		$EC_4 \times 10^3 = 4$
Alkali sacaton	White sweetclover	Wheat (hay)	White Dutch clover
Saltgrass	Yellow sweetclover	Oats (hay)	Meadow foxtail
Nuttall alkaligrass	Perennial ryegrass	Orchardgrass	Alaike clover
Bermuda grass	Mountain brome	Blue grama	Red clover
Rhodes grass	Strawberry clover	Meadow fescue	Ladino clover
Rescue grass	Dallis grass	Reed canary	Burnet
Canada wildrye	Sedan grass	Big trefoil	
Western wheatgrass	Hubam clover	Smooth brome	
Barley (bay)	Alfalfa (California common)	Tall meadow oatgrass	
Bridefoot trefoil	Tall fescue	Cicer milk vetch	
	Rye (hay)	Sourclover	
		Sickle milk vetch	
$EC_4 \times 10^3 = 12$	$EC_4 \times 10^3 = 4$		$EC_4 \times 10^3 = 2$

Field Crops

$EC_4 \times 10^3 = 16$	$EC_4 \times 10^3 = 10$		$EC_4 \times 10^3 = 4$
Barley (grain)	Rye (grain)	Sorghum (grain)	Field beans
Sugar beet	Wheat (grain)	Corn (field)	
Rape	Oats (grain)	Flax	
Cotton	Rice	Sunflower	
		Castorbeans	
$EC_4 X 10^3 = 10$	$EC_4 X 10^3 = 6$		

Source: Richards, 1954.

The numbers following: $EC_4 \times 10^3$ are the EC values of the saturation extract in mmhos/cm at 25°C associated with 50% decrease in yield.

Crop Salt-Tolerance Levels for Different Crops.

		Yield Potential								
		100%		90%		75%		50%		Max.
	Crop	ECe	ECw	ECe	ECw	ECe	ECw	ECe	ECw	ECe
Field:	Barley[a]	8.0	5.3	10.0	6.7	13.0	8.7	18.0	12.0	28
	Beans (field)	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	7
	Broad beans	1.6	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12
	Corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
	Cotton	7.7	5.1	9.6	6.4	13.0	8.4	17.0	12.0	27
	Cowpeas	1.3	0.9	2.0	1.3	3.1	2.1	4.9	3.2	9
	Flax	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
	Groundnut	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	7
	Rice (paddy)	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	12
	Safflower	5.3	3.5	6.2	4.1	7.6	5.0	9.9	6.6	15
	Sesbania	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	17
	Sorghum	4.0	2.7	5.1	3.4	7.2	4.8	11.0	7.2	18
	Soybean	5.0	3.3	5.5	3.7	6.2	4.2	7.5	5.0	10
	Sugarbeet	7.0	4.7	8.7	5.8	11.0	7.5	15.0	10.0	24
	Wheat[a]	6.0	4.0	7.4	4.9	9.5	6.4	13.0	8.7	20
Vegetable:	Beans	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	7
	Beets[b]	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15
	Broccoli	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	14
	Cabbage	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12
	Cantaloupe	2.2	1.5	3.6	2.4	5.7	3.8	9.1	6.1	16
	Carrot	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.1	8
	Cucumber	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10
	Lettuce	1.3	0.9	2.1	1.4	3.2	2.1	5.2	3.4	9
	Onion	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	8
	Pepper	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3.4	9
	Potato	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
	Radish	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	9
	Spinach	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15
	Sweet corn	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
	Sweet potato	1.5	1.0	2.4	1.6	3.8	2.5	6.0	4.0	11
	Tomato	2.5	1.7	3.5	2.3	5.0	3.4	7.6	5.0	13
Forage :	Alfalfa	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	16
	Barley hay[a]	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7	20
	Bermuda grass	6.9	4.6	8.5	5.7	10.8	7.2	14.7	9.8	23
	Clover, berseem	1.5	1.0	3.2	2.1	5.9	3.9	10.3	6.8	19
	Corn (forage)	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	16
	Harding grass	4.6	3.1	5.9	3.9	7.9	5.3	11.1	7.4	18
	Orchard grass	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	18
	Perennial rye	5.6	3.7	6.9	4.6	8.9	5.9	12.2	8.1	19
	Soudan grass	2.8	1.9	5.1	3.4	8.6	5.7	14.4	9.6	26
	Tall fescue	3.9	2.6	5.8	3.9	8.6	5.7	13.3	8.9	23
	Tall wheat grass	7.5	5.0	9.9	6.6	13.3	9.0	19.4	13.0	32
	Trefoil, big	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	8
	Trefoil, small	5.0	3.3	6.0	4.0	7.5	5.0	10.0	6.7	15
	Wheat grass	7.5	5.0	9.0	6.0	11.0	7.4	15.0	9.8	22

Source: Ayers and Westcot, 1977b.

a During germination and seedling stage, ECe should not exceed 4 or 5 mmhos/cm. Data may not apply to new semi-dwarf varieties of wheat.

b During germination, ECe should not exceed 3 mmhos/cm.

where: ECw - EC of the irrigation water, mmhos/cm.

ECe - EC of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction.

MaxECe - Maximum tolerable EC of the soil saturation extract for a given crop.

List of seed and/or planting stock sources for the Texas-Oklahoma area.

Inclusion on this list should not be construed as an endorsement by API. This list should not be considered exhaustive, there may be other sources for seed and planting stock.

TEXAS

1 Asgrow Seed Company
P.O. Drawer A
San Antonio, TX 78211
512-922-6361

2 Austin Tree Farm, Inc.
1935 Berkeley
Austin, TX 78745
512-444-3117

3 Bamert Seed Company
Route 3, Box 192
Muleshoe, TX 79347
806-272-4787

4 Conlee Seed Company
P.O. Box 267
Waco, TX 76228
817-772-5680

5 Dallas Nurseries, Inc.
12501 Preston Road
Dallas, TX 75230
214-239-1331

6 Douglas W. King Company
Box 20320
San Antonio, TX 78286
512-661-4191

7 Empire Seed Company
109 East Avenue A
Temple, TX 76501
817-778-7109

8 Foster-Rambie Grass Seed
326 North 2ND Street
Uvalde, TX 78801
512-278-2711

9 Garrison Seed Company
Box 927 Hereford, TX 79045
806-364-0560

10 George Warner Seed Company, Inc.
P.O. Box 1448
Hereford, TX 79045
806-364-4470

11 Green Horizon
500 Thompson Drive
Kerrville, TX 78028
512-257-51410

12 Green Valley Nurseries, Inc.
500 Thompson Drive
Kerrville, TX 78028
512-257-5141

13 Harpool Seed Inc.
P.O. Drawer B
Denton, TX 76201
817-387-0541

14 Hawkins Nursery & Landscape
P.O. Box 208
Grand Saline, TX 75140
214-962-3622

15 Horizon Seed, Inc.
P.O. Box 886
Hereford, TX 79045
806-364-5250

16 McVicar Organic Nursery
2710 South Street
Nacogdoches, TX 75961
713-564-7691

17 Pogue Seed Company
P.O. Box Drawer 389
Kenedy, TX 78119
512-583-3456

18 Robinson Seed Company
1107 Yonkers
Plainview, TX 79072
806-293-4959

19 Rudy-Patrick Seed Company
Box 218
Garland, TX 75040

23 Texas Forest Service
Indian Mound Nursery
P.O. Box 617
Alto, TX 75925
713-858-4202

24 Texas Native Plants Nursery
3105 Lafayette Street
Austin, TX 78722
512-473-8718

25 Texas Pecan Nursery, Inc.
Box 306
Chandler, TX 75758
214-849-6203

20 Sharp Brothers Seed Company
4378 Canyon Drive
Amarillo, TX 79109
806-353-2781

21 Star Seed & Grain Corp.
415 Blue Star Street
San Antonio, TX 78204
513-227-5344/800-292-5686

22 Soil Conservation Service
Plant Materials Center
Route 1, Box 155
Knox City., TX 79529
817-658-3922

26 Texas-West Indies Company
P.O. Box 110
El Campo, TX 77437
713-543-2741

27 W.H. Anton Seed Company
P.O. Box 667
Lockhart, TX 78644
512-398-2433

28 Womack's Nursery Company
Route 1, Box 80
DeLeon, TX 76444
817-893-6497

OKLAHOMA

29 Cedarlake Sod Farm, Inc.
Route 2, Box 43K
Shawnee, OK 74801
405-273-4920

30 Coury Enterprises
2828 Northwest 57th
Oklahoma City, OK 73112
405-848-4411

33 Honey Creek Nursery
Rt. 4, Box 514
Grove, OK 74344
918-786-2771

34 Johnston Seed Company
Box 1392
Enid, OK 73701
405-233-5800

35 Melot's Inc.
P.O. Box 154
Bethany, OK 73701
405-721-4394

36 Mid-Western Nurseries, Inc.
P.O. Box 768
Tahlequah, OK 74464
918-456-6185/800-331-4145

37 OK Dept. of Agriculture
Forestry Division Nursery
Route 1, Box 44
Washington, OK 73093
405-288-2385

38 Ross Seed & Grain Company
P.O. Box 769
Chickasha, OK 73018
405-224-2224

31 Eckroat Seed Company, Inc.
P.O. Box 17610
Oklahoma City, OK 73136
405-427-2484

32 Greenleaf Nursery Company
Route 1, Box 163
Park Hill, OK 74451
918-457-5172

39 Spears Tree Farm
Route 1, Box 138
Tahlequah, OK 74464
918-456-4293

40 The Great American Seed Co.
P.O. Box 725
Hennessey, OK 73742
405-853-7811

41 Twam Nurseries, Inc.
Route 1
Pauls Valley, OK 73075
405-283-5116

42 Valley View Nursery
Route 1, Box 400
Park Hill, OK 74451
918-456-3241

43 Weyerhaeuser Company
Route 1, Box 10A
Ft. Townson, OK 74734
405-873-2717

ADDITIONAL SOURCES

44 Bomar Feed and Seed Company
P.O. Box 1327
Tuscaloosa, AL 35401
205-758-3671

45 Montgomery Seed and Supply
243 Dexter Avenue
Montgomery, AL 36104
205-265-8241

48 Bingham Seed Company, Inc.
P.O. Box 1166
Jacksonville, FL 32201
904-768-1503

49 Sharp Brothers Seed Company
Healy, KA 67850
316-398-2231

50 Louisiana Seed Company, Inc.
P.O. Box 7498
Alexandria, LA 71306
318-445-6900

51 Richard's Nursery, Inc.
P.O. Box 130
Forest Hill, LA 71430
318-748-8587 (8484)

52 VBM Seeds
4607 Wendover Blvd.
Alexandria, LA 71301
318-443-7902

46 Kaufman Seeds, Inc.
P.O. Box 398
Ashdown, AR 71822
501-898-3328

47 Clyde Robin Seed Co., Inc.
P.O. Box 2855
Castro Valley, CA 94545
415-581-3467

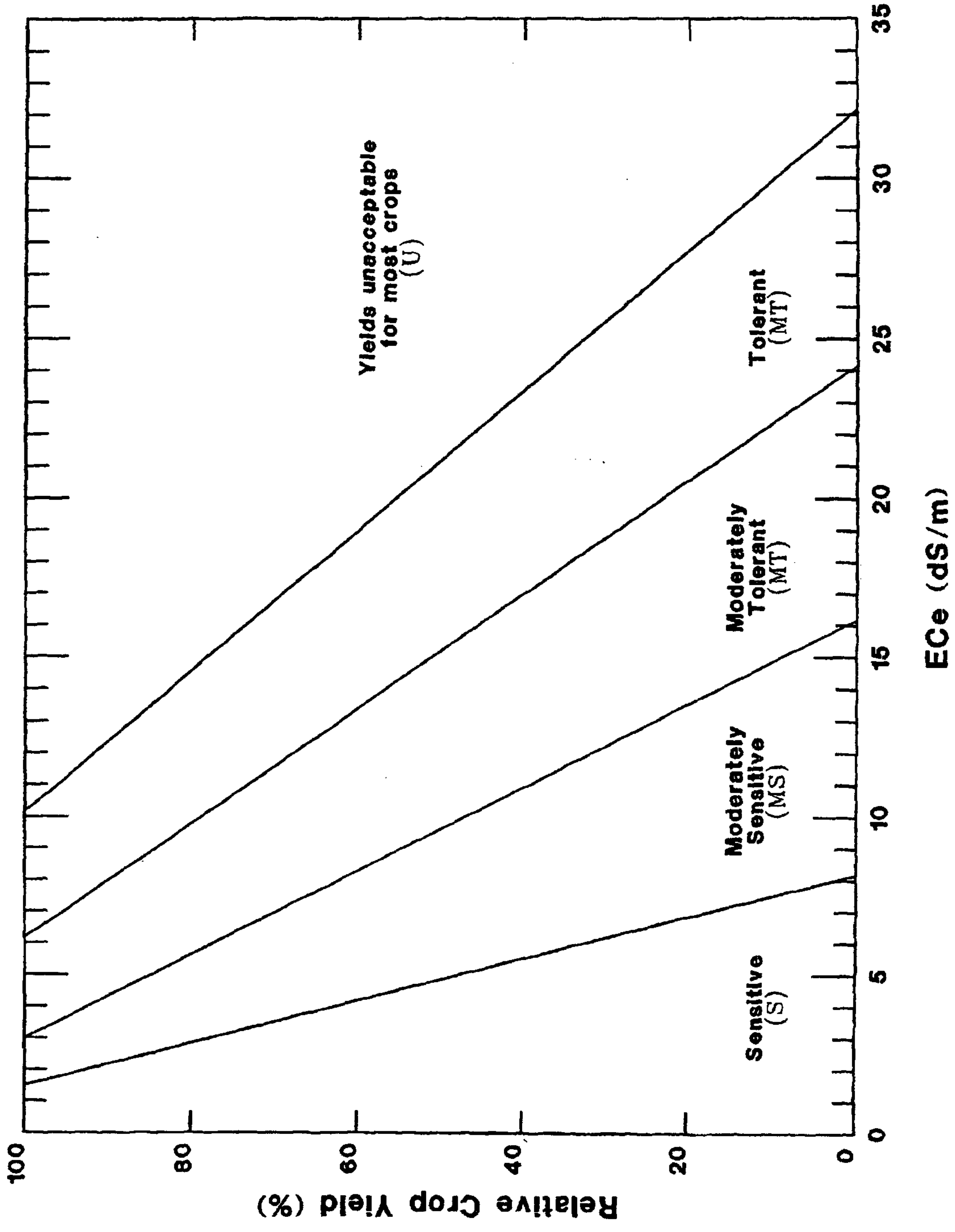
53 Forest Keeling Nursery
Elsberry, MO 63343
314-898-5571

54 Plumfield Nurseries, Inc.
P.O . Box 410
Fremont, NE 68025
402-721-3622

55 Hillis Nursery Company
Route 2, Box 142
McMinnville, TN 37110
615-688-4364

56 Native Plants
University Research Park
400 Wakara Way
Salt Lake City, UT 84108

57 Kester's Wild Game Food
Nurseries, Inc.
P.O. Box V
Omro, WI 54963
414-685-2929



Divisions for Classifying Crop Tolerance to Salinity (adapted from Tanji, 1990).

Salt Tolerance of Herbaceous Crops.[a]—Fiber, Grain and Special Crops

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	Slope % per dS/m (4)	Rating[d] (5)	References (6)
Barley[e]	*Hordeum vulgare*	8.0	5.0	T	Maas and Hoffman (1977)
Bean	*Phaseolus vulgaris*	1.0	19.0	S	Maas and Hoffman (1977)
Broad bean	*Vicia faba*	1.6	9.6	MS	Maas and Hoffman (1977)
Corn[f]	*Zea Mays*	1.7	12.0	MS	Maas and Hoffman (1977)
Cotton	*Gossypium hirsutum*	7.7	5.2	T	Maas and Hoffman (1977)
Cowpea	*Vigna unguiculata*	4.9	12.0	MT	West and Francois (1982)
Flax	*Linum usitatissimum*	1.7	12.0	MS	Maas and Hoffman (1977)
Guar	*Cyamopsis tetragonoloba*	8.8	17.0	T	Francois et al. (1989b)
Kenaf	*Hibiscus cannabinus*			MT	Francois (1988c)
Millet, foxtail	*Setaria italica*			MS	Maas and Hoffman (1977)
Oats	*Avena sativa*			MT[*]	
Peanut	*Arachis hypogaea*	3.2	29.0	MS	Maas and Hoffman (1977)
Rice, paddy	*Oryza sativa*	3.0[g]	12.0[g]	S	Maas and Hoffman (1977)
Rye	*Secale cereale*	11.4	10.8	T	Francois et al. (1989a)
Safflower	*Carthamus tinctorius*			MT	Maas and Hoffman (1977)
Sesame[j]	*Sesamum indicum*			S	Yousif et al. (1972)
Sorghum	*Sorghum bicolor*	6.8	16.0	MT	Francois et al. (1984)
Soybean	*Glycine max*	5.0	20.0	MT	Maas and Hoffman (1977)

(continued)

Salt Tolerance of Herbaceous Crops.[a]—Fiber, Grain Speciai Crops (Continued)

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	Slope % per dS/m (4)	Rating[d] (5)	References (6)
Sugar beet[h]	*Beta vulgaris*	7.0	5.9	T	Maas and Hoffman (1977)
Sugar-cane	*Saccharum officinarum*	1.7	5.9	MS	Maas and Hoffman (1977)
Sunflower	*Helianthus annuus*			MS*	
Triticale	*X Triti-cosecale*	6.1	2.5	T	Francois et al. (1988)
Wheat	*Triticum aestivum*	6.0	7.1	MT	Maas and Hoffman (1977)
Wheat (semi-dwarf)[i]	*T. aestivum*	8.6	3.0	T	Francois et al. (1986)
Wheat, durum	*T. turgidum*	5.9	3.8	T	Francois et al. (1986)

[a]These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending on 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 EC_es about 2 dS/m higher than indicated.
[d]Ratings are defined by the boundaries in Fig. 13.3. Ratings with an * are estimates. For references, consult the indexed bibliography by Francois and Maas (1978, 1985).
[e]Less tolerant during seedling stage, EC_e at this stage should not exceed 4 dS/m or 5 dS/m.
[f]Grain and forage yields of DeKalb XL-75[e] grown on an organic muck soil decreased about 26% per dS/m above a threshold of 1.9 dS/m (Hoffman et al. 1983).
[g]Because paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil water while plants are submerged. Less tolerant during seedling stage.
[h]Sensitive during germination and emergence, EC_e should not exceed 3 dS/m.
[i]Data from one cultivar, "Probred."
[j]Sesame cultivars, Sesaco 7 and 8, may be more tolerant than indicated by the S rating (Francois 1988b).

Salt Tolerance of Herbaceous Crops[a]—Grasses and Forage Crops

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	slope % per dS/m (4)	Rating[d] (5)	References (6)
Alfalfa	*Medicago sativa*	2.0	7.3	MS	Maas and Hoffman (1977)
Alkali grass, Nuttall	*Puccinellia airoides*			T*	
Alkali sacaton	*Sporobolus airoides*			T*	
Barley (forage)[e]	*Hordeum vulgare*	6.0	7.1	MT	Maas and Hoffman (1977)
Bentgrass	*Agrostis stolonifera palustris*			MS	Maas and Hoffman (1977)
Bermuda grass[h]	*Cynodon Dactylon*	6.9	6.4	T	Maas and Hoffman (1977)
Bluestem, Angleton	*Dichanthium aristatum*			MS*	
Brome, mountain	*Bromus marginatus*			MT*	
Brome, smooth	*B. inermis*			MS	Maas and Hoffman (1977)
Buffelgrass	*Cenchrus ciliaris*			MS*	
Burnet	*Poterium Sanguisorba*			MS*	
Canary grass, reed	*Phalaris arundinacea*			MT	Maas and Hoffman (1977)
Clover, alsike	*Trifolium hybridum*	1.5	12.0	MS	Maas and Hoffman (1977)
Clover, Berseem	*T. alexandrinum*	1.5	5.7	MS	Maas and Hoffman (1977)
Clover, Hubam	*Melilotus alba*			MT*	
Clover, ladino	*Trifolium repens*	1.5	12.0	MS	Maas and Hoffman (1977)
Clover, red	*T. pratense*	1.5	12.0	MS	Maas and Hoffman (1977)
Clover, strawberry	*T. fragiferum*	1.5	12.0	MS	Maas and Hoffman (1977)

(continued)

Salt Tolerance of Herbaceous Crops[a]—Grasses and Forage Crops (Continued)

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	slope % per dS/m (4)	Rating[d] (5)	References (6)
Clover, sweet	*Melilotus*			MT*	
Clover, white Dutch	*Trifolium repens*			MS*	
Corn (forage)[f]	*Zea Mays*	1.8	7.4	MS	Maas and Hoffman (1977)
Cowpea (forage)	*Vigna unguiculata*	2.5	11.0	MS	West and Francois (1982)
Dallis grass	*Paspalum dilatatum*			MS*	
Fescue, tall	*Festuca elatior*	3.9	5.3	MT	Maas and Hoffman (1977)
Fescue, meadow	*F. pratensis*			MT*	
Foxtail, meadow	*Alopecurus pratensis*	1.5	9.6	MS	Maas and Hoffman (1977)
Grama, blue	*Bouteloua gracilis*			MS*	
Harding grass	*Phalaris tuberosa*	4.6	7.6	MT	Maas and Hoffman (1977)
Kallar grass	*Diplachne fusca*			T*	
Love grass[i]	*Eragrostis* sp.	2.0	8.4	MS	Maas and Hoffman (1977)
Milkvetch, Cicer	*Astragalus cicer*			MS*	
Oat grass, tall	*Arrhenatherum, Danthonia*			MS*	
Oats (forage)	*Avena sativa*			MS*	
Orchard grass	*Dactylis glomerata*	1.5	6.2	MS	Maas and Hoffman (1977)
Panic grass, blue	*Panicum antidotale*			MT*	
Rape	*Brassica napus*			MT*	
Rescue grass	*Bromus unioloides*			MT*	

(continued)

Salt Tolerance of Herbaceous Crops[a]—Grasses and Forage Crops (Continued)

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Thresh-old[c] dS/m (3)	slope % per dS/m (4)	Rating[d] (5)	References (6)
Rhodes grass	*Chloris Gayana*			MT	Maas and Hoffman (1977)
Rye (forage)	*Secale cereale*			MS*	
Ryegrass, Italian	*Lolium italicum multiflorum*			MT*	
Ryegrass, perennial	*L. perenne*	5.6	7.6	MT	Maas and Hoffman (1977)
Salt grass, desert	*Distichlis stricta*			T*	
Sesbania	*Sesbania exaltata*	2.3	7.0	MS	Maas and Hoffman (1977)
Sirato	*Macroptilium atropurpureum*			MS	Maas and Fisher (1986)
Sphaerophysa	*Sphaerophysa salsula*	2.2	7.0	MS	Francois and Bernstein (1964)
Sundan grass	*Sorghum sudanense*	2.8	4.3	MT	Maas and Hoffman (1977)
Timothy	*Phleum pratense*			MS*	
Trefoil, big	*Lotus uliginosus*	2.3	19.0	MS	Maas and Hoffman (1977)
Trefoil, narrowleaf bird's foot	*L. corniculatus tenuifolium*	5.0	10.0	MT	Maas and Hoffman (1977)
Trefoil, broadleaf bird's foot[f]	*L. corniculatus arvenis*			MT	Maas and Hoffman (1977)
Vetch, common	*Vicia angustifolia*	3.0	11.0	MS	Maas and Hoffman (1977)
Wheat (forage)[g]	*Triticum aestivum*	4.5	2.6	MT	Francois et al. (1986)
Wheat, Durum (forage)	*T. turgidum*	2.1	2.5	MT	Francois et al. (1986)

(continued)

Salt Tolerance of Herbaceous Crops[a]—Grasses and Forage Crops (Continued)

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	slope % per dS/m (4)	Rating[d] (5)	References (6)
Wheat grass, standard crested	*Agropyron sibiricum*	3.5	4.0	MT	Maas and Hoffman (1977)
Wheat grass, fairway crested	*A. cristatum*	7.5	6.9	T	Maas and Hoffman (1977)
Wheat grass, intermediate	*A. intermedium*			MT*	
Wheat grass, slender	*A. trachycaulum*			MT	Maas and Hoffman (1977)
Wheat grass, tall	*A. elongatum*	7.5	4.2	T	Maas and Hoffman (1977)
Wheat grass, western	*A. Smithii*			MT*	
Wild rye, Altai	*Elymus angustus*			T	Maas and Hoffman (1977)
Wild rye, beardless	*E. triticoides*	2.7	6.0	MT	Maas and Hoffman (1977)
Wild rye, Canadian	*E. canadensis*			MT*	
Wild rye, Russian	*E. Junceus*			T	Maas and Hoffman (1977)

[a]These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending on 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 EC_e about 2 dS/m higher than indicated.
[d]Ratings are defined by the boundaries in Fig. 13.3. Ratings with an * are estimates. For references, consult the indexed bibliography by Francois and Maas (1978, 1985).

(Continued)

[e]Less tolerant during seedling stage, EC_e at this stage should not exceed 4 dS/m 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 (Hoffman et al. 1983).
[g]Data from one cultivar, "Probred."
[h]Average of several varieties. Suwannee and Coastal are about 20% more tolerant, and common and Greenfield are about 20% less tolerant than the average.
[i]Average for Boer, Wilman, Sand, and Weeping cultivars. Lehmann seems about 50% more tolerant.

TABLE 13.1c Salt Tolerance of Herbaceous Crops[a]—Vegetables and Fruit Crops

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	slope % per dS/m (4)	Rating[d] (5)	References (6)
Artichoke	*Helianthus tuberosus*			MT*	
Asparagus	*Asparagus officinalis*	4.1	2.0	T	Francois (1987)
Bean	*Phaseolus vulgaris*	1.0	19.0	S	Maas and Hoffman (1977)
Beet, red[e]	*Beta vulgaris*	4.0	9.0	MT	Maas and Hoffman (1977)
Broccoli	*Brassica oleracea botrytis*	2.8	9.2	MS	Maas and Hoffman (1977)
Brussel sprouts	*B. oleracea gemmifera*			MS*	
Cabbage	*B. oleracea capitata*	1.8	9.7	MS	Maas and Hoffman (1977)
Carrot	*Daucus carota*	1.0	14.0	S	Maas and Hoffman (1977)
Cauliflower	*Brassica oleracea botrytis*			MS*	
Celery	*Apium graveolens*	1.8	6.2	MS	Francois and West (1982)

(continued)

Salt Tolerance of Herbaceous Crops[a]—Vegetables and Fruit Crops (Continued)

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	slope % per dS/m (4)	Rating[d] (5)	References (6)
Corn, sweet	*Zea Mays*	1.7	12.0	MS	Maas and Hoffman (1977)
Cucumber	*Cucumis sativus*	2.5	13.0	MS	Maas and Hoffman (1977)
Eggplant	*Solanum Melongena esculentum*	1.1	6.9	MS	Heuer et al. (1986)
Kale	*Brassica oleracea acephala*			MS[*]	
Kohlrabi	*B. oleracea gongylode*			MS[*]	
Lettuce	*Lactuca sativa*	1.3	13.0	MS	Maas and Hoffman (1977)
Muskmelon	*Cucumis Melo*			MS	Shannon and Francois (1978)
Okra	*Abelmoschus esculentus*			S	Maas and Hoffman (1977)
Onion	*Allium Cepa*	1.2	16.0	S	Maas and Hoffman (1977)
Parsnip	*Pastinaca sativa*			S[*]	
Pea	*Pisum sativum*			S[*]	
Pepper	*Capsicum annum*	1.5	14.0	MS	Maas and Hoffman (1977)
Potato	*Solanum tuberosum*	1.7	12.0	MS	Maas and Hoffman (1977)
Pumpkin	*Cucurbita Pepo Pepo*			MS[*]	
Radish	*Raphanus sativus*	1.2	13.0	MS	Maas and Hoffman (1977)
Spinach	*Spinacia oleracea*	2.0	7.6	MS	Maas and Hoffman (1977)
Squash, scallop	*Cucurbita Pepo Melopepo*	3.2	16.0	MS	Francois (1985)

(continued)

Salt Tolerance of Herbaceous Crops[a]—Vegetables and Fruit Crops (Continued)

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Thresh-old[c] dS/m (3)	slope % per dS/m (4)	Rating[d] (5)	References (6)
Squash, zucchini	*C. Pepo Melopepo*	4.7	9.4	MT	Francois (1985)
Strawberry	*Fragaria* sp.	1	33	S	Maas and Hoffman (1977)
Sweet potato	*Ipomoea Batatas*	1.5	11	MS	Maas and Hoffman (1977)
Tomato	*Lycopersicon Lycopersicum*	2.5	9.9	MS	Maas and Hoffman (1977)
Turnip	*Brassica Rapa*	0.9	9	MS	Francois (1984a)
Water-melon	*Citrullus lanatus*			MS*	

[a]These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary, depending on 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 EC_e about 2 dS/m higher than indicated.
[d]Ratings are defined by the boundaries in Fig. 13.3. Ratings with an * are estimates. For references, consult the indexed bibliography by Francois and Maas (1978, 1985).
[e]Sensitive during germination and emergence, EC_e should not exceed 3 dS/m.

Salt Tolerance of Woody Crops[a]

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	Slope % per dS/m (4)	Rating[d] (5)	References (6)
Almond[e]	*Prunus duclis*	1.5	19.0	S	Maas and Hoffman (1977)
Apple	*Malus sylvestris*			S	Maas and Hoffman (1977)
Apricot[e]	*Prunus armeniaca*	1.6	24.0	S	Maas and Hoffman (1977) (continued)
Avocado[e]	Persea americana			S	Maas and Hoffman (1977)
Blackberry	*Rubus* sp.	1.5	22.0	S	Maas and Hoffman (1977)
Boysenberry	*Rubus ursinus*	1.5	22.0	S	Maas and Hoffman (1977)
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	Maas and Hoffman (1977)
Fig	*Ficus carica*			MT*	
Gooseberry	*Ribes* sp.			S*	
Grape[e]	*Vitis* sp.	1.5	9.6	MS	Maas and Hoffman (1977)
Grapefruit[e]	*Citrus paradisi*	1.8	16.0	S	Maas and Hoffman (1977)
Guayule	*Parthenium argentatum*	15.0	13.0	T	Maas et al. (1988)
Jojoba[e]	*Simmondsia chinensis*			T	Yermanos et al. (1967)
Jujube	*Ziziphus jujuba*			MT*	
Lemon[e]	*Citrus Limon*			S	Maas and Hoffman (1977)

(continued)

Salt Tolerance of Woody Crops[a] (Continued)

Crop		Electrical conductivity of saturated-soil extract			
Common name (1)	Botanical name[b] (2)	Threshold[c] dS/m (3)	Slope % per dS/m (4)	Rating[d] (5)	References (6)
Lime	*C. aurantifolia*			S*	
Loquat	*Eriobotrya japonica*			S*	
Mango	*Mangifera indica*			S*	
Olive	*Olea europaea*			MT	Maas and Hoffman (1977)
Orange	*Citrus sinensis*	1.7	16.0	S	Maas and Hoffman (1977)
Papaya[e]	*Carica papaya*			MT	Siegel (1982)
Passion fruit	*Passiflora edulis*			S*	
Peach	*Prunus Persica*	1.7	21.0	S	Maas and Hoffman (1977)
Pear	*Pyrus communis*			S*	
Persimmon	*Diospyros virginiana*			S*	
Pineapple	*Ananus comosus*			MT*	
Plum; Prune[e]	*Prunus domestica*	1.5	18.0	S	Hoffman et al. (1989)
Pomegranate	*Punica granatum*			MT*	
Pummelo	*Citrus maxima*			S*	
Raspberry	*Rubus idaeus*			S	Maas and Hoffman (1977)
Rose apple	*Syzygium jambos*			S*	
Sapote, white	*Casimiroa edulis*			S*	
Tangerine	*Citrus reticulata*			S*	

[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.

GENERAL GUIDE TO SELECTED GRASSES AND FORBS

Note:
Original source of these data are unknown. The authors of this manual, in their professional experience, have found this information to be reliable.

GRASSES USEFUL IN REVEGETATING DISTURBED LANDS

	HABIT Sod S Bunch-B	PRECIPITATION RATES Min (in)	Max (in)	SOIL TYPE (L-M-H)*	TOLERANCE (Low-Med-High) Salt	Alkali	PLANTING SEASON	SEEDING RATE (lbs/ac pls drilled)	SEEDING Drill Depth (in)
NATIVE GRASSES									
Bluebunch Wheatgrass	B	6	9	L-M-H	L	-	Fall/Early Spring	7	1/4 - 3/4
Streambank Wheatgrass	S	8	15	L-M	M	-	Spring thru Fall	5	3/4
Indian Ricegrass	B	6	10	L-M-H	L	L	Spring thru Fall	4	1 1/2 - 4
Little Bluestem	B	10	40	L-M	L	-	Spring	20	1/4 - 3/4
Alpine Timothy	B	20	Irr.	M-H	L	-	Spring thru Fall	2	1/4 - 1/2
Thickspike Wheatgrass	S	6	201	L-M	L	-	Spring thru Fall	6	1/2 - 1
Idaho Fescue	B	10	15	M	L	L	Late Fall/Spring	3	1/4 - 3/4
Blue Grama	S	10	15	M	M	M	Spring	2	1/4 - 1/2
Alkali Sacaton	B	8	18	L-M-H	H	M	Summer	1/5	1/4
Basin Wildrye	B	9	Irr.	L-M-H	H	-	Late Fall/Spring	5	1
Western Wheatgrass	S	10	20	M-H	H	-	Early Fall/Spring	8	1/2 - 1
Prairie Sandreed	S	12	20	L-M	L	L	Spring	6	1
Big Bluegrass	B	12	20	L-M	L	L	Fall/Early Spring	4	1/4 - 3/4
Green Needlegrass	B	12	30	M-H	L	M	Late Summer/Early Fall	5	3/4 - 1 1/2
Switchgrass	S	16	Irr.	L-M-H	M	-	Spring	3	1/4 - 3/4
Sideoats Grama	S	17	20	L-M	M	-	Spring	5	1/4 - 3/4
Mountain Brome	B	18	Irr.	L-M-H	M	-	Late Fall/Spring	10	1/2 - 1 1/2
Beardless Wildrye	S	20	Irr.	M-H	H	-	Late Fall/Spring	8	3/4
Big Bluestem	S	20	Irr.	M-H	M	-	Spring	6	1/4 - 1 1/2
Reed Canarygrass	S	Irr.	Flood	L-M	M	M	Spring thru Fall	4	1/4 - 3/4
INTRODUCED GRASSES									
Pubescent Wheatgrass	S	12	15	L-M-H	M	-	Early Spring	7	3/4 - 1
Crested Wheatgrass	B	5	15	L-M	M	-	Spring thru Fall	6	1/4 - 1
Siberian Wheatgrass	B	5	15	L-M-H	M	-	Spring thru Fall	5	3/4
Intermediate Wheatgrass	S	10	15	M-H	M	-	Early Spring	7	1/2 - 1
Timothy	B	20	Irr.	M-H	L	-	Spring thru Fall	2	1/4 - 1/2
Tall Wheatgrass	B	5	20	L-M-H	H	-	Spring	8	1/2 - 2
Smooth Brome	S	16	20	L-M-H	M	L	Late Fall/Early Spring	7	1/2 - 1
Tall Fescue	B	18	20	M-H	M	-	Late Spring	5	1/4 - 1

FORBS USEFUL IN REVEGETATING DISTURBED LANDS (continued)

	LEGUME*** (Yes/No)	PRECIPITATION RATES Min (In)	PRECIPITATION RATES Max (In)	SOIL TYPE (L-M-H)*	TOLERANCE (Low-Med-High) Salt	TOLERANCE (Low-Med-High) Alkali	PLANTING SEASON	SEEDING RATE** (lbs/ac pls drilled)	SEEDING Drill Depth (In)
NATIVE FORBS									
Maximilian Sunflower	NO	5	12	L-M	L	-	Fall/Spring	1/5	1/8 - 1
Rocky Mountain Penstemon	NO	15	20	L	L	L	Late Fall/Early Spring	5	1/4
Northern Sweetvetch	YES	10	18	L-M-H	M	M	Late Fall/Early Spring	1/2	1/2 - 3/4
Arrowleaf Balsamroot	NO	10	20	M	L	M	Late Fall/Early Spring	-	1/2 - 1
Lewis Flax	NO	10	20	L	M	-	Late Fall/Spring	4	1/4 - 3/4
Upright Prairie Coneflower	NO	10	20	L-M	L	M	Spring	-	-
Purple Prairie Clover	YES	12	20	M-H	-	M	Fall thru Spring	-	-
Missouri Goldenrod	NO	12	20	L-M-H	L	-	Late Fall/Early Spring	1/2	1/4 - 1/2
American Vetch	YES	14	20	L-M	M	M	Late Fall/Early Spring	8	1/2 - 1 1/2
INTRODUCED FORBS									
Yellow Sweetclover	YES	10	15	L-M-H	M	-	Early Spring	4	1/2 - 2
Common Sainfoin	YES	16	20	L-M-H	M	-	Spring	25	1/2 - 1 1/2
Alfalfa	YES	12	20	L-M-H	M	-	Late Fall/Early Spring	5	1/4 - 1 1/2

* SOIL TYPE L = LIGHT - sands, loamy fine sands, sandy loams
M = MEDIUM - silty loams, loams, very fine sandy loams, sandy clay loams
H = HEAVY - clay loams, silty clays, clay

** SEEDING RATE If seeds are broadcast, double drilled amount; pls = pure live seed

*** Best plant growth is obtained if legumes are inoculated with appropriate culture

Care must be taken as noxious or poisonous weed seed may be imported with the desired grass or forb seed.

Assumed Note: Irr. = Irrigation

APPENDIX G

Sampling Procedures

SUMMARY

Appendix G provides a detailed description of sampling procedures used to delineate a pit or spill site. It covers the following:

- Soil Sampling Methods
- Surface Soil Samples
- Subsurface Soil Samples
- Background and Duplicate Soil Samples
- Factors Influencing Sample Collection
- Electromagnetic Devices
- Soil and Water Salinity Primer
- Soil Saturation Extract Levels
- Water Salinity Levels for Livestock Use
- Salinity Levels of Irrigation Water
- Preparing a Saturated Soil Paste

SAMPLING PROCEDURES

The initial steps in evaluating a site are to identify the magnitude of the damage in terms of area and depth, and to determine if "uniform land areas" are present throughout the site. Uniform land areas can be defined as land areas with similar soils, vegetation, topography, and other significant surface features. For this purpose, an adequate soil sampling strategy is one that delineates the boundaries of the contamination, yet also recognizes natural differences in soil or landscape position.

Although field personnel have considerable flexibility in designing a site sampling plan, certain general features will influence any sampling strategy. Land areas having obvious differences or various degrees of impact need to be sampled separately. If present, the full range of contamination levels should be sampled. Generally speaking, the sampling team should try to collect samples from the most impacted area, an area of moderate contamination, a sample at the furthest edge of the contamination, and an associated background or unimpacted area sample.

As a general rule, initial site delineation may be accomplished by evaluating samples on the basis of surface appearance and odor, in the case of hydrocarbon spills. The forms and worksheets to aid in the site delineation are in Appendix B. The site delineation is conducted, using Forms 3 and 4 (Appendix B, pages B-10 and B-13, respectively), to record data and prepare a site sketch.

Sampling can be guided by measuring electrical conductivity (EC) during the site assessment and sampling. Surface EC measurements can also help determine optional sample locations, and during sampling, can indicate when sufficient sampling depth has been reached.

A simple sample strategy could involve evaluation of surface samples at depths of approximately 0–12 inches, at spaced intervals around the periphery of the contaminated area. Deeper samples may also be determined as necessary for this initial screening and delineation. After determining the total spill area, actual site sampling is conducted using transect lines across the delineated area, or dividing the area into quadrants and collecting representative samples.

SOIL SAMPLING METHODS

Soil sample collection entails two types of samples: surface and subsurface. Surface samples may be collected using a hand-held trowel, shovel, or auger. For subsurface samples, a 3-inch bucket auger is recommended, but a sharpshooter spade or post-hole digger may also be used. Care should be taken when sampling subsurface samples so that contaminated soil from the surface layer does not fall into the sample hole and contaminate the deeper sample. Depending on the complexity of the site, the budget, and the type and size of the contaminated area, samples may be composited to reduce sample numbers. A composite sample is defined as a combination of samples from similar depths and contamination levels. Samples can be composited in the laboratory prior to being analyzed. Submission of discrete samples to the laboratory will give the freedom of analyzing any chosen sample independently at a later date, if sample holding time permits. Table G-1 lists useful equipment for conducting site sampling activities.

Table G-1. Soil Sampling Equipment and Supplies.

Soil collection tool (bucket auger, post-hole digger, spade, spatula, or knife)
Stainless steel bowl
Water for rinsing (tap water or distilled)
Gallon-size sealable plastic bags
Sample jars
Permanent felt-tip marker
Site evaluation and investigation forms (Appendix B)
Site sketch (Form 3, Appendix B, page B-10)
Chain-of-custody form (Appendix J)

An example soil sampling procedure is as follows:

Step 1. Prepare site sketch (Form 3, Appendix B, page B-10) and delineate uniform land areas.

Step 2. Decide on the number of samples to be collected and the number of composites to be submitted for analysis.

Step 3. Record surface and sample observations on Forms 3 and 4 (Appendix B, pages B-10 and B-13, respectively).

Step 4. Collect samples with either a hand auger, spade, shovel, or post-hole digger.

Step 5. Place samples to be composited into a large, inert container (such as a clean stainless steel mixing bowl), thoroughly mix the contents, and subsample.

Step 6. Place the composite sample (or the individual grab sample, if appropriate), into a suitable container (if the laboratory conducting the analysis is contacted prior to the sampling event, they will usually supply the proper containers).

Step 7. Label the sample container with the site name and number, sample number, sample depth interval, date, and sampler's initials.

Step 8. Clean the sampling tool and mixing bowl between composite sample locations or each individually collected sample using a brush and washwater. Rinse the tool a final time with distilled water.

Step 9. Record sample description, location, and site data on Form 4 (Appendix B, page B-13).

Step 10. Identify the sample location on Form 3 (Appendix B, page B-10).

SURFACE SOIL SAMPLES

It is recommended that multiple surface samples (0–12 inches) be collected and composited into separate samples for each uniform land area or area of similar contamination level. An equal mass of each sample to comprise the composite is desired. A minimum of four surface samples for each uniform land area is desirable. Two composite soil samples should be prepared by combining two samples into one composite and the other two samples into a second composite. Both composites should be analyzed to provide an indication of site variability.

Representative sampling can be best accomplished by either collecting samples from designated quadrants, or from along transect lines. Size and length of transect lines are completely site-dependent and will have to be adjusted on a site-by-site basis. A suggested sampling scheme is to collect surface samples along a transect line at each quarter length of the transect line. If delineation of separate or uniform land areas is not clear, the samples should be packaged and analyzed separately, rather than in composites. An attempt should be made to place transects in areas of different contamination levels or ensure that the transects are long enough to completely cover the range of contamination.

SUBSURFACE SOIL SAMPLES

Sample depths can be divided into two increments during the assessment: 0–12 and 12–24 inches, or at visible soil contamination breaks. Fewer subsurface samples will be required for uniform areas, but each uniform area will require at least one set of subsurface samples. If contamination is determined to be deeper than 24 inches, deeper samples may be required to delineate the extent of the contamination.

BACKGROUND AND DUPLICATE SOIL SAMPLES

Background soil samples should be collected from the same soil depths as samples collected in contaminated areas, and using the same methods and materials. These background samples should be collected from an undisturbed area of similar topography and soils as the impacted site. Data from these samples can be used in determination and comparison of contaminated areas to native or natural conditions.

Care should be taken that sampling equipment has been properly cleaned prior to and between samples to avoid any cross-contamination. More than one sampler can also be used to collect soil samples, thus avoiding any field decontamination of equipment.

In order to assure that data obtained from the analytical laboratory are accurate, duplicate or split samples may be collected and analyzed. As a general rule, for each 20 samples collected, one duplicate sample (5%) should be collected from a randomly selected sample. At least one duplicate sample should be collected for each sample set regardless of the total number of samples taken. Duplicate samples are to be numbered in a similar manner as other samples so that they are indistinguishable to the analytical laboratory.

Maintaining chain-of-custody forms for samples is essential when collecting samples for laboratory analysis. These forms are intended to document the handling history of samples from the time of collection. The purpose of the chain-of-custody form is to eliminate questions of sample handling, post-collection contamination, or potential for sample tampering. These forms must be filled out correctly and completely, and may become important documents regarding potential litigation. An example chain-of-custody form is included in Appendix J.

FACTORS INFLUENCING SAMPLE COLLECTION

The total number and type of samples to be collected at an impacted area can vary significantly according to specific site conditions. In particular, the nature of the release will greatly influence the relationship between depth and total surface area affected. In this regard, the two factors to be considered are the total volume of released material and the rate at which the release occurred. For instance, a rapid release (e.g., from a serious pipeline rupture) may contaminate a large surface area but extend only to a relatively shallow depth provided the release is of short duration. Alternately, the same volume released over a longer period (from a smaller, but less quickly detected leak) may spread across a lower total surface area, but result in soil contamination to a greater depth. In other situations, a relatively low-volume leak (such as a fine spray of materials from a pump unit) may extend over a wide area but be present only to a very shallow depth.

Other factors influencing the number and type of samples to be collected are the soil type and land contour characteristics in the area of the release. Liquids will penetrate more quickly into a very sandy soil, resulting in a lower overall areal surface of contamination, but at a greater depth. In addition, local topography can result in a pooled concentration of contaminants in low-lying areas, also resulting in lower total affected surface area, but greater depth of contamination. During the preliminary assessment, an evaluation of the depth to groundwater should have been conducted on the site, if not already known. Due to the potential migration of salts in near surface groundwater, additional sampling of salt-affected soil and groundwater may be advisable in order to determine the flow direction, areal extent, and concentration of subsurface salts. As a general rule, sites where the depth to groundwater is less than 6 ft are in a high-risk category.

As discussed above, the nature of the release, soil characteristics, and site topography and hydrology must all be taken into account prior to the development of a sample plan. Because the variability of each of these factors is potentially great, personnel must be alert for the observance of site-specific characteristics and design each sampling plan accordingly.

ELECTROMAGNETIC DEVICES

Site delineation for large sites, or sites which may have lateral subsurface migration, may be aided by an electromagnetic (EM) sensing device. This device can be used at walking speed. The flux density shown on the meter corresponds to salt content in the soil. Readings can be recorded every 5 to 20 steps. Prime sample locations can be selected based on EM readings. The analytical data from the actual sample locations are used later to calibrate the instrument for the entire spill area. An entire 0.25-acre site, including background, can be examined in this manner in about one-half hour. The primary disadvantage of EM devices is that nearby electric lines, metal pipes, and equipment can influence readings; but in general, they are very useful and relatively inexpensive to rent and operate.

SOIL AND WATER SALINITY PRIMER

Soil or water salinity is measured in terms of electrolytic or electrical conductivity (EC), which is representative of the total ionic content of a water sample or of an extract drawn from a soil sample. Since dissolved salts are the primary contributors of free ions in soil and water samples, EC is a meaningful assessment of salt content. In keeping with the range of EC values normally found in soil and irrigation water, EC is expressed in millimhos/cm.

The following salinity levels and tolerances are gathered from information from the U.S. Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS), formerly known as Soil Conservation Service. While they can be used as guidelines, they are not presented as absolutes. Further information and local guidelines can be obtained from your local USDA-NRCS.

SOIL SATURATION EXTRACT LEVELS

Range	Typical Response for Agricultural Crops
0–2 mmhos/cm	Salinity effects are mostly negligible
2–4 mmhos/cm	Yields of very sensitive crops may be restricted
4–8 mmhos/cm	Yields of many crops are restricted
8–16 mmhos/cm	Only tolerant crops' yields are satisfactory
16 + mmhos/cm	Only very tolerant crops' yields are satisfactory

WATER SALINITY LEVELS FOR LIVESTOCK USE

Range	Typical Response
0–1.5 mmhos/cm	Water is satisfactory for all classes of livestock
1.5–5.0 mmhos/cm	Usable level for all classes of livestock/may cause temporary diarrhea in livestock non-accustomed to this level
5.0–8.0 mmhos/cm	Reasonable level for livestock/may cause temporary diarrhea/poor level for poultry/may decrease growth
8.0–11.0 mmhos/cm	Reasonable level for dairy and beef cattle, sheep, swine, and horses/not for use with pregnant animals/unacceptable for poultry
11.0–16.0 mmhos/cm	Unacceptable for poultry or swine/not acceptable for pregnant cattle, horses, sheep, or their young
16.0 + mmhos/cm	Unacceptable for all uses

SALINITY LEVELS OF IRRIGATION WATER

Range	Hazard Level
0.000–0.075 mmhos/cm	Low salinity hazard
0.075–1.500 mmhos/cm	Medium salinity hazard
1.500–3.000 mmhos/cm	High salinity hazard
3.000+ mmhos/cm	Very high salinity hazard

Your local USDA-NRCS can provide more detailed information, as well as the tolerance levels of specific crops, plants, grasses, and livestock. The EC salinity levels and ranges listed above are meant to be used only as guidelines.

PREPARING A SATURATED SOIL PASTE

Any soil sample must be brought to a prescribed standard, repeatable condition of wetness so that the salts present can go into solution, making the sample conductive and amenable to EC measurement. The objective is to attain a water-to-soil ratio that bears a consistent relationship with the particular type of soil in question, and the natural conditions prevailing in the field.

A relevant soil sample formulation is known as the saturated soil paste or saturated paste. A saturated paste is prepared by adding water to the soil until it is saturated. At saturation, any additional water would pond on the surface or run off. This saturation point is similar to the condition briefly attained near the soil surface after heavy field irrigation. The U.S. Salinity Laboratory maintains that the saturated soil paste is representative of the soil condition to which plant roots are exposed.

Place an amount of soil sufficient to provide enough sample for intended measurements into a wide-mouth container such as a plastic cup. It is advisable to weigh the soil and cup if replicate measurements will be required or if calculation of the saturation percentage is desired.

Slowly add distilled water to the soil while gently tapping the container on a counter top or other hard surface. Water should be added until all soil pores are filled, but not so much that any water remains standing on the soil surface. Some stirring is usually required, but stirring should be kept to a minimum in order to avoid puddling the sample. At saturation, the paste glistens as it reflects light and flows slightly when the container is tipped. With the exception of high clay content samples, the saturated paste sample should slide cleanly off the stirring device (spatula). Samples containing high shrink-swell clays present special problems. The initial volume of samples containing high shrink-swell clays should be noted before any water is added. Water additions should cease if the volume of the soil plus water appears to be increasing due to swelling. Experienced analytical laboratories will probably have refinements of this technique.

After the saturated paste is prepared, the sample should be covered (e.g., with aluminum foil) and allowed to stand for at least 1 hour to allow salts and water to approach equilibrium. The paste should be checked at the end of this time to verify that the saturated paste moisture content has been achieved. If free water has formed on the surface, the sample has lost its glisten, or the paste has stiffened, then additional water or soil should be added to reestablish the saturated condition.

The extractable water from the saturated paste (saturated paste extract) can be separated from the solid phase by positive pressure using a filter and syringe assembly, or under vacuum using a vacuum pump or venturi. Laboratory analyses are usually performed after the saturated paste has been allowed to equilibrate for 12 to 24 hours, but field measurements of EC and chlorides can be obtained after 1 hour of equilibration. The saturation percentage moisture content is 100 times the weight of the soil water (wet weight of the soil minus the dry weight of the soil) divided by the dry weight of the soil.

APPENDIX H

Mechanical Remediation

SUMMARY

A number of remediation techniques are considered mechanical remediation:

- Authorized Disposal in a Landfill or Pit
- Road Spreading
- Land Spreading
- Burial Procedures
- Disposal Well Injection
- *In Situ* and *Ex Situ* Soil Washing

Each of these techniques is *ex situ* (except *in situ* soil washing) in that they involve removing the soil from the site even though the soil may be replaced in the site when complete. *In situ* soil washing is the placement of a drainage system in the soil and flooding the soil with water, effectively washing the salt into the collection system.

MECHANICAL REMEDIATION

Normally, the least expensive remediation procedure is performed in place (*in situ*). However, *in situ* techniques are sometimes inappropriate for adequate remediation. Among situations in which *in situ* remediation may not be appropriate are:

- Shallow potable water table
- Shallow soils overlying an impermeable barrier (bedrock, fragipan, tight clay, etc.)
- Runoff concerns exist
- Limitations placed on remediation by the landowner
- Regulatory restrictions
- Potential future liability

Even though more expensive, in situations similar to those mentioned above, future concerns may be reduced by mechanically removing the salt-affected soil from the root zone to allow rapid revegetation. If the choice is made to dispose or remediate salt-affected soils by means of mechanical removal, there are a number of different procedures which can be used, such as:

- Disposal in an authorized landfill or pit
- Road spreading
- Land spreading
- Burial
- Disposal well injection

AUTHORIZED DISPOSAL IN A LANDFILL OR PIT

Many states allow disposal in authorized facilities. Some states will allow salt-affected soils to be placed in a municipal landfill. Other states have specific designated pits or landfills for receiving oil and gas waste. Some of these landfills or pits will accept salt-affected soils.

Disposal at these facilities tends to be fairly expensive. The cost of removing salt-affected soil and replacing it with fresh soil is normally between $10 and $20 per yard and may be more depending upon the distance to the disposal site and the availability of replacement soil.

As with the disposal of any waste, care should be taken to avoid future liability. Just because a facility is permitted by a regulatory agency does not release the company from liability. A site audit is recommended prior to disposing wastes in a commercial facility. If a waste disposal site must be cleaned and remediated in the future, the expenses incurred will normally be paid by those contributing waste.

ROAD SPREADING

Some states allow the road spreading of oil and gas waste. This permission often includes the road spreading of salt-affected soil.

The process of road spreading salt-affected soils entails excavation of the soil and working it into a lease road with a grader or maintainer. The excavation is then normally returned to grade by adding virgin soil. In situations where all the affected soil is not removed, the salt remaining in the excavation may be diluted by mixing with the virgin fill.

Apart from *in situ* remediation, road spreading may be among the least expensive alternatives; on a cubic-yard basis the cost is approximately one-half that of commercial disposal. If the road spread is diluted, the final lease road may be in better condition than before application, although salt-affected soil rarely makes good roadbed material. However, road spreading of salt-affected soils may have serious drawbacks. Roads are subject to mechanical compaction and therefore, may resist the tendency of water to soak in. The resulting runoff may concentrate the salts in the bar ditch and impact vegetation growing there. (Especially in arid areas, the bar ditch is often a source of vegetation for the ranches.)

Even if the soil is low in salt and applied dilutely, road spreading of salt-affected soils should be limited to once or twice for any given section of road. Salt on road surfaces accumulates with each application.

LAND SPREADING

Land spreading differs from road spreading in two respects: (1) the soil is not mechanically compacted, and (2) the acreage used for land spreading is typically used only once.

LAND SPREADING CALCULATION

The land spreading technique is intended to lower salt concentrations to acceptable levels by diluting the salt-affected soil with unimpacted "receiver" soil. Land spreading may be used in conjunction with other remediation methods, such as halophytic vegetation and/or application of chemical amendments.

In land spreading, the salt-affected soil is removed from the spill area and spread over an area at a thickness of no greater than 3 inches. This allows a conventional 6-inch-radius disc to mix 3 inches of salt-affected soil with 3 inches of receiver soil for a total mixed depth of 6 inches. Incorporated in this manner, the salt concentration would decrease to one-half the original value, assuming the salt level of the receiver soil was negligible. Other concentration reduction factors are shown in below:

Salt-Affected Spill Soil Thickness (inches)	Receiver Soil Thickness (inches)	Final Salt Concentration (divide by)
.5	5.5	12
1.0	5.0	6
2.0	4.0	3
3.0	3.0	2

Example 1: 300 cu ft soil has an electrical conductivity (EC) of 24 mmhos/cm. What final area of soil is required to bring the EC to <4 mmhos/cm?

The soil volume must be expanded by a factor of 6 to decrease the EC from 24 to 4 mmhos/cm

Therefore, (300 cu ft)(6) = 1,800 cu ft final volume required

And (1,800 cu ft) = 1,800 sq ft @ 1 ft thick

Since effective incorporation is only 6 inches, then 3,600 sq ft @ 6 inches thick is required

Then, [(300 cu ft)/(3,600 sq ft)][12 in/ft] = 1 inch thick spread

Therefore, 300 cu ft salt-affected soil spread to 1 inch thickness over 3,600 sq ft and incorporated to a final depth of 6 inches will decrease EC from 24 to 4 mmhos/cm.

However, if the receiver soil also contains a measurable salt concentration, a more refined calculation may be required. The following data are required: target salt concentration (salt criteria to be met), salt level of the salt-affected soil, salt level of the receiver soil, and volume of spill-affected soil. The calculation provides the final soil volume required, which is then converted into final land area required based on 3 inches of available depth. The calculation is performed as follows:

Final volume needed = [(spill volume)(spill soil EC - target soil EC)]/(target EC - receiver EC)

Using previous example (assumes receiver EC = 0 mmhos/cm):

Final soil volume needed = ([300 cu ft)(24 - 4]/(4 - 0) = 1,500 cu ft

Then, (1,500 cu ft) = 1,500 sq ft @ 1 ft thickness

Since incorporated thickness is 0.5 ft, then 3,000 sq ft total area is required

Then, [(300 cu ft)/(3,000 sq ft)][12 in/ft] = 1.2 inch thick salt-affected soil spread over 3,000 sq ft

Example 2: Spill soil volume = 300 cu ft; spill soil EC = 24 mmhos/cm; receiver EC = 1.5 mmhos/cm; target EC = 4 mmhos/cm

Final soil volume needed = [(300 cu ft)(24 - 0]/(4 - 1.5) = 2,400 cu ft

Then, (2,400 cu ft) = 2,400 sq ft @ 1 ft thickness

Since incorporated thickness is 0.5 ft, then 4,800 sq ft total area required.

Then, [(300 cu ft)/(4,800 sq ft)][12 in/ft] = 0.75 inches (or 3/4 inch) thick salt-affected soil spread over 4,800 sq ft and incorporated to a final 6 inch thickness will decrease EC from 24 to 4 mmhos/cm

Similar calculations can be made for exchangeable sodium percentage (ESP), total petroleum hydrocarbons (TPH), and other constituents with linear concentration expressions. Because its concentration is expressed in logarithmic form, pH cannot be calculated by this method.

The land area required and thickness of spreading should be adjusted to allow for sampling and analytical variability. An expansion of the final land area required and a corresponding reduction of spreading thickness of about 1.3 times should provide for this variability.

Because of the potential for salt concentrations to increase at the soil surface during evaporative periods, a top dressing of gypsum may help minimize soil dispersion.

BURIAL PROCEDURES

Shallow burial (<4 ft) is undesirable because the salt will typically remain in the root zone and may cause significant vegetative stress for many years.

The process of deep burial involves cutting a slot the width of a bulldozer blade of sufficient depth to allow 5 ft of freeboard when the salt-affected soil is placed in the excavation. The soil removed from the slot is then used to cover the slot and replace the salt-affected soil.

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The 5-ft depth is normally sufficient to prevent capillary action from bringing the salt back to the surface. If desired, a capillary barrier of clay or plastic can also be used if the slot is kept narrow. (The slot may have to be wider than a bulldozer blade for safety. The salt-affected soil should be placed only in the center of the excavation when backfilling.)

Groundwater is the critical issue in deep burial. Deep burial is most appropriate in arid areas with deep soils and groundwater. If groundwater is >100 ft and a plastic or clay cap is used, the potential risk of groundwater contamination is minimal.

The cost of deep burial techniques (if there is sufficient soil) is on the order of $2,000 for a modest-sized spill site. If the soil is shallow with underlying bedrock, the cost of deep burial can be ten times as great.

DISPOSAL WELL INJECTION

If produced water spillage is in a shallow depression with relatively loose soil, slurry and injection may be appropriate. In slurry/injection, freshwater is added to the spill site and mixed with the salt-affected soil. The slurry is then removed by vacuum truck and taken to a commercial disposal well permitted for oil and gas waste. This procedure is limited to very small spills where the slurry can be thin enough not to cause injection problems.

IN SITU AND *EX SITU* SOIL WASHING

Soil washing is a very fast but often costly operation which combines high mechanical energy agitation with application of chemical amendments in order to remove salts, including sodium, from the salt-affected soil. The soil is often, but not always, removed from its original location. Soil washing is typically performed by soil washing contractors who have appropriate equipment and are aware of the soil chemistry involved. Generally, the soil is kept in a chemically flocculated slurry during the entire process. Depending on soil texture, salinity, sodicity, and pH levels, salts are leached with increasingly less saline water to a certain salinity level before chemical amendments are added to begin to displace sodium. When the soil is at an acceptable salinity and sodicity level, it can be returned to its original location or taken to another site. Although this process is rapid and has the potential to be very thorough, it tends to be expensive.

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APPENDIX I

Precipitation/Evaporation Maps

SUMMARY

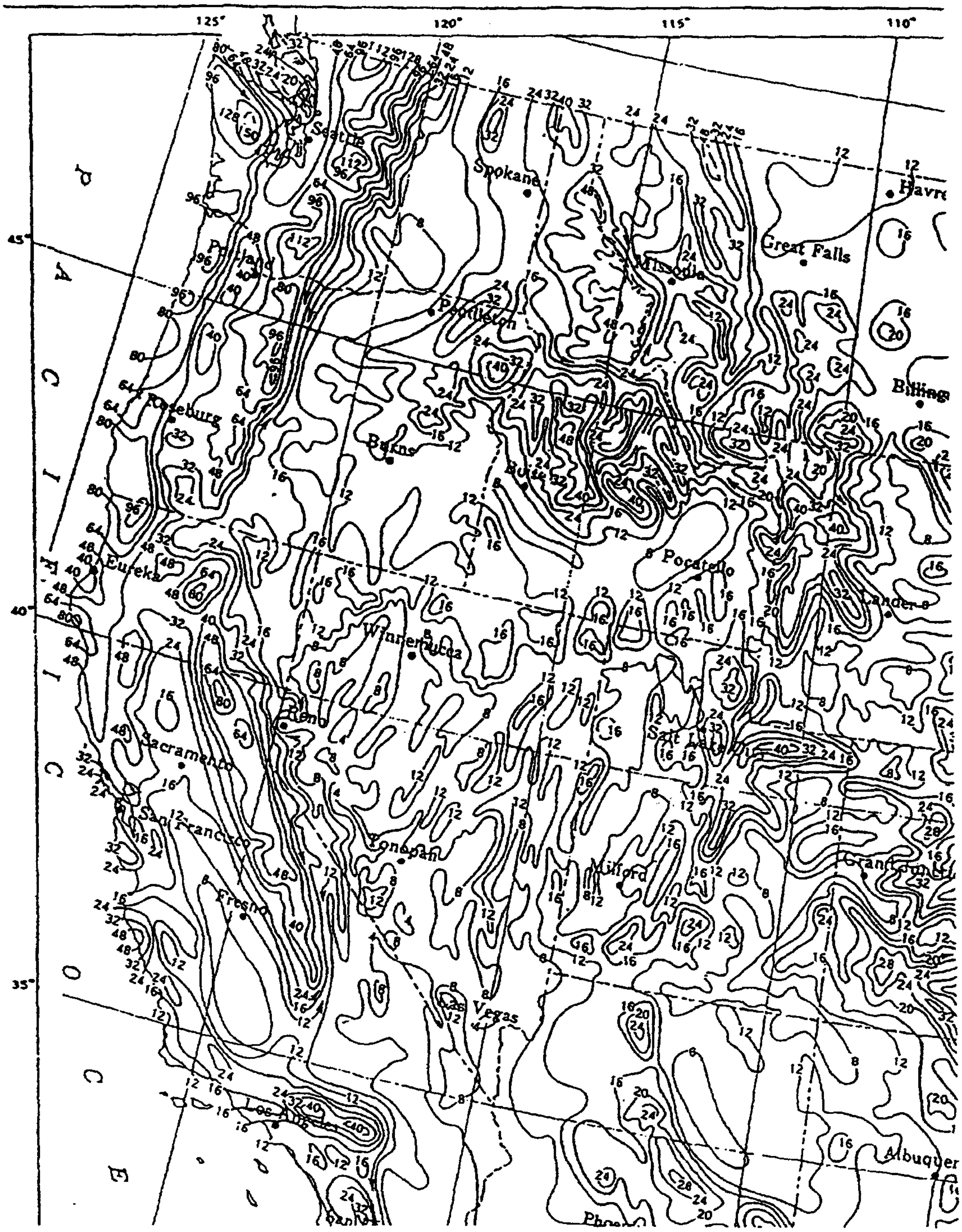
Appendix I contains both the precipitation and evaporation maps necessary to calculate the precipitation evaporation index (PEI). For any given location, the PEI (in inches) is calculated by subtracting the mean annual class A pan evaporation from the normal annual total precipitation. For example, the PEI in Dallas, Texas, would be 80 inches - 32 inches = -48 inches, which represents an annual net deficit of 48 inches of water per year. The PEI is therefore -48 inches. The following maps are contained in this appendix:

Notes:

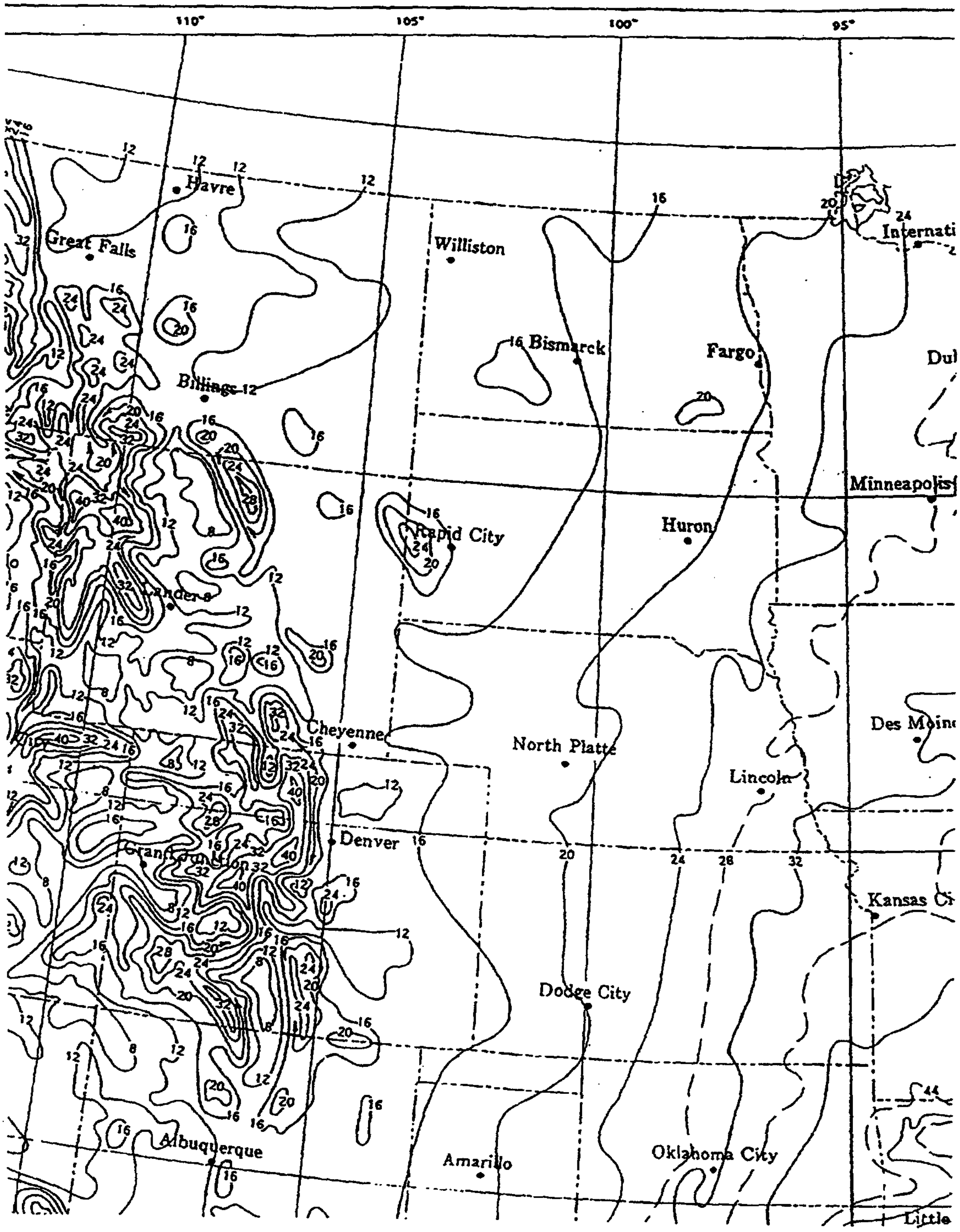
All maps reproduced from U.S. Department of Commerce, 1979.
All contours in inches.

* USA Normal Annual Total Precipitation Maps are based on the period of 1931–1960.

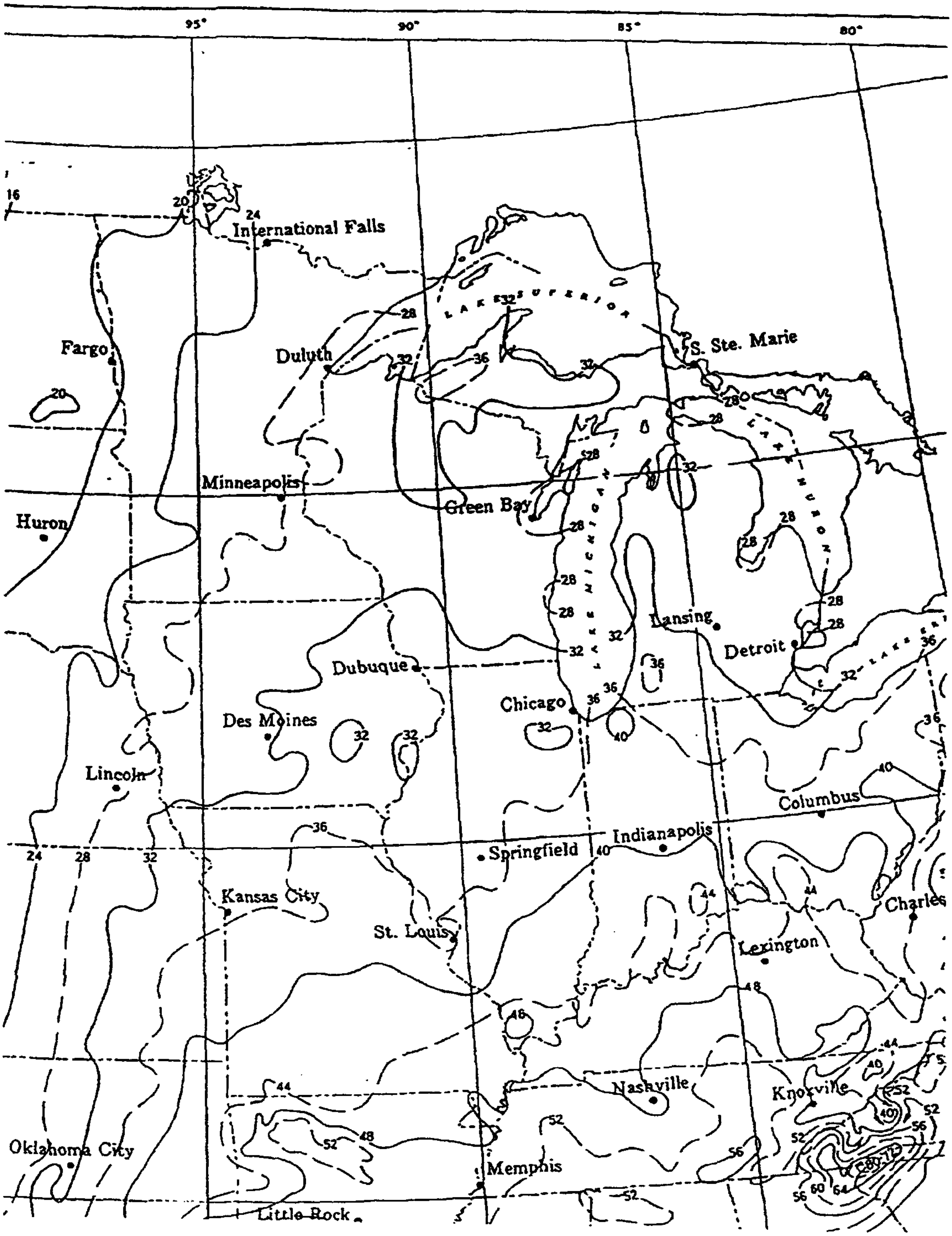
** USA Mean Annual Class A Pan Evaporation Maps are based on the period of 1946–1955.



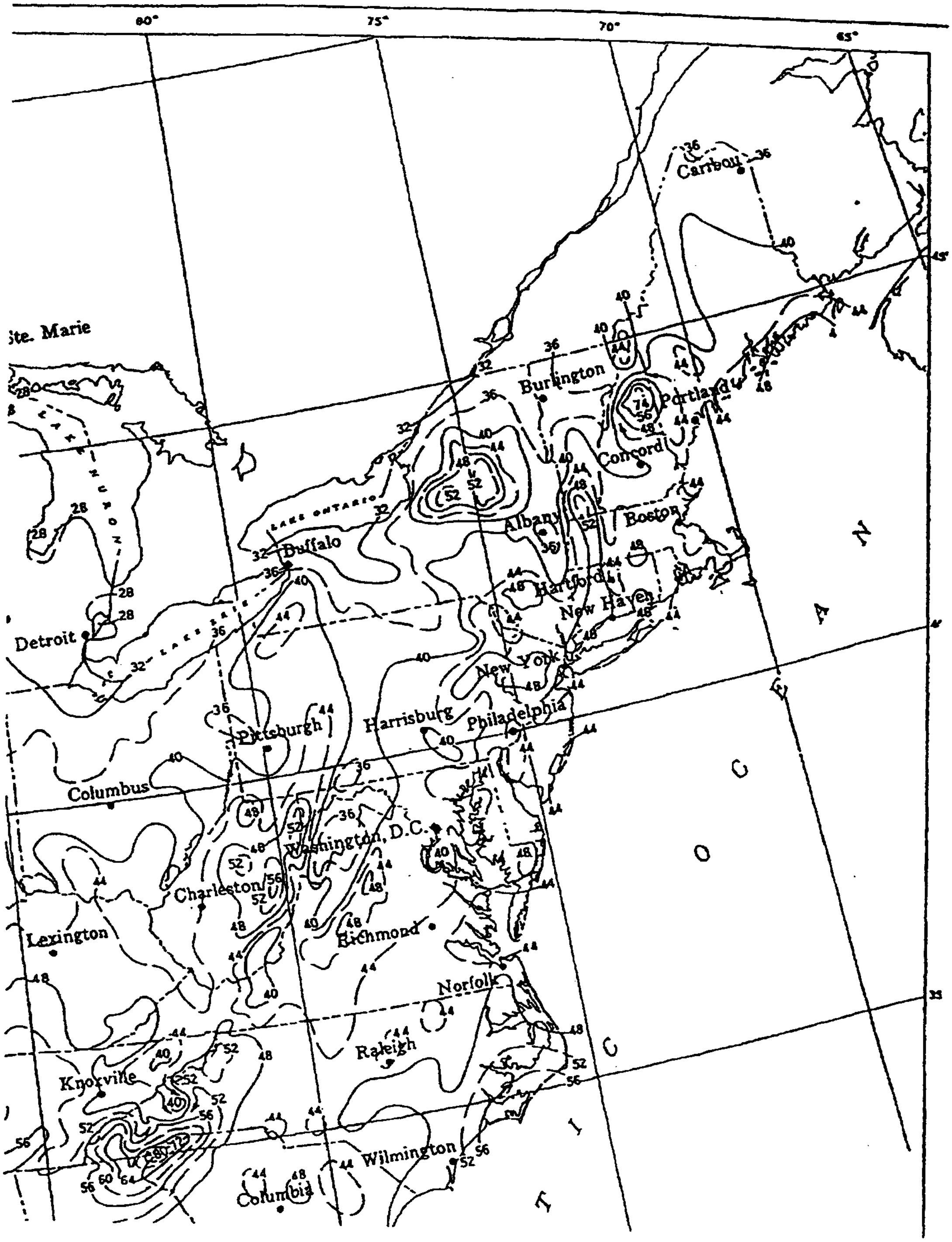
Northwest USA Normal Annual Total Precipitation Map



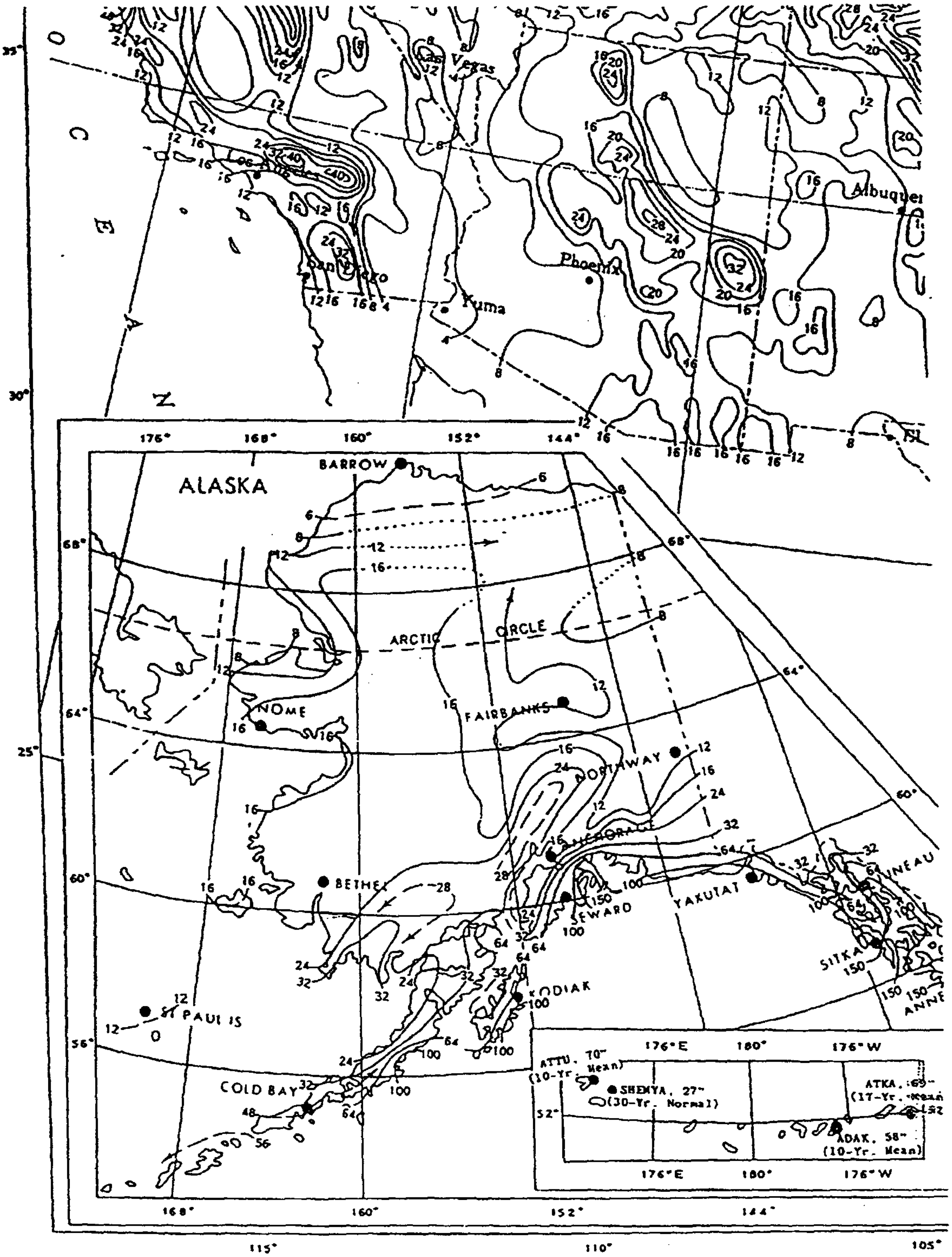
Central Northwest USA Normal Annual Total Precipitation Map



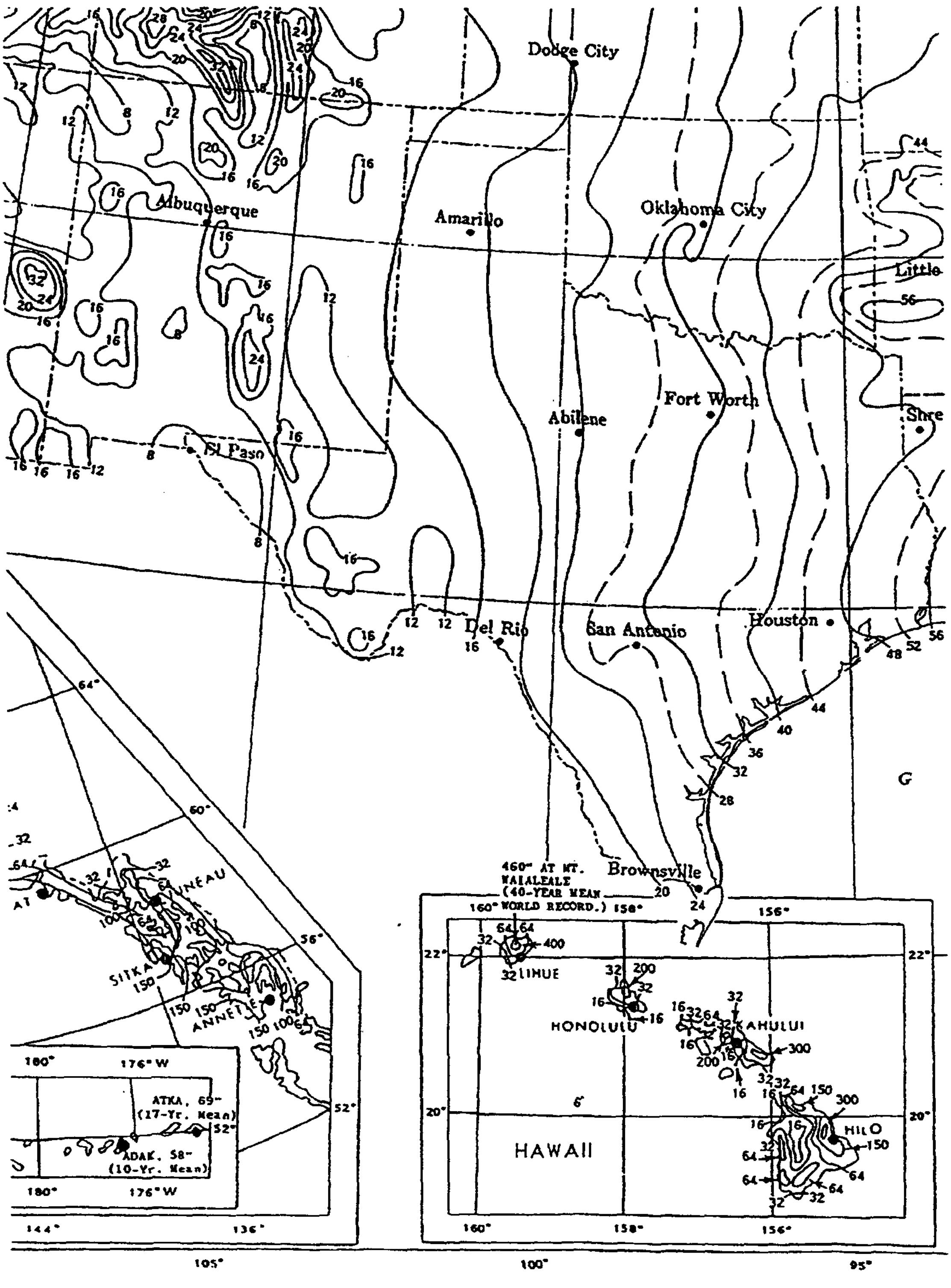
Central Northeast USA Normal Annual Total Precipitation Map



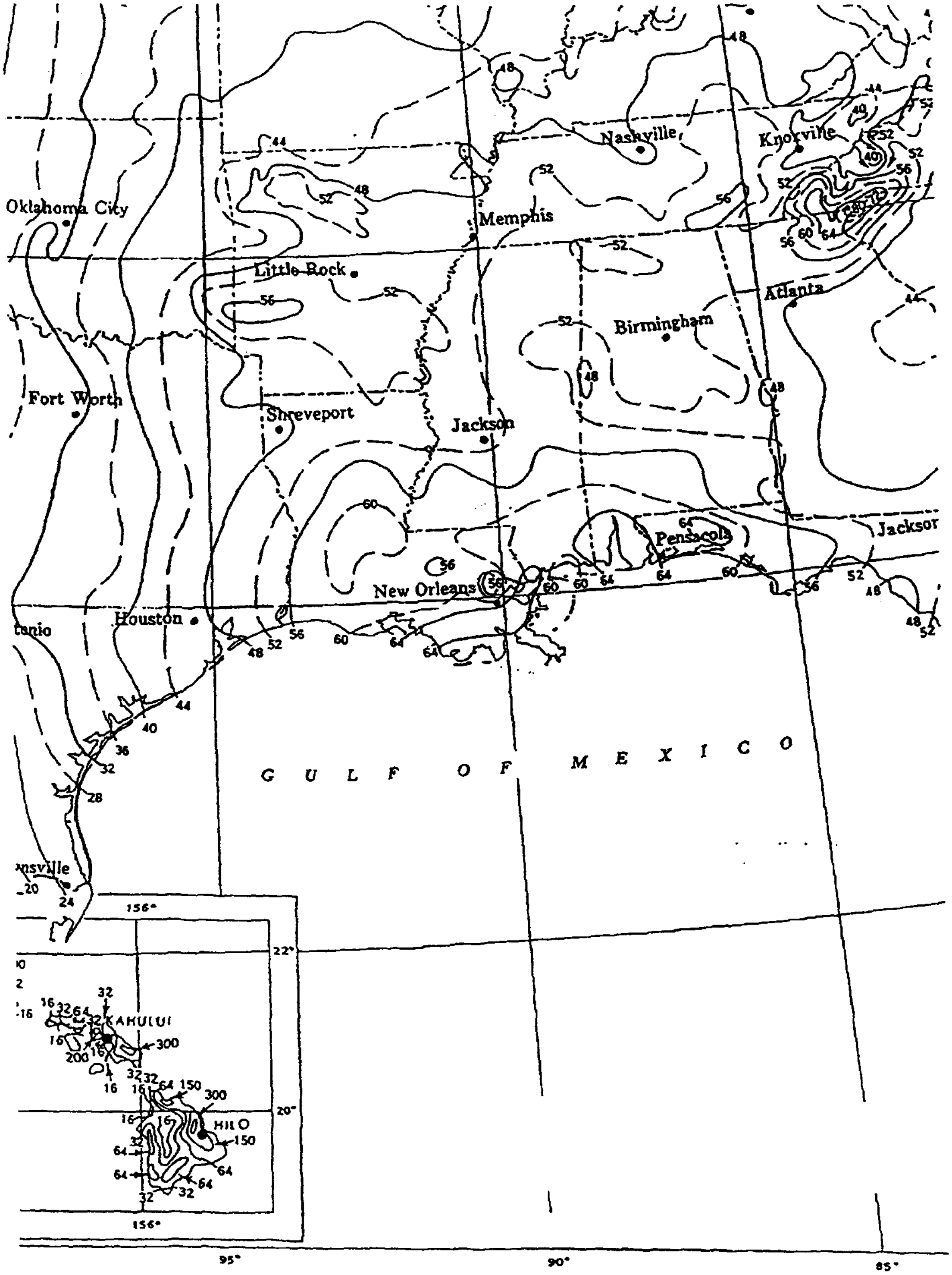
Northeast USA Normal Annual Total Precipitation Map



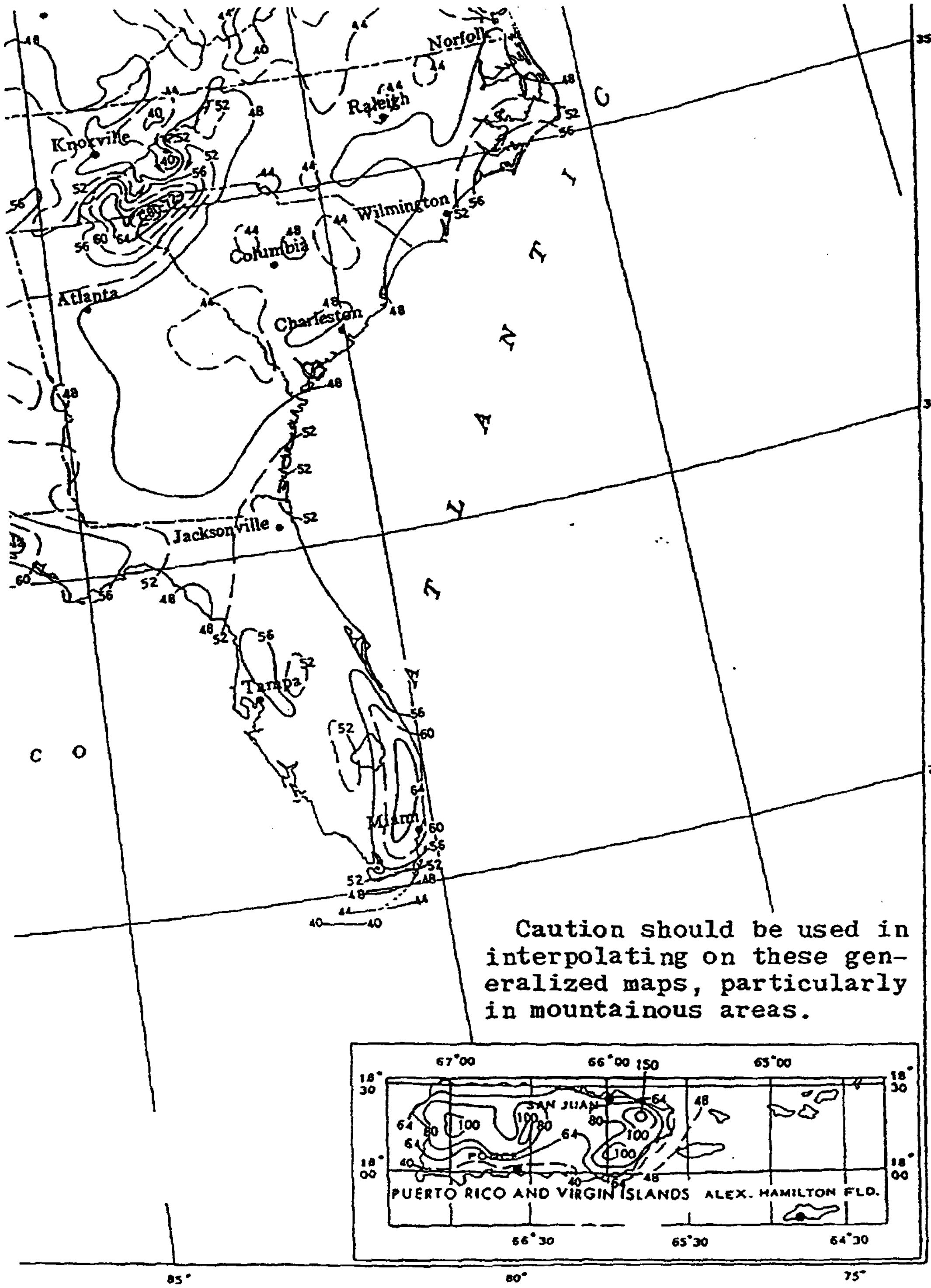
Southwest USA Normal Annual Total Precipitation Map



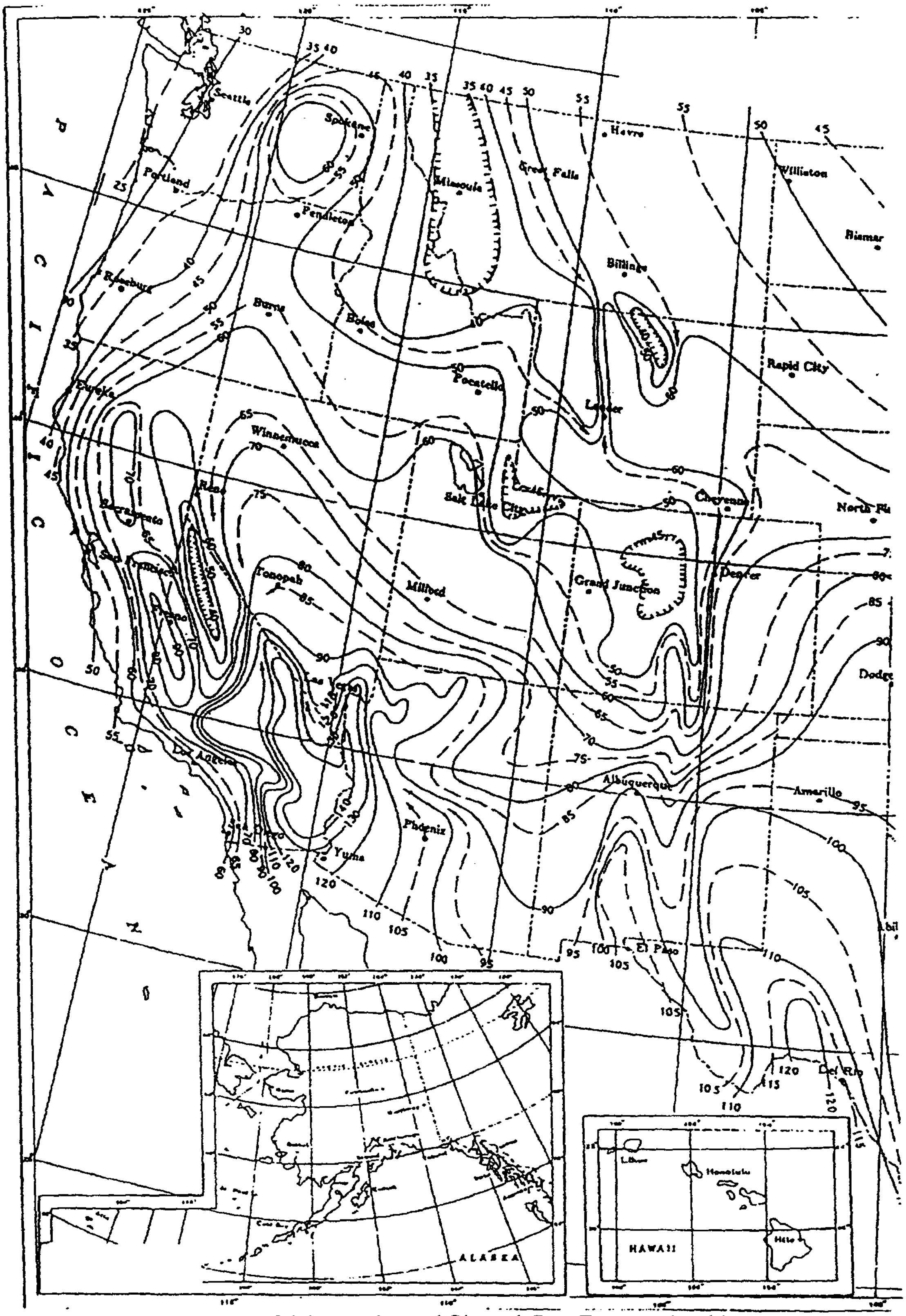
Central Southwest USA Normal Annual Total Precipitation Map



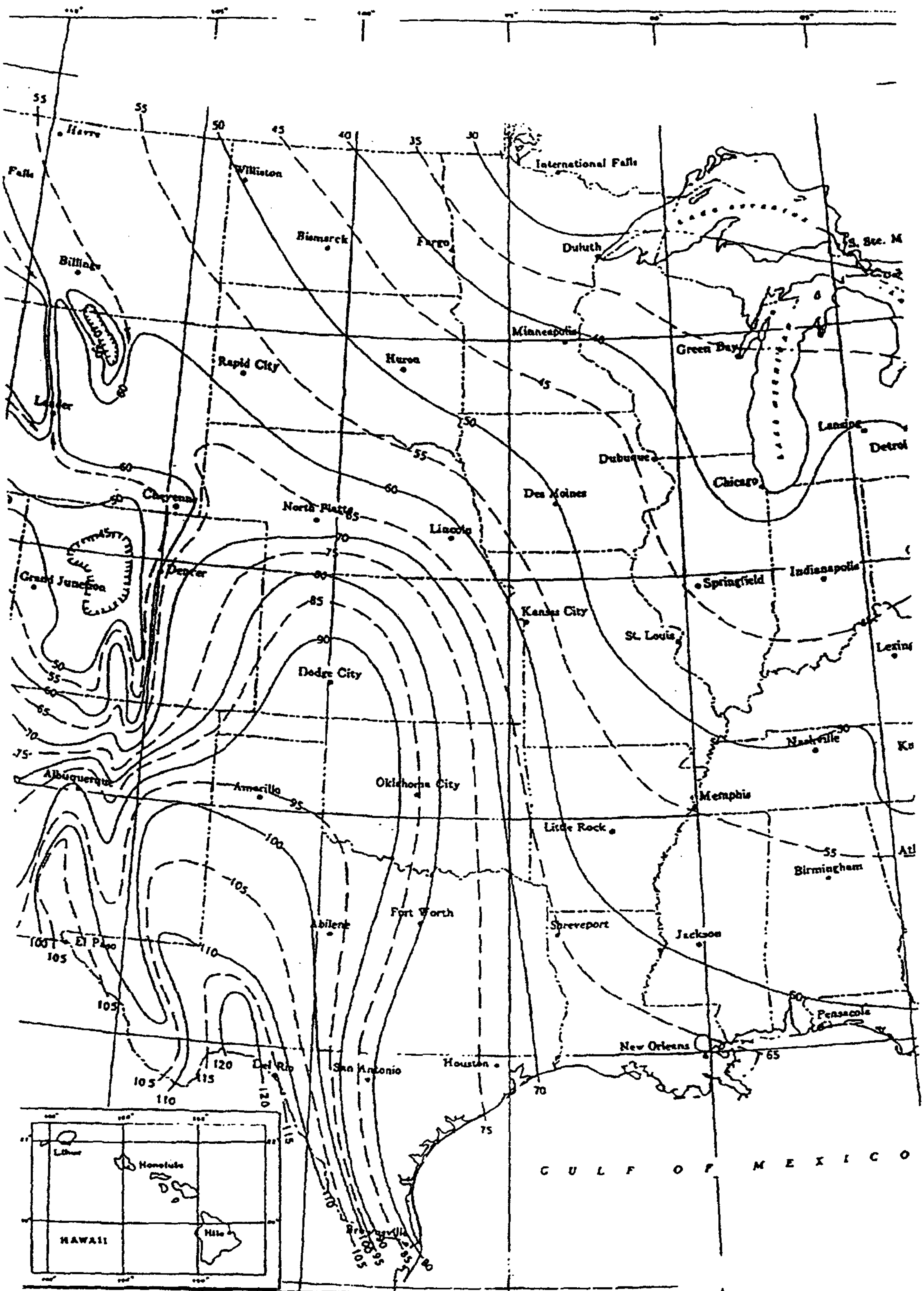
Central Southeast USA Normal Annual Total Precipitation Map



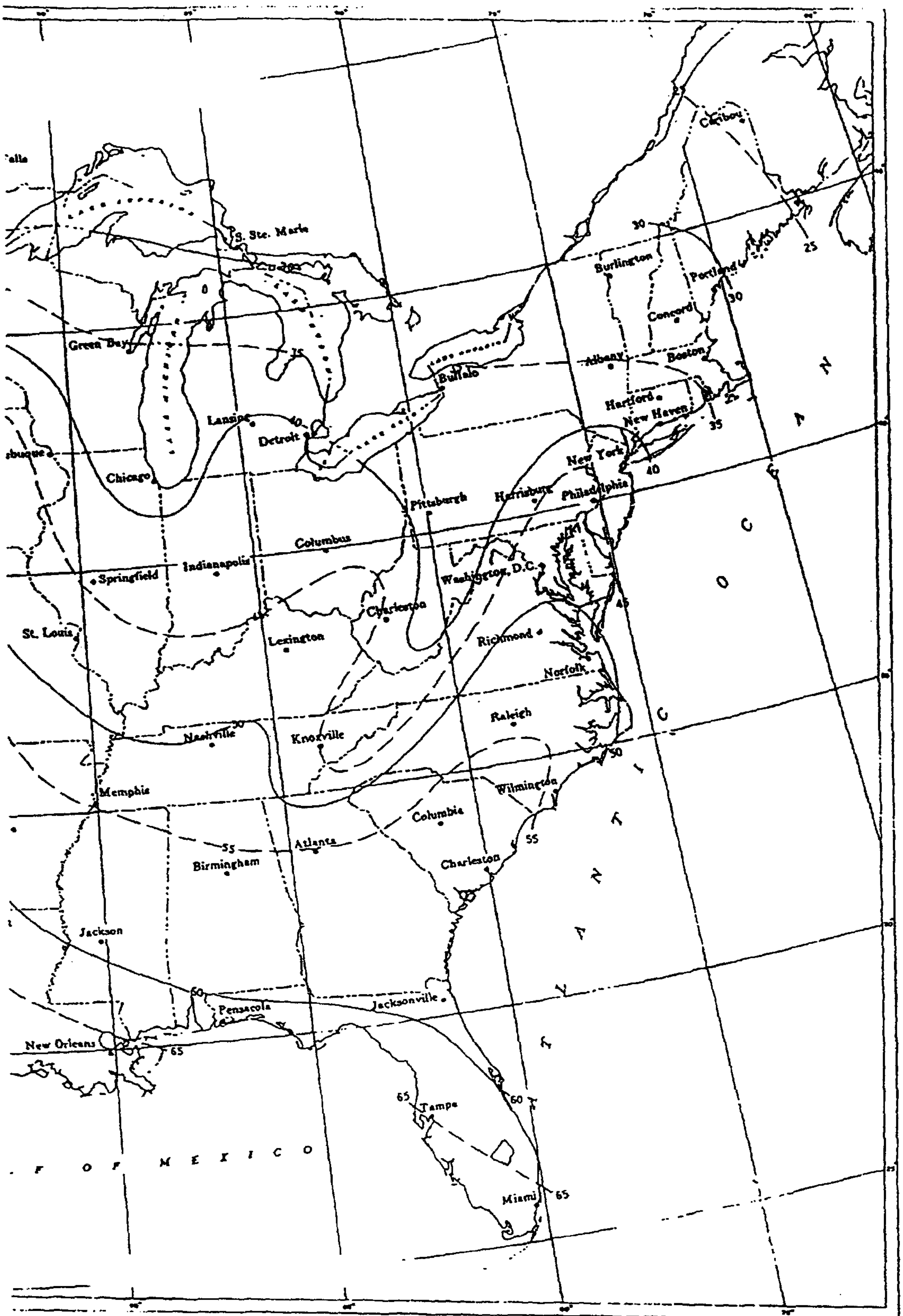
Southeast USA Normal Annual Total Precipitation Map



Western USA Mean Annual Class A Pan Evaporation Map



Central USA Mean Annual Class A Pan Evaporation Map



Eastern USA Mean Annual Class A Pan Evaporation Map

APPENDIX J

Laboratory Interactions

SUMMARY

Appendix J contains information pertaining to interactions with analytical laboratories. The following topics are covered in this appendix:

- Suggested Laboratory Analyses and Method Citations for Soils
- Approximate Analytical Laboratory Data Correlations
- Sample Quantities Commonly Requested by Analytical Laboratories
- Considerations for Selecting a Laboratory to Analyze Soil Samples
- Chain-of-Custody Usage
- Sample Label Usage
- Chain-of-Custody Record (form)

SUGGESTED LABORATORY ANALYSES AND METHOD CITATIONS FOR SOILS

Parameter	Source	Method
Percent Moisture (dry wt. basis) As Received	1	7-2.2.2.2
Saturated Paste Extract Preparation	1	62-1.3.2.1
Saturation Percentage Moisture Content	1	62-1.3.2.1
pH (saturated paste)	1	60-3.1
Electrical Conductivity (EC) of Saturated Paste Extract (EC_e)	1	62-2.2
EC of Water (EC_w)	2	120.1
Sodium in Water (or saturated paste extract)	2	200.7
Calcium in Water (or saturated paste extract)	2	200.7
Magnesium in Water (or saturated paste extract)	2	200.7
Potassium in Water (or saturated paste extract)	2	200.7
Sodium Adsorption Ratio (SAR)	NA	Calculation
Carbonate/Bicarbonate in Water (or saturated paste extract)	1	62-3.4
Chloride in Water (or saturated paste extract)	2	325.2
Sulfate in Water (or saturated paste extract)	2	375.4
Exchangeable Sodium	1	72-3
Exchangeable Sodium Percentage (ESP)	NA	Calculation
Cation Exchange Capacity (CEC)	1	57-3
Particle Size Distribution	3	15-5
Fertility	4	Varies
Oil and Grease (O&G) (could analyze TPH as an alternative in certain locations)	5	9017A
Total Petroleum Hydrocarbons (TPH) (could analyze O&G as an alternative in certain locations)	2	418.1
Soluble Boron	6	10-3.8
Acid (sulfur) Requirement to pH 8.3	7	Titration
Lime (calcium carbonate) Requirement to pH 7.0	7	Titration

Sources:
1 Black, 1965.
2 EPA, 1979.
3 Klute, 1986.
4 Local agricultural laboratory calibrated to fertilizers.
5 EPA, 1994; Deuel, 1993.
6 Page, 1982.
7 Deuel, 1995.

APPROXIMATE ANALYTICAL LABORATORY DATA CORRELATIONS

The following correlations are only approximations and depend on a number of assumptions and in some instances, equilibrium conditions in the soil. If analytical data from the same sample are substantially divergent from these approximations, the analytical laboratory can be requested to address the differences. These are general relationships which apply under most circumstances, but are not absolute. Laboratories will often reanalyze samples at the request of the client.

(EC in mmhos/cm)(613) ~ TDS in mg/L for EC between 0.1 and 5 mmhos/cm

(EC in mmhos/cm)(800) ~ TDS in mg/L for EC above 5 mmhos/cm

(EC in mmhos/cm)(10) ~ Sum of cations or anions in meq/L

Sum of cations (Ca^{+2}, Mg^{+2}, K^+, Na^+) in meq/L ~ Sum of anions (Cl^-, SO_4^{-2}, HCO_3^-, CO_3^{-2}) in meq/L

Ca^{+2} in meq/L usually > Mg^{+2} in meq/L

CO_3^{-2} measurable if pH above 9.0

CO_3^{-2} not detected if pH below 7.0

ESP ~ SAR when either are below 40 and soil is at equilibrium

(ESP)(2) ~ SAR when ESP about 65 and soil is at equilibrium

ESP usually >15 when pH >9.0

SAR usually >12 when pH >9.0

SAMPLE QUANTITIES COMMONLY REQUESTED BY ANALYTICAL LABORATORIES

Water samples	1 liter for salts and 1 additional liter for O&G or TPH
Soil samples	500 grams or 0.5-liter volume

CONSIDERATIONS FOR SELECTING A LABORATORY TO ANALYZE SOIL SAMPLES

Soil is a very difficult matrix to analyze. It is essential that laboratory managers and technicians have both specific training and experience in soils analyses if valid analytical results are to be expected. It is quite common for different analytical laboratories to obtain substantially different (sometimes orders of magnitude) analytical results from similar soil samples. This occurs because (1) soil samples are typically much more difficult to analyze than liquid samples because constituents to be measured must often be converted from the solid or semi-solid form into a dissolved form for analyses, (2) compared to analysis of liquids, consistent application of soil analytical procedures requires more interpretative judgment and experience, and (3) unlike commonly available water reference samples, there are no commonly available soil reference samples for laboratories to test in order to assure uniformity among laboratories. Although most laboratories can achieve good precision (consistent results due to consistent handling and analysis of samples), it is difficult for them to determine if they are achieving accuracy (the correct result) since there are few, if any, commonly available reference samples to help laboratories determine if they are obtaining the same results as other laboratories.

Choosing an appropriate analytical laboratory represents an important investment in remediating salt-affected soils. It is advisable to tour at least two analytical laboratories prior to making a selection. Once an analytical laboratory has been selected it is advisable to continue to use that laboratory for as many related jobs as possible. The best opportunity to generate a consistent database for remediating salt-affected soils without additional variations being introduced by use of different laboratories is by continued use of the same analytical laboratory. In addition, preferred customer discounts can often be obtained, and laboratory staff can provide important insights into data interpretations. Using an analytical laboratory which is capable of defending its data, if required, also is highly desirable. The following may be considered prior to retention of an analytical laboratory for sample analysis:

- Location
- Organization, ownership, structure, and stability
- Client references
- Manager training and experience
- Staff training, experience, and turnover
- Certifications
- Quality assurance/quality control (QA/QC) program and implementation
- Analytical equipment
- Housekeeping practices (cleanliness)
- Business policies, including prices, turnaround time, and sample storage
- Work schedule (Monday through Friday, weekends, and/or nights)
- Experience in handling soil and oily samples, and what analyses performed (citations)
- Customer services, including sampling and sample pick-up
- Customer supplies, including sample containers, chain-of-custody forms, and EC and pH standards
- Experience, including preparation of a saturated paste extract, CEC, and soil texture*
- Capabilities, including list of analytical method citations
- Fee schedule, including volume discounts, rush rates, and sample storage
- Fertility analysis practices and reporting**

* Ask for a copy of the saturated paste preparation procedure used by their technicians.

** Many state university laboratories and laboratories serving fertilizer dealers will provide detailed fertilizer recommendations based on soil sample data.

CHAIN-OF-CUSTODY USAGE

The chain-of-custody form is a document which records the name of the individual who protected the collected samples from tampering, and the time period in which they were responsible. The chain-of-custody form is attached to the container in which one or more samples are contained (e.g., box or ice chest), provides an inventory and other information on the samples within the container, and remains with the samples from the time of sampling through delivery to the analytical laboratory. The chain-of-custody form is used mostly with regulated samples, but may become important anytime the validity of any analytical data is challenged. For this reason, using a chain-of-custody form is an excellent precaution to take in conjunction with environmental samples even if the samples are not regulated. The analytical laboratory will typically supply chain-of-custody forms and can explain proper usage.

SAMPLE LABEL USAGE

A sample with a missing or illegible label is of little value. The analytical laboratory will usually supply sample labels designed to withstand field conditions. An ink resistant to moisture is recommended. The label should contain the following information:

- Sample ID (can clearly describe its location or be coded)
- Date and time collected
- Client name
- Sampler name or signature

APPENDIX K

Chemical Amendments and Application Procedures

SUMMARY

Appendix K provides background for the application of chemical amendments. It includes the following:

- Chemical Amendments for Relatively Neutral Soils
- Chemical Amendments for Acid Soils (pH <5.5)
- Chemical Amendments for Alkaline Soils (pH >8.5)
- Other Chemical Amendments
- Mixing Chemical Amendments

CHEMICAL AMENDMENTS AND APPLICATION PROCEDURES

Chemical amendments are used to displace sodium from soil clays. In a dilute electrolyte solution, [low electrical conductivity (EC)] soil clays with more than 10% to 15% sodium on cation exchange sites will cause soil dispersion. In smectitic soils, the critical exchangeable sodium percentage (ESP) is as low as 5%. The dispersion of soil particles results in structural disintegration and a reduction of drainage which greatly impedes remedial efforts. Dispersion can be avoided by applying a chemical amendment before leaching begins. Chemical amendments will prevent the soil from dispersing until the sodium has been displaced from cation exchange sites. As the ESP decreases, the need for soil electrolytes (e.g., total soluble anions and cations) also decreases. After the ESP has decreased to less than 10% to 15%, the leaching in most soils can be completed without concern for additional dispersion.

The chemical amendments discussed below include materials to be used at relatively neutral pH (5.5 to 8.5), and in more acid (pH <5.5) and more alkaline (pH >8.5) solutions. A variety of chemical of amendments typically applied as both solids and liquids are discussed below (see also Table K-1).

Concentrated amendment solutions (e.g., liquid chemical amendments and fertilizers), may shorten the remediation time and require less water compared to solid amendments like gypsum. However, they are typically more expensive, thus making them less practical in most situations than solid amendments. Concentrated amendments can often be applied with irrigation water, but it is important that the irrigation process equally distribute the chemical amendment over the affected area.

With the exception of the acidifying amendments and calcium nitrate, an efficiency correction factor should be used for increasing the amount of the chemical amendment applied. Often, unrepresentative sampling and inaccurate analytical results cause chemical amendment calculations to underestimate the amount of amendment actually needed. Practice has shown that about 1.25 times the amount calculated using the laboratory analyses will provide sufficient chemical amendment to accomplish remediation objectives. As noted below, regardless of other chemical amendments used, a final top dressing of gypsum will provide long-lasting protection of the soil surface while the soil recuperates.

CHEMICAL AMENDMENTS FOR RELATIVELY NEUTRAL SOILS

GYPSUM ($CaSO_4{:}2H_2O$)

Gypsum is the most commonly used amendment. It dissolves slowly to provide low but adequate electrolyte (as expressed by EC) and a slow release of calcium. Various particle sizes of gypsum physically keep pore sizes open while soil chemistry is slowly converted from the dispersive to aggregative condition. The solubility of gypsum increases as salt concentration increases—gypsum is twice as soluble when EC is 15 mmhos/cm compared to when EC is 3.5 mmhos/cm, and is about four times more soluble when ESP is 100% compared to when ESP is near 0%. Because of low solubility, gypsum must be mechanically mixed into the soil to be effective. For various reasons the solubility of industrial-grade gypsum is several times more than mined gypsum. One ft of water is required to dissolve each 10 ton/acre application of gypsum under optimal dissolving conditions (e.g., high EC, high ESP, and gypsum in powdered form).

Gypsum is normally applied by broadcasting, followed by incorporation via discing. Gypsum should be mixed throughout the upper 2 ft of soil (when possible) if salts occur throughout that

Table K-1. Chemical Amendments Used to Remediate Salt-Affected Soils.

Amendment	Chemical Formula	Commercial Availability	Purpose	Positive Attributes	Application Method	Follow-up Procedures	Warnings or Cautions
Bulk or sack gypsum/calcium sulfate	$CaSO_4{:}2H_2O$	Bulk or sack	Sodium displacement	Slow release; residual benefits	Surface spread, then till	Light surface application	Poor solubility; about 1 vertical ft water required to dissolve about 50 pounds of gypsum/100 sq ft of very salt-affected soil
Calcium chloride	$CaCl_2{:}2H_2O$	Bulk, sack, or liquid	Sodium displacement; supplies Ca	Quick acting; faster results	Slurry or dissolved in water	Surface apply gypsum for residual benefit	Increases chlorides; protect shallow groundwater
Calcium nitrate	$Ca(NO_3)_2$	Bulk, sack, or liquid	Fertilizer; sodium displacement; supplies Ca and N	Quick acting; enhances biodegradation and vegetation growth	Broadcast on surface and incorporate, or apply as liquid	Surface apply gypsum for residual benefit	Protect drinking water, nitrate toxic to some animals
Calcium carbonate	$CaCO_3$	Bulk or sack	Soil alkalizer; sodium displacement; supplies Ca	Good for use in acidic soils	Broadcast on surface	Surface apply gypsum for residual benefit	Will not work in alkaline soils
Dolomite	$CaCO_3{:}MgCO_3$	Bulk or sack	Soil alkalizer; sodium displacement; supplies Ca and Mg	Good for use in acidic soils	Broadcast on surface	Surface apply gypsum for residual benefit	Will not work in alkaline soils
Calcium oxide	CaO	Sack	Soil alkalizer; sodium displacement	Quick acting; good for use in acidic soils	Broadcast on surface, then incorporate; co-apply with gypsum	Surface apply gypsum for residual benefit	Will not work in alkaline soils; can burn skin and eyes, reactive with water; overuse can cement soil; determine quantity by titration
Calcium hydroxide	$Ca(OH)_2$	Bulk or sack	Soil alkalizer; sodium displacement	Quick acting; good for use in acidic soils	Broadcast on surface, then incorporate; co-apply with gypsum	Surface apply gypsum for residual benefit	Will not work in alkaline soils; can burn skin and eyes, reactive with water; overuse can cement soil; determine quantity by titration
Sulfur	S	Bulk or sack	Soil acidifier; sodium displacement	Slow release	Apply as slurry or powder, then incorporate; co-apply with gypsum	Surface apply gypsum for residual benefit	Corrosive to metals after oxidation; requires water and thiobacillus; determine quantity by titration
Sulfuric acid	H_2SO_4	Bulk, drum, or liquid	Soil acidifier; sodium displacement	Rapid response	Apply liquid to surface, then incorporate; co-apply with gypsum	Surface apply gypsum for residual benefit	Corrosive to metals; use with caution; determine quantity by titration
Aluminum sulfate	$Al_2(SO_4)_3{:}18H_2O$	Bulk or sack	Soil acidifier; enhanced drainage; sodium displacement	Rapid response in developing soil macropores	Broadcast on surface, then incorporate; co-apply with gypsum	Surface apply gypsum for residual benefit	Can become toxic to plants at pH <5; determine quantity by titration;
Iron sulfate	$FeSO_4{:}7H_2O$	Sack	Soil acidifier; drainage enhancement; sodium displacement	Provides iron and sulfate to vegetation	Broadcast on surface, then incorporate; co-apply with gypsum	Surface apply gypsum for residual benefit	Determine quantity by titration
Diammonium phosphate	$(NH_4)_2(HPO_4)$	Bulk or sack	Fertilizer; sodium displacement; soil binder	Provides nitrogen and phosphate to vegetation	Broadcast on surface, then incorporate; co-apply with gypsum	Surface apply gypsum for residual benefit	Very water soluble; protect shallow groundwater
Displacer polymers	Various chemicals	Bucket or drum	Drainage enhancement; aggregate stabilizer	Fast acting	Apply sodium displacer first, then broadcast or spray on surface, incorporate, allow to dry	Surface apply gypsum for residual benefit	Soil must be allowed to dry after wetting for polymers to bind soil

depth. In most reclamation circumstances, at least 50% of the gypsum applied should be placed within the upper 1 ft.

A final top dressing of gypsum is suggested to protect the soil surface from dispersion, regardless of the principal type of chemical amendment used. A top dressing of gypsum provides the slow release of calcium to the uppermost clay particles which incorporated chemical amendments may have bypassed. The following top dressing rates are suggested in pounds per acre: coarse, 250; medium 500; fine 1,500. Some practitioners recommend that the maximum single application of gypsum not exceed 5 ton/acre for each 6-inch depth into which it will be incorporated. If additional gypsum is required, it can be applied at 6-month intervals until all required gypsum has been applied.

Gypsum can also be applied as a slurry. Gypsum rocks placed along the irrigation water route line will slowly dissolve, supplying calcium to the irrigation water.

CALCIUM CHLORIDE ($CaCl_2$:$2H_2O$) AND CALCIUM NITRATE [$Ca(NO_3)_2$]
Calcium chloride and calcium nitrate are very soluble and provide solutions of high electrolyte concentration. The reaction time of these chemicals is very rapid, and they penetrate the soil at approximately the same rate as water, except for the fraction that becomes adsorbed onto clay. For this reason, they provide for rapid remediation as long as the solution they are in can penetrate the soil.

These chemicals are typically applied as a slurry or as dissolved ions in water. They are preferred by remediation contractors because they show rapid results. Gypsum may be co-applied to provide more residual benefits, especially at the soil surface.

Because the anions of calcium nitrate (NO_3^-) and calcium chloride (Cl^-) are very mobile and move at the same rate as water, it is very important to have an understanding of where application and subsequent leaching water will go. If the receiving groundwater is to be sacrificed (because it is already too salty to reclaim), this may be an acceptable location for additional chloride (and sodium). However, it is not usually an acceptable location for nitrate, as noted below.

Calcium nitrate supplies nitrogen in a plant-available form and also improves the biodegradation rate of petroleum hydrocarbons. However, the amount applied may exceed the ability of the plants or microbes to consume it before it leaches into groundwater. Only 10 mg/L nitrate is allowed in drinking water due to its extreme toxic effects on animals. Therefore, nitrate must be contained to the extent possible and not allowed to migrate overland into surface water or leach into groundwater. This is difficult because nitrate is one of the most mobile ions in soil. As a general rule, use of calcium nitrate is not advised in coarse-textured soils, and only with caution in medium- and fine-textured soils. It should never be used close to surface water, or where nitrate can migrate into usable groundwater.

Calcium chloride and calcium nitrate are expensive, except that sometimes calcium chloride can be obtained as a waste byproduct. Both are also corrosive, and consideration should be given to the type of application equipment to be used. The amount of calcium chloride and calcium nitrate equivalent to 1 pound of gypsum is 0.85 and 0.95 pounds, respectively. This means that 0.85 pounds of calcium chloride and 0.95 pounds of calcium nitrate can displace the same amount of sodium as 1 pound of gypsum in a soil if the entire amount of each chemical is dissolved and used appropriately.

CHEMICAL AMENDMENTS FOR ACID SOILS (PH <5.5)

LIMESTONE ($CaCO_3$) AND DOLOMITE ($CaCO_3$:$MgCO_3$)

Limestone (calcium carbonate) and dolomite are only effective in acid soils because these amendments are not very soluble at alkaline pH levels. The soil pH should be less than 6.0 if limestone is to be used. These liming agents are usually applied as a powder or in crushed form, but can also be applied as a slurry. Dolomite (also known as dolomitic limestone) is slightly less soluble than calcite and also supplies magnesium (Mg^{++}), which is a divalent cation capable of displacing sodium, and is an important plant nutrient. In general, soils west of a line running due north from Houston, Texas, are not suitable for lime applications due to their alkalinity, whereas many soils east of that line are acidic and respond very well to lime.

Both lime and dolomite are relatively inexpensive. They are easy to apply and not corrosive. In addition, they constitute excellent pH buffers in the soil, and overapplication is not as much of a concern as it is for calcium oxide, calcium hydroxide, and the acidifying amendments.

CALCIUM OXIDE (CaO) AND CALCIUM HYDROXIDE [$Ca(OH)_2$]

Calcium oxide (burned lime, quick lime, oxide, or burned oyster-shell lime) and calcium hydroxide (hydrated lime or slaked lime) are concentrated liming agents. Their use is not recommended in a general sense because they may cause some soil cementation. However, they are very fast-acting and can be used to raise the pH of acid soils. Both present handling problems and cause a burning sensation when they come into contact with water (or perspiration). They are also serious hazards to the eye and have a high heat of reaction. When calcium oxide first comes into contact with water, it can actually raise the temperature of nearby paper and wood to ignition temperature. Calcium oxide and calcium hydroxide are, respectively, 1.6 and 1.25 times as effective by weight as calcium carbonate for neutralizing soil acidity.

CHEMICAL AMENDMENTS FOR ALKALINE SOILS (PH >8.5)

SULFUR (S)

Elemental sulfur must be oxidized in the soil to be effective. In the presence of certain types of bacteria which occur in most soils, the sulfur oxidizes and combines with soil-pore water to become sulfuric acid. The soil must contain sufficient water to assist in the microbial oxidation of the sulfur. The acid dissolves calcium carbonate in the soil and releases calcium for exchange with sodium on exchange sites. The soil pH is simultaneously decreased as the hydrogen ions are released from the sulfuric acid. Remediation time usually requires several months.

Sulfur can be applied at the soil surface as a dry powder, then mechanically incorporated into the soil. However, the dust may be problematic. Sulfur can also be applied as a slurry, typically as a solution of about 55% to 60% sulfur. Typically, sulfur should not be applied to a soil which does not contain calcium carbonate.

It is important to not overapply the acidifying amendments, and generally, they should be applied only when calcium carbonate is present in the soil layers being treated. Incorporation of manure with acidifying amendments has been especially efficient at improving the soil for plant growth and improving drainage of salt-affected soils.

SULFURIC ACID (H_2SO_4)
Sulfuric acid also reacts with calcium carbonate to produce a soluble source of calcium and sulfate. Water intake and percolation rates are increased due to increased electrolyte concentration and dissolution of aluminum and iron compounds which promote aggregation.

As a liquid, sulfuric acid can move at a rate in the soil similar to the rate of water percolation. Because downward movement in soil may be slow if the soil is dispersed, incorporation of elemental sulfur to greater depths may be more rapid. However, elemental sulfur must be in oxidizing conditions to form sulfuric acid.

Sulfuric acid is generally inexpensive because it can be obtained as an industrial byproduct. Approximately 3.06 pounds of sulfuric acid is equivalent to 1 pound of elemental sulfur. However, special handling and equipment may be required. Caution should be exercised when working with sulfuric acid and because it is corrosive, selection of application equipment should be appropriate.

Sulfuric acid is less damaging to the soil when applied in concentrated form directly to the soil, instead of as a diluted solution. It can also be applied by spray equipment, or in irrigation water.

ALUMINUM SULFATE [$Al_2(SO_4)_3$:$18H_2O$] AND IRON SULFATE ($FeSO_4$:$7H_2O$)
Aluminum sulfate and iron sulfate act like dilute sulfuric acid in the soil, and they supply a trivalent cation (Al^{+++}) or divalent cation (Fe^{++}). Both aluminum and iron are very strong aggregating agents and can rapidly create macropores in a soil. Although iron is an important plant nutrient, especially at high pH where it is not very soluble, aluminum has no fertility value, and in fact, can be toxic when the pH is less than 5.0.

These chemicals would be expected to work faster than elemental sulfur, and at about the same rate as sulfuric acid, calcium nitrate, or calcium chloride. Approximately 6.94 and 8.69 pounds of aluminum sulfate and iron sulfate, respectively, are equivalent to 1 pound of elemental sulfur. In other words, 6.94 pounds of aluminum sulfate and 8.69 pounds of iron sulfate can displace the same amount of sodium in soil as 1 pound of elemental sulfur if the entire amount of each chemical reacts or is dissolved and used appropriately.

OTHER CHEMICAL AMENDMENTS

POLYMERS
Several organizations manufacture and distribute or use their own staff to apply salt-remediation materials which contain polymers. There are several different types of polymers (such as polyvinyl alcohols, polyacrylamides, and natural plant polymers) currently on the market. Initial studies indicate that polymers may aid in remediation of salt-affected soils by rapidly aggregating soil particles. These polymers are usually applied in a mix of other salt-remediating chemical amendments, most often being calcium nitrate.

PROPRIETARY CHEMICALS
A number of organizations are working on proprietary chemical amendments for salt remediation. These materials should not be given widespread use without prior performance demonstrations.

DIAMMONIUM PHOSPHATE [$(NH_4)_2(HPO_4)$]
Although technically a fertilizer, diammonium phosphate provides a unique opportunity to speed remediation of a salt-affected soil. The ammonium ion (NH_4^+) will behave similarly to potassium (K^+) as a mild displacing agent for sodium. However, the ammonium is also a plant-available

form of nitrogen. The phosphorus supplied with diammonium phosphate is also an important plant nutrient and has been demonstrated to help plants withstand stress due to excessive salts and sodium. Rapid growth of plant seedlings is especially stimulated. Diammonium phosphate is also completely water soluble and can move quickly into the soil.

Diammonium phosphate should be applied only at a rate indicated by fertility testing. When fertilizer results are to be reported, the analytical laboratory should be asked to recommend a rate which will utilize diammonium phosphate.

Diammonium phosphate is usually provided in the fertilizer grade 18-46-0. This means that the fertilizer contains 18% nitrogen, 46% phosphate as P_2O_5, and no potassium. Fertilization application rates are site-specific depending on soil type and can be readily identified by the analytical laboratory conducting the soil analysis.

MIXING CHEMICAL AMENDMENTS

Often the best remediation results are obtained when more than one chemical amendment is used at a given site. Examples are gypsum and sulfuric acid, and calcium nitrate or calcium chloride and gypsum. Studies indicate combining calcium chloride or sulfuric acid with gypsum appreciably reduces the time and leaching needed to achieve reclamation as compared to gypsum alone. This process, while more costly, may be applicable in situations where expediency is deemed necessary. Use of substantial mulch is almost always advisable, and use of manure is highly recommended when nitrate and phosphorus migration into surface water or groundwater are not concerns. Manure is especially effective for soil redevelopment.

APPENDIX L

Mulching Materials and Procedures

SUMMARY

Appendix L provides information regarding various mulches and typical application rates, as well as the advantages and disadvantages of each. The following tables are included in this appendix:

- Guide to Short-Term Mulch Materials, Rates, and Uses
- Mulch Anchoring Guide

Note:
Original source of these data are unknown. The authors of this manual, in their professional experience, have found this information to be reliable.

Guide to Short-Term Mulch Materials, Rates, and Uses*

Mulch Material	Quality Standards	Per 1,000 sq ft	Per Acre	Depth of Application	Advantages	Disadvantages	Remarks
Sawdust, green or composted	Free from objectionable coarse materials	83–500 cu ft	--	1"–7"	Protects surface; adds organic matter; no weed seeds; more fire resistant than straw; long lasting	Shavings and sawdust blow; causes temporary; nitrogen deficiency in soil; packing may occur resulting in less aeration; may float on running water	Most effective as a mulch around ornamentals, small fruits, and other nursery stock; special application rates: fruit trees 5"–7", vegetables and flowers 2"–3", blackberries and raspberries 4"–7", strawberries 3"; good resistance to wind blowing; requires 30–35 lb N/ton to prevent N deficiency while mulch is decaying; one cu ft weighs 24 lb
Wood chips	Green or air dried; free from objectionable coarse materials	500–900 lb	10–15 tons	2"–"7	Easy to apply; chips resistant to wind movement	May prevent precipitation from reaching soil	Has about the same use and application as sawdust but requires less N/ton (10–12 lb); resistant to wind blowing; decomposes slowly
Wood excelsior	Green or air dried burred wood fibers 0.024 in x 0.041 in x 4 in	90 lb (1 bale)	2 tons	--			Effective for erosion control; tiedown needed on windy sites; decomposes slowly; packaged in 80–90 lb bales
Wood fiber cellulose (partly digested wood fibers)	Usually dyed green; no growth organism inhibiting factors; air dried 30% fibers	25–30 lb	1,000–1,500 lb	--			When used for erosion control on critical areas, double application rate; apply with hydromulcher; no tiedown required; packaged in 100 lb bags; has not been very satisfactory for establishing seedlings on arid sites
Compost or manure	Well shredded; free from excessive coarse material	400–600 lb	8–10 tons	--	Can protect soil surface; adds nutrients, such as N, P, K, S	When used alone, it becomes wet, then dry, can lose much of N through volatilization of ammonia	Use a strawy manure when erosion control is needed; may create problems with weeds; excellent moisture conserver; resistant to wind blowing
Cornstalks or sorghum stover, shredded or chopped	Air dried; shredded in to 8–12 inch lengths	150–300 lb	4–6 tons	--			Effective for erosion control, relatively slow to decompose; excellent for mulch crop on fields; has about the same effectiveness for erosion control as a cover crop; resistant to wind blowing

Guide to Short-Term Mulch Materials, Rates, and Uses* (continued)

Mulch Material	Quality Standards	Per 1,000 sq ft	Per Acre	Depth of Application	Advantages	Disadvantages	Remarks
Grass hay or grain or straw	Air dried, free from undesirable seeds and coarse materials	75–100 lb 2–3 bales	1.5–2.5 tons 90–120 bales	Lightly covers 75% to 90% of surface	Generally most economical; usually satisfactory under many circumstances	Weed seeds usually present; even hay seeds may be considered a weed on a particular site; straw may "wick-out" moisture from soils in very dry conditions, thus resulting in poor germination and seedling establishment	Use straw where mulch effort to be maintained for more than 3 months; subject to wind blowing unless kept moist or tied down; *most common and widely used*
In situ mulches (cereal grains or summer annual crops like wheat, barley, or rye)					Produces quick cover to stabilize disturbed areas; provides uniform mulch; more economical than artificially applied mulching materials		Fall crops killed with herbicides in spring before maturity, summer annuals killed by frost in fall; interseed with permanent grasses and legumes species; produces up to 2.5 tons/acre dry matter
		Unit Size	**Unit and Weight**	**Area Covered/Unit**			
Mats and netting					Especially useful on steep slopes; nets good in high wind areas	Expensive: 4–5 times more than tacked straw; high labor input for anchoring; not effective on rough surfaces or rocky areas; erosion from beneath may be a problem	Used only on limited critical areas due to high cost
Twisted craft paper yarn	Plain weave, warp 7/inch, filling 4/inch selvage edge with polypropylene filament	45 in x 250 yd	Roll - 100 lb	312-1/2 sq yd			Used to hold seed and aid in germination without mulch; tie down according to manufacturing specifications; not effective in seedling establishment on arid sites; lasts about one year
Twisted craft paper yarn	Fungicide treated warp 1.1 pairs/in., filling 2.5/in.	45 in x 250 yd	Roll - 80 lb	312-1/2 sq yd			Use over bare soil or sod to prevent erosion and hold seed; good for waterways and critical ditch bottoms; tie down with staples as per manufacturing specifications and on critical areas; lasts about one year

Guide to Short-Term Mulch Materials, Rates, and Uses* (continued).

Mulch Material	Quality Standards	Unit Size	Unit and Weight	Area Covered Per Unit	Advantages	Disadvantages	Remarks
Jute, twisted yarn	Undyed, unbleached plain weave; warp 78 ends/yd 43 ends/yd	45 in x 50 yd or 48 x 75 yd	Roll - 60 lb 90 lb	60 sq yd 100 sq yd			Use without additional mulch; tie down as per manufacturing specifications; effective for erosion control in waterways and ditches; lasts about one year
Excelsior wood fiber mats	Interlocking web of excelsior fibers w/mulch net backing on one side only	36 in x 30 yd	Roll	16-1/2 sq yd			Use without additional mulch; tie down as per manufacturing specifications; good for establishing seedlings on critical areas
Plastic	2–4 mils	Variable up to 50 ft wide	--	--	Excellent vapor barrier; good weed control; light colored, perforated, found effective in New Mexico; soil temperature in summer 18°F lower than in soil with no mulch	Labor intensive; high cost	Use black for weed control, use white for seeding establishment without organic mulch; release plastic after seeding is established; information on temperature effect varies; the materials allow air and water interchange but prevent evaporation of soil moisture; usually must be renewed each season; some users place a 1-inch layer of sand underneath to prevent it from tearing when stepped upon; must be punctured with frequent small holes for penetration of air and water and weighted down around edges

*All mulches will provide some degree of erosion control, moisture conservation, weed control, and reduction of soil crusting.

Mulch Anchoring Guide

Anchoring Method or Material	Kind of Mulch to be Anchored	How to Apply
Manual		
Peg and twine	Hay or straw, pine straw, corn stalks	After mulching, divide areas into blocks approximately 1 sq yd in size. Drive 4–6 pegs per block to within 2" to 3" of soil surface. Secure mulch to surface by stretching twine between pegs in criss-cross pattern on each block. Secure twine around each peg with two or more turns. Drive pegs flush with soil where mowing and maintenance are planned.
Mulch netting	Hay or straw, shredded sugar cane, pine straw, compost, wood shavings, tanbark, corn stalks	Staple with lightweight paper, jute, wood fiber, or plastic nettings to soil surface according to manufacturer's recommendations.
Soil and stones	Plastic	Plow a single furrow along edge of area to be covered with plastic, fold about 6" of plastic into the furrow and plow furrow slice back over plastic. Use stones to hold plastic down in other places as needed.
Silt	Hay or straw, corn stalks	Cut mulch into soil surface with square-edge spade. Make cuts in contour rows spaced 18" apart.
Mechanical		
Asphalt spray (emulsion)	Compost, wood chips, wood shavings, hay or straw	Apply with suitable spray equipment using the following rates: asphalt emulsion 0.04 gal/sq yd; liquid asphalt (rapid, medium, or slow setting) 0.10 gal/sq yd.
Wood cellulose fiber	Hay or straw	Apply with hydroseeder immediately after mulching. Use 750 lb wood fiber per acre.
Pick chain	Hay or straw, manure compost, pine straw	Use on slopes steeper than 3:1. Pull across slopes with suitable power equipment.
Mulch anchoring tool or disk (smooth or notched)	Hay or straw, manure, pine straw	Apply mulch and pull a mulch anchoring tool over mulch. When a disc (smooth) is used, set in straight position and pull across slope with suitable power equipment. Mulch material should be "tucked" into soil surface about 3".
Sheepsfoot roller or packer	Hay or straw, manure, corn stalks	Pull sheepsfoot roller over the areas after mulch is applied. Can be operated up and down the slope.
Chemical	Hay or straw	Apply Terra Tack II (45 lb) or Aerospray 70 (60 gal/acre) according to manufacturer's instructions. Avoid application during rain. A 24-hr curing period required and soil temperature higher than 45°F.

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December 8, 1998

To: Consumers of API's Publication 4663, *Remediation of Salt-Affected Soils at Oil and Gas Production Facilities*

From: The American Petroleum Institute: Health and Environmental Sciences Department

Enclosed is a single, double-sided, replacement sheet for pages H-3 and H-4 of Appendix H of the *Remediation of Salt-Affected Soils at Oil and Gas Production Facilities* publication. Note the following changes in bold type to page H-3 only:

Final volume needed = [(spill volume)(spill soil EC - target soil EC)]/(target EC - receiver EC)

Using previous example (assumes receiver EC = 0 mmhos/cm):

Final soil volume needed = ([300 cu ft](24 - 4]/(4 - 0) = ~~1,800~~ **1,500** cu ft

Then, (~~1,800~~ **1,500** cu ft) = ~~1,800~~ **1,500** sq ft @ 1 ft thickness

Since incorporated thickness is 0.5 ft, then ~~3,600~~ **3,000** sq ft total area is required

Then, [(300 cu ft)/(~~3,600~~ **3,000** sq ft)][12 in/ft] = ~~1~~ **1.2** inch thick salt-affected soil spread over ~~3,600~~ **3,000** sq ft

Please remove the old sheet and insert the corrected version.

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American
Petroleum
Institute

1220 L Street, Northwest
Washington, DC 20005-4070
Tel: 202-682-8321
Fax: 202-682-8270
E-mail: ehs-api@api.org

Name: Pamela Greene
Title: Publications Assistant

10/15/98

To: Purchasers of Publication 4663, Remediation of Salt-Affected Soils at Oil and Gas Production Facilities

From: Health and Environmental Sciences Department

Attached are errata pages B-34 and H-3 – H-4 for API Publication 4663, *Remediation of Salt-Affected Soils at Oil and Gas Production Facilities*. Page B-34, Worksheet 5 – Post-Remediation Monitoring and Project Termination, was excluded from your publication in error. Insert this page at the end of Appendix B (as the final page). A correction was made to page H-3 of Appendix H, which is backed to page H-4. Both pages should be replaced.

Thank you.

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Therefore, 300 cu ft salt-affected soil spread to 1 inch thickness over 3,600 sq ft and incorporated to a final depth of 6 inches will decrease EC from 24 to 4 mmhos/cm.

However, if the receiver soil also contains a measurable salt concentration, a more refined calculation may be required. The following data are required: target salt concentration (salt criteria to be met), salt level of the salt-affected soil, salt level of the receiver soil, and volume of spill-affected soil. The calculation provides the final soil volume required, which is then converted into final land area required based on 3 inches of available depth. The calculation is performed as follows:

Final volume needed = [(spill volume)(spill soil EC - target EC)]/(target EC - receiver EC)

Using previous example (assumes receiver EC = 0 mmhos/cm):

Final soil volume needed = ([300 cu ft)(24 - 4)]/(4 - 0) = 1,800 cu ft

Then, (1,800 cu ft) = 1,800 sq ft @ 1 ft thickness

Since incorporated thickness is 0.5 ft, then 3,600 sq ft total area is required

Then, [(300 cu ft)/(3,600 sq ft)][12 in/ft] = 1 inch thick salt-affected soil spread over 3,600 sq ft

Example 2: Spill soil volume = 300 cu ft; spill soil EC = 24 mmhos/cm; receiver EC = 1.5 mmhos/cm; target EC = 4 mmhos/cm

Final soil volume needed = [(300 cu ft)(24 - 4)]/(4 - 1.5) = 2,400 cu ft

Then, (2,400 cu ft) = 2,400 sq ft @ 1 ft thickness

Since incorporated thickness is 0.5 ft, then 4,800 sq ft total area required.

Then, [(300 cu ft)/(4,800 sq ft)][12 in/ft] = 0.75 inches (or 3/4 inch) thick salt-affected soil spread over 4,800 sq ft and incorporated to a final 6 inch thickness will decrease EC from 24 to 4 mmhos/cm

Similar calculations can be made for exchangeable sodium percentage (ESP), total petroleum hydrocarbons (TPH), and other constituents with linear concentration expressions. Because its concentration is expressed in logarithmic form, pH cannot be calculated by this method.

The land area required and thickness of spreading should be adjusted to allow for sampling and analytical variability. An expansion of the final land area required and a corresponding reduction of spreading thickness of about 1.3 times should provide for this variability.

Because of the potential for salt concentrations to increase at the soil surface during evaporative periods, a top dressing of gypsum may help minimize soil dispersion.

BURIAL PROCEDURES

Shallow burial (<4 ft) is undesirable because the salt will typically remain in the root zone and may cause significant vegetative stress for many years.

The process of deep burial involves cutting a slot the width of a bulldozer blade of sufficient depth to allow 5 ft of freeboard when the salt-affected soil is placed in the excavation. The soil removed from the slot is then used to cover the slot and replace the salt-affected soil.

The 5-ft depth is normally sufficient to prevent capillary action from bringing the salt back to the surface. If desired, a capillary barrier of clay or plastic can also be used if the slot is kept narrow. (The slot may have to be wider than a bulldozer blade for safety. The salt-affected soil should be placed only in the center of the excavation when backfilling.)

Groundwater is the critical issue in deep burial. Deep burial is most appropriate in arid areas with deep soils and groundwater. If groundwater is >100 ft and a plastic or clay cap is used, the potential risk of groundwater contamination is minimal.

The cost of deep burial techniques (if there is sufficient soil) is on the order of $2,000 for a modest-sized spill site. If the soil is shallow with underlying bedrock, the cost of deep burial can be ten times as great.

DISPOSAL WELL INJECTION

If produced water spillage is in a shallow depression with relatively loose soil, slurry and injection may be appropriate. In slurry/injection, freshwater is added to the spill site and mixed with the salt-affected soil. The slurry is then removed by vacuum truck and taken to a commercial disposal well permitted for oil and gas waste. This procedure is limited to very small spills where the slurry can be thin enough not to cause injection problems.

IN SITU AND *EX SITU* SOIL WASHING

Soil washing is a very fast but often costly operation which combines high mechanical energy agitation with application of chemical amendments in order to remove salts, including sodium, from the salt-affected soil. The soil is often, but not always, removed from its original location. Soil washing is typically performed by soil washing contractors who have appropriate equipment and are aware of the soil chemistry involved. Generally, the soil is kept in a chemically flocculated slurry during the entire process. Depending on soil texture, salinity, sodicity, and pH levels, salts are leached with increasingly less saline water to a certain salinity level before chemical amendments are added to begin to displace sodium. When the soil is at an acceptable salinity and sodicity level, it can be returned to its original location or taken to another site. Although this process is rapid and has the potential to be very thorough, it tends to be expensive.

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Petroleum
Institute

1220 L Street, Northwest
Washington, DC 20005-4070
Tel: 202-682-8321
Fax: 202-682-8270
E-mail: ehs-api@api.org

Name: Pamela Greene
Title: Publications Assistant

10/15/98

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WORKSHEET 5 - POST-REMEDIATION MONITORING AND PROJECT TERMINATION

Site Name: ____________________ **Spill ID No.:** ____________________

Date Initially Reported: ____________ **Date Remediation Completed:** ________

Date Termination Anticipated (2 yr from date remed. complete): ____________________

Category of Remediation Used: ____________________

Criteria for Soil Monitoring and Completion of Remediation (list below):

Report to	Date		Criteria	Result		Acceptable (Y/N)
	Due	Sent		Spill Site	Background	

Comparative Plant Yield Documentation:

Report to	Date		Plant Type	Plant				Acceptable (Y/N)
				Height		Biomass		
	Due	Sent		Site	Bkgd.	Site	Bkgd.	

Photographs of Site and Background:

Year	Winter Date Taken	Spring Date Taken	Fall Date Taken
0–1			
1–2			

Project Termination:

Interest Group	Declared to	Declared Date
Regulatory		
Legal		
Corporate		

Therefore, 300 cu ft salt-affected soil spread to 1 inch thickness over 3,600 sq ft and incorporated to a final depth of 6 inches will decrease EC from 24 to 4 mmhos/cm.

However, if the receiver soil also contains a measurable salt concentration, a more refined calculation may be required. The following data are required: target salt concentration (salt criteria to be met), salt level of the salt-affected soil, salt level of the receiver soil, and volume of spill-affected soil. The calculation provides the final soil volume required, which is then converted into final land area required based on 3 inches of available depth. The calculation is performed as follows:

Final volume needed = [(spill volume)(spill soil EC - target EC)]/(target EC - receiver EC)

Using previous example (assumes receiver EC = 0 mmhos/cm):

Final soil volume needed = ([300 cu ft)(24 - 4)]/(4 - 0) = 1,800 cu ft

Then, (1,800 cu ft) = 1,800 sq ft @ 1 ft thickness

Since incorporated thickness is 0.5 ft, then 3,600 sq ft total area is required

Then, [(300 cu ft)/(3,600 sq ft)][12 in/ft] = 1 inch thick salt-affected soil spread over 3,600 sq ft

Example 2: Spill soil volume = 300 cu ft; spill soil EC = 24 mmhos/cm; receiver EC = 1.5 mmhos/cm; target EC = 4 mmhos/cm

Final soil volume needed = [(300 cu ft)(24 - 4)]/(4 - 1.5) = 2,400 cu ft

Then, (2,400 cu ft) = 2,400 sq ft @ 1 ft thickness

Since incorporated thickness is 0.5 ft, then 4,800 sq ft total area required.

Then, [(300 cu ft)/(4,800 sq ft)][12 in/ft] = 0.75 inches (or 3/4 inch) thick salt-affected soil spread over 4,800 sq ft and incorporated to a final 6 inch thickness will decrease EC from 24 to 4 mmhos/cm

Similar calculations can be made for exchangeable sodium percentage (ESP), total petroleum hydrocarbons (TPH), and other constituents with linear concentration expressions. Because its concentration is expressed in logarithmic form, pH cannot be calculated by this method.

The land area required and thickness of spreading should be adjusted to allow for sampling and analytical variability. An expansion of the final land area required and a corresponding reduction of spreading thickness of about 1.3 times should provide for this variability.

Because of the potential for salt concentrations to increase at the soil surface during evaporative periods, a top dressing of gypsum may help minimize soil dispersion.

BURIAL PROCEDURES

Shallow burial (<4 ft) is undesirable because the salt will typically remain in the root zone and may cause significant vegetative stress for many years.

The process of deep burial involves cutting a slot the width of a bulldozer blade of sufficient depth to allow 5 ft of freeboard when the salt-affected soil is placed in the excavation. The soil removed from the slot is then used to cover the slot and replace the salt-affected soil.

The 5-ft depth is normally sufficient to prevent capillary action from bringing the salt back to the surface. If desired, a capillary barrier of clay or plastic can also be used if the slot is kept narrow. (The slot may have to be wider than a bulldozer blade for safety. The salt-affected soil should be placed only in the center of the excavation when backfilling.)

Groundwater is the critical issue in deep burial. Deep burial is most appropriate in arid areas with deep soils and groundwater. If groundwater is >100 ft and a plastic or clay cap is used, the potential risk of groundwater contamination is minimal.

The cost of deep burial techniques (if there is sufficient soil) is on the order of $2,000 for a modest-sized spill site. If the soil is shallow with underlying bedrock, the cost of deep burial can be ten times as great.

DISPOSAL WELL INJECTION

If produced water spillage is in a shallow depression with relatively loose soil, slurry and injection may be appropriate. In slurry/injection, freshwater is added to the spill site and mixed with the salt-affected soil. The slurry is then removed by vacuum truck and taken to a commercial disposal well permitted for oil and gas waste. This procedure is limited to very small spills where the slurry can be thin enough not to cause injection problems.

IN SITU AND *EX SITU* SOIL WASHING

Soil washing is a very fast but often costly operation which combines high mechanical energy agitation with application of chemical amendments in order to remove salts, including sodium, from the salt-affected soil. The soil is often, but not always, removed from its original location. Soil washing is typically performed by soil washing contractors who have appropriate equipment and are aware of the soil chemistry involved. Generally, the soil is kept in a chemically flocculated slurry during the entire process. Depending on soil texture, salinity, sodicity, and pH levels, salts are leached with increasingly less saline water to a certain salinity level before chemical amendments are added to begin to displace sodium. When the soil is at an acceptable salinity and sodicity level, it can be returned to its original location or taken to another site. Although this process is rapid and has the potential to be very thorough, it tends to be expensive.

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Removed

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