U.S. Department of Energy

UMTRA Ground Water Project

# Monument Valley Ground Water Remediation Work Plan: Native Plant Farming and Phytoremediation Pilot Study

August 1998

Prepared for
U.S. Department of Energy
Albuquerque Operations Office
Grand Junction Office

Prepared by MACTEC Environmental Restoration Services, LLC
Grand Junction, Colorado

Project Number UGW–511–0015–10–000
Document Number U0029501

Work Performed under DOE Contract No. DE–AC13–96GJ87335

# Signature Page

Approved by: ______________________________ 25 August 98
William J. Waugh, Author*
MACTEC Environmental Restoration Services, LLC
Date

Approved by: ______________________________ August 25, 1998
Sam J. Marutzky, Project Manager
MACTEC Environmental Restoration Services, LLC
Date

Approved by: ______________________________ 8/25/98
Roberta Bowen, Ground Water Programs Coordinator
MACTEC Environmental Restoration Services, LLC
Date

Approved by: ______________________________ 8/26/98
Don Metzler, DOE Project Manager
U.S. Department of Energy
Grand Junction Office
Date

*Edward Glenn and Stefani Hines of the University of Arizona are co-authors. Discussions of the task plan with Casey Begay, Lonnie Bernally, Ray Russell, and Judy Willeto of the Navajo Nation, are gratefully acknowledged.

**Note: Some of the section page numbers in the Table of Contents may not correspond to the page on which the section appears when viewing them in Adobe Acrobat.**

# Contents

# Figures



# Tables



# Appendix

# Acronyms

| | |
|---|---|
| C:N | carbon:nitrogen (ratio) |
| cm | centimeters |
| DOE | U.S. Department of Energy |
| dS/m | decisiemens per minute |
| EPA | U.S. Environmental Protection Agency |
| ha | hectare(s) |
| kg/ha | kilograms per hectare |
| kg/ha/yr | kilograms per hectare per year |
| $m^2$ | square meters |
| MCL | maximum concentration limits |
| mg/L | milligrams per liter |
| ppm | parts per million |
| SAR | Sodium Absorption Ratio |
| TDS | total dissolved solids |
| UMTRA | Uranium Mill Tailings Remedial Action (Project) |
| WUE | water use efficiency |
| yr | year(s) |

# 1.0 Introduction

The U.S. Department of Energy (DOE) is developing plans to remediate ground water at the Uranium Mill Tailings Remedial Action (UMTRA) Project site at Monument Valley, Arizona (DOE 1998). Soils and ground water at the site were contaminated as a consequence of milling operations between 1955 and 1968. Starting in 1992, tailings piles, leach area soils, evaporation pond sediments, and associated surface contamination were removed from the site and placed in an engineered disposal cell near Mexican Hat, Utah. The Mexican Hat disposal cell was closed in 1994. During the interim years, recharge through tailings materials and soils polluted with mill process chemicals moved contaminants into underlying ground water. Elevated nitrate levels moving in an alluvial aquifer downgradient from the former mill and tailings piles exceed standards developed by the U.S. Environmental Protection Agency (EPA) for protection of human health. Residual ammonium in soils where tailings piles were removed—subpile soils—may be a continuing source of ground water nitrate as well as a direct source of soil contamination due to high ammonium levels which may be phytotoxic.

Revegetation of the site was initially attempted using direct seeding without irrigation, but that effort was not successful. Most of the former mill site and tailings areas are now bare. Establishing vegetation is essential for controlling erosion and returning the site to a state of productivity.

DOE believes that management of native vegetation at the Monument Valley site may also play an important role in remediation of the alluvial aquifer. Nitrate in the alluvial aquifer can be recovered and used for a native plant farming operation to greatly enhance livestock forage production on areas disturbed during remediation of surface contamination. Native plants used for revegetation will also extract residual ammonium in subpile soils. Because of high evapotranspiration/precipitation ratios in arid ecosystems, revegetation of subpile soils coupled with a controlled irrigation program can prevent leaching of soil contaminants. Finally, management of existing and planted stands of native phreatophytes can enhance extraction of nitrate from the alluvial aquifer. Phreatophytes are plants that survive in the desert by rooting into ground water.

This work plan describes a pilot study designed to evaluate the above uses of native plants at Monument Valley for remediation—phytoremediation—of the alluvial aquifer and subpile soils. Background information concerning the nature and extent of ground-water contamination and the plant ecology of the site is summarized in Section 2.0. The feasibility of recovering ammonium and nitrate from subpile soils and from the alluvial aquifer using native plant farming and phytoremediation is addressed in Section 3.0. Section 4.0 summarizes the data needed and the experimental design of the pilot study. Task sequences and schedules for all components of the pilot study are outlined in Section 5.0.

# 2.0 Background Information

## 2.1 Nature and Extent of Ground-Water Contamination

DOE recently completed a thorough water quality evaluation at the Monument Valley site. The results indicate that contamination from the milling operation is primarily limited to an unconfined alluvial aquifer (DOE 1998; Section 5.3). Alluvial water collected from the most contaminated test wells was chemically similar to tailings pore fluids; elevated levels of many constituents in the alluvial aquifer were attributed to the milling operation. Aquifers in underlying sandstone units have not been significantly impacted by site-related contamination.

Several site-related constituents in the alluvial aquifer exceeded maximum concentrations in upgradient (background) wells. Only nitrate, however, consistently exceeded the maximum concentration limits (MCL) established by the EPA for ground-water protection at UMTRA project sites (44 milligrams per liter [mg/L] nitrate). Concentrations of ammonium and sulfate in the alluvial aquifer, constituents absent from EPA's MCL list for UMTRA sites, also consistently exceeded maximum background levels. Ammonium in the alluvial aquifer and residual ammonium in soils and substrates where the "new tailings pile" was removed may be a continuing source of nitrate in the alluvial aquifer (DOE 1998; Section 5.3.2).

Ground-water monitoring since 1988 documents lateral and vertical movement of the alluvial nitrate plume downgradient from the new tailings pile (DOE 1998; Section 5.3.3 and Figures 5–23 through 5–34). The leading edge of the 44 mg/L plume has migrated approximately 1,400 meters in the direction of the hydraulic gradient of the alluvial aquifer north of the former mill site. If we assume that nitrate entered the aquifer at the onset of the 1967 milling operation, then the linear flow velocity has been approximately 46 meters per year (yr). A mass of relatively high nitrate, concentrations greater than 500 mg/L, begins near the former new tailings pile and extends approximately 790 meters downgradient. The highest nitrate concentrations (1,030 mg/L) occur within approximately 250 meters of the former new tailings pile.

The depth from the ground surface to the top of the 44 mg/L nitrate plume ranges from approximately 1.5 meters on the east side to approximately 14 meters on the west side of the plume. The downgradient, leading edge of the 44 mg/L nitrate plume is about 26 meters below the ground surface and about 17 meters below the phreatic surface. The depth from the ground surface to the 500 mg/L zone of the plume ranges from 6 to 12 meters east to west. The rooting depth of the site vegetation was misstated in the 1994 BLRA; *Atriplex canescens* and *Sarcobatus vericulatus* are phreatophytes, with roots penetration to 8 and 18 meters, respectively (Nichols 1993 and 1994, Charles et al. 1987), within reach of a portion of the plume.

The vertical thicknesses of the entire 44 mg/L nitrate plume increases downgradient to about the center of the plume, and then tapers off toward the leading edge (DOE 1998; Figure 5–31). The thickness of the highest nitrate zone (greater than 1,000 mg/L), at the head of the plume near the former new tailing pile, is approximately 6 meters. At the leading edge of the 500 mg/L zone, about 790 meters downgradient, the plume is approximately 15 meters thick. Progressing toward the leading edge of the 44 mg/L nitrate plume, the thickness tapers to about 3 meters.

## 2.2 Subpile Soil Ammonium

The Monument Valley site had several periods of uranium milling activities. During these activities, mill tailings, heap leach residues, and various processing chemicals were stored in unlined cells. Any tailings and residuals in the soils that exceeded 15 picocuries per gram radium-226 were removed from the site during the surface remediation. However, some site-related inorganic constituents from these former source areas may have leached into the soils below the storage cells and gone undetected during the radiometric assessment for the tailings removal (DOE 1998; Section 5.3.2). In 1997, samples of the soils directly beneath the former sources areas were collected and analyzed for manganese, nitrate, strontium, sulfate, uranium, vanadium, and ammonium. Although there is no regulatory concentration limit for ammonium, it was analyzed because it is present in ground water and will oxidize to $NO_3$.

Leaching experiments conducted on subpile and background soil samples indicate that Mn, Sr, and U are probably not being leached from subpile soils at concentrations that will contaminate ground water (DOE 1998; Section 5.3.2). Sulfate concentrations appeared to be elevated in the subpile soils but this may be an artifact of non-representative sampling of the background soils. Vanadium concentrations were elevated in the subpile soils but do not appear to be contaminating ground water.

Ammonium was anomalously high to a depth of 2 meters at one location in soils beneath the northern portion of the former New Tailings Pile. While $NH_4$ does not have a MCL it can oxidize to $NO_3$, which does. Nitrate concentrations appeared to be elevated somewhat in the same boring; however, one background sample had a comparable $NO_3$ concentration. $NH_4$ may have persisted at the mill site due to its strong affinity for ion exchange sites, while $NO_3$ would have readily flushed out. It is possible that the $NH_4$-rich soils are generating $NO_3$, which then enters the ground-water system. The 1997 sampling was too sparse to determine the lateral extent of the $NH_4$-rich soils.

## 2.3 Plant Ecology

The plant ecology of the former mill site and tailings areas, and the area overlying the nitrate plume, was characterized in 1997 (DOE 1998; Section 4.7). The activity consisted of identifying species in these areas, defining and mapping plant associations, and estimating the abundance, distribution, and structure of phreatophyte populations. This information was acquired as part of an evaluation of the feasibility of revegetating the site with useful native shrubs and of recovering ammonium and nitrate from subpile soils and from the alluvial aquifer using native plant farming and phytoremediation.

### 2.3.1 Plant Species, Associations, and Vegetation Mapping

Table 2–1 lists plant species identified at the site. The occurrence and relative abundance of species coupled with knowledge of their physiological and ecological tolerances provide a measure of the health of the ecosystem and evidence of environmental conditions that are of importance for evaluating native plant farming and phytoremediation. A plant association is a vegetation classification unit. An association generally has a consistent floristic composition, a uniform appearance, and a distribution

*Table 2–1. Plants Growing on the Reclaimed Tailings and Plume Areas of Monument Valley*

| Scientific Name[a] | Acronym[b] | Common Names[c] |
|---|---|---|
| Shrubs | | |
| *Artemisia filifolia* Torr. | ARFI | sand sagebrush, old-man sagebrush |
| *Atriplex canescens* (Pursh) Nutt. | ATCA | fourwing saltbush, cenizo, chamizo |
| *Atriplex confertifolia* (Torr. & Frem.) Wats. | ATCO | shadscale, spiny saltbush, sheep fat |
| *Chrysothamnus nauseosus* (Pall.) Britt. | CHNA | rubber rabbitbrush, chamisa |
| *Ephedra torreyana* S. Wats. | EPTO | joint fir, Mormon tea, Brigham tea |
| *Gutierrezia sarothrae* (Pursh) Britt. & Rusby | GUSA | broom snakeweed, |
| *Haplopappus pluriflorus* (Gray) Hall | HAPL | jimmyweed, jimmy goldenbush |
| *Lycium pallidium* Miers | LYPA | tomatillo, desert wolfberry |
| *Opuntia phaeacantha* Engelm. | OPPH | prickly pear, many-spined cactus |
| *Poliomintha incana* (Torr.) Gray | POIN | bush mint, rosemary-mint, purple sage |
| *Sarcobatus vermiculatus* (Hook.) Torr. | SAVE | black greasewood, chico, chicobush |
| *Senecio douglasii* DC. | SEDO | threadleaf groundsel, creek senecio |
| *Tamarix ramosissima* Ledeb. | TARA | tamarisk, salt cedar, tamarisco |
| *Yucca angustissima* Engelm. | YUAN | narrowleaf yucca, fineleaf yucca |
| Grasses | | |
| *Aristida purpurea* Nutt. | ARPU | Purple threeawn, wiregrass |
| *Bromus tectorum* L. | BRTE | cheatgrass brome, downy brome |
| *Festuca microstacys* Nutt. | FEMI | small fescue, vulpia |
| *Hilaria jamesii* (Torr.) Benth. | HIJA | galleta, curly grass |
| *Oryzopsis hymenoides* (R. & S.) Ricker | ORHY | Indian ricegrass, sand bunchgrass |
| *Sporabolis airoides* (Torr.) Torr. | SPAI | alkali saccaton |
| *Sporabolis cryptandrus* (Torr.) Gray | SPCR | sand dropseed |
| *Sporabolus contractus* A.S. Hitchc. | SPCO | spike dropseed |
| *Sporabolus giganteous* Nash | SPGI | giant dropseed |
| Forbs | | |
| *Tripterocalyx carneus* (Greene) Galloway | TRCA | wooton sandverbena |
| *Chenopodium album* L. | CHAL | common lambsquarter, goosefoot |
| *Ambrosia acanthacarpa* Hook. | AMAC | bur ragweed |
| *Amsinkia tessellata* Gray | AMTE | rough fiddleneck |
| *Arabis* L. species | AR sp. | rockcress mustard |
| *Astragalus* L. species | AS sp. | milkvetch, locoweed |
| *Datura wrightii* Regel | DAWR | sacred datura, angels trumpet |
| *Descurainia pinnata* (Walter) Britt. | DEPI | pinnate tansey-mustard |
| *Erigeron* L. species | ER sp1. | daisy |
| *Eriogonum* Michx. species | ER sp2. | wild buckwheat, skeletonweed |
| *Kochia scoparia* (L.) Schrader | KOSC | kochia, summer cypress |
| *Lepidium* L. species | LE sp. | pepperweed, peppergrass |
| *Lupinus* L. species | LU sp. | lupine |
| *Machaeranthera* Nees. species | MA sp. | aster |
| *Oenothera albicaulis* Pursh | OEAL | white-stemmed evening primrose |
| *Plantago patagonica* Jacq. | PLPA | wooly plantain |
| *Salsola iberica* Sennen & Pau | SAIB | Russian thistle, tumbleweed |
| *Sphaeralcea coccinea* (Pursh) Rydb. | SPCO | scarlet globemallow, falsemallow |
| *Sphaeralcea parvifolia* A. Nels | SPPA | Nelson globemallow |

[a]The scientific nomenclature and authorities is consistent with Voss (1983) and the choices of Welsh et al. (1987).
[b]Acronyms combine the first two letters of the genus and species names.
[c]English and Spanish common names are from a variety of sources (Mayes and Lacy 1989; Dodge 1985; Elmore and Janish 1976; Dunmire and Tierney 1995; Whitson 1992).

that reflects a certain mix of environmental factors that can be shown to be different from other associations. The association is a synthesis of local examples of vegetation called stands. Associations are named for their dominant species.

For the purpose of mapping vegetation at Monument Valley, a modified releve' method was used to characterize plant cover in stands near monitoring wells and then stands were grouped into associations using simple ordination and gradient analysis techniques (e.g., Barbour et al. 1987). Associations were identified by first grouping stands with similar species composition and cover. Because species composition and cover vary across the site as a continuum rather than as discrete units, no clear breaks between groups of stands were apparent. A simple gradient analysis of dominant species was used to group stands. Figure 2–1 illustrates how the abundance of dominant species varies along a gradient from stand to stand.

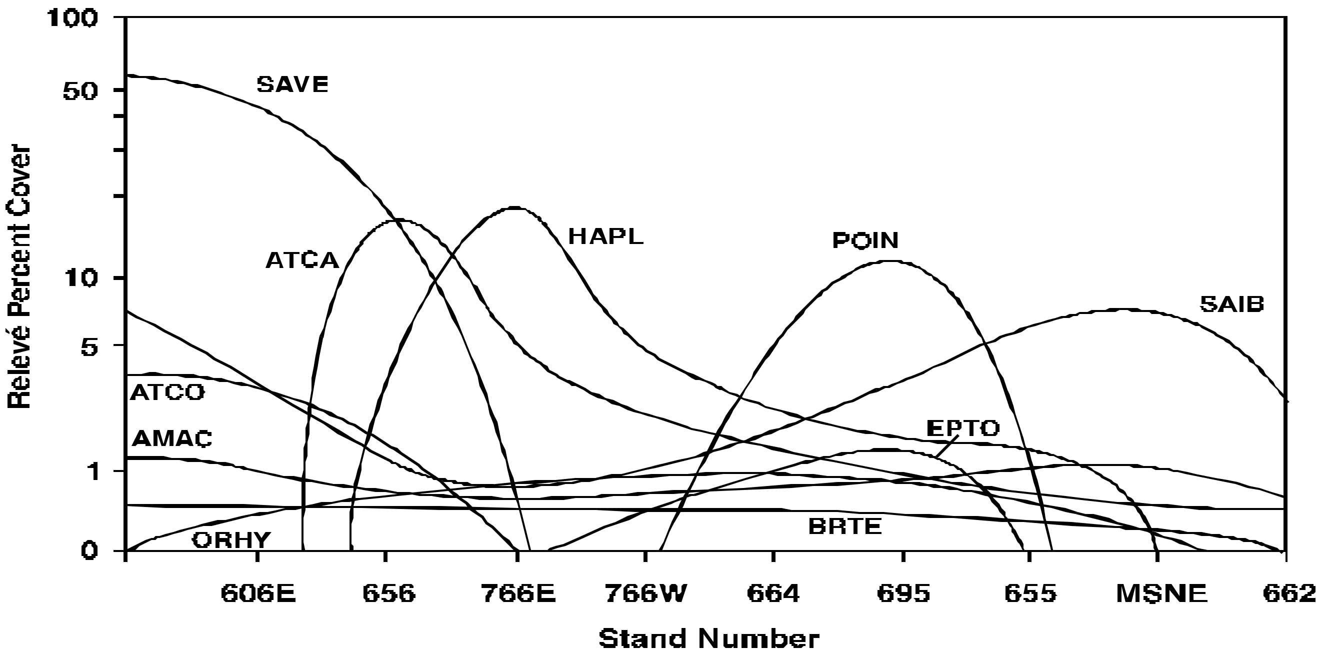


*Figure 2–1. Indirect Gradient Analysis of Monument Valley Plume Vegetation*

Results of the gradient analysis suggest that some dominant species are associated and that associations overlap—a given stand may occur in more than one association. Four associations occur, named for their two most abundant shrubs.

- *Sarcobatus vermiculatus* (black greasewood) and *Atriplex confertifolia* (shadscale),
- *Atriplex canescens* (fourwing saltbush) and *Haplopappus pluriflorus* (jimmyweed),
- *Poliomintha inicana* (bush mint) and *Ephedra torreyana* (joint fir), and
- *Salsola iberica* (Russian thistle) and *Ambrosia acanthacarpa* (bur ragweed).

Production of a vegetation map (Figure 2–2) involved (1) mapping stand locations on a 1995 aerial photograph; (2) identifying vegetation patterns in the photograph, under magnification, that were consistent with the plant associations; (3) outlining mapping unit boundaries using a combination of stand locations and vegetation patterns; and (4) returning to the field to check the reliability of the reliability of the photograph interpretation. Acronyms of dominant plants in associations are used for mapping unit titles in Figure 2–2.

### 2.3.2 Native Phreatophyte Populations

Phreatophytes (literally “well plants”) at the Monument Valley site may act, in essence, as passive, solar-powered, pump-and-treat systems for nitrates in the alluvial aquifer and ammonium in subpile soils. Two phreatophyte populations grow over the plume area: *Sarcobatus vermiculatus* (black greasewood) and *Atriplex canescens* (fourwing saltbush). *Sarcobatus* is an obligate phreatophyte requiring a permanent ground-water supply, and can transpire water from aquifers as deep as 18 meters below the land surface (Nichols 1993). *Atriplex* is a facultative phreatophyte; it takes advantage of ground water when present but can tolerate periods of low water availability. The rooting depth of *Atriplex* may exceed 8 meters (Foxx et al. 1984).

A line intercept method (Bonham 1989) and high-resolution aerial photography were used to estimate *Sarcobatus* cover in the SAVE/ATCO(1) mapping unit (Figure 2–2). Field measurement methods were abandoned because of recent widespread injury and mortality in the *Sarcobatus* population, apparently as a consequence of herbicide spraying during the surface remediation phase of the project. The population now appears to be recovering. We estimated the potential *Sarcobatus* cover from a February 1995 photograph, and not the current condition (DOE 1998; Section 4.7.2). The results show 37 percent *Sarcobatus* cover (95% C.I. = ±5.8%) in 1995, before the population was sprayed. The percent cover of *Atriplex* in the ATCA/HAPL mapping unit (Figure 2–2), estimated using a releve’ method (Bonham 1989), was about 5 percent. *Atriplex* is a highly palatable browse species for livestock in the area, and, therefore, a grazing decreaser.

Because the *Sarcobatus* and *Atriplex* populations overlying the nitrate plume have been decimated by heavy grazing and herbicides, these populations may have to be rehabilitated, using a combination of transplanting and grazing exclosures, if they are to be useful for nitrate phytoremediation. The feasibility of the phytoremediation alternative may be dependent on rapid establishment and growth of *Sarcobatus* and *Atriplex* transplants in overgrazed and denuded areas overlying the plume.

A few volunteer *Sarcobatus* and *Atriplex* plants have established in the new tailings pile area. The age and size of these volunteer plants were evaluated as measures of growth rate. Three *Sarcobatus* plants and two *Atriplex* plants that volunteered in the tailings subpile soils were sampled. Plant height, the long diameter of the canopy, and the short diameter of the canopy were measured for all five plants. Cross sections of the primary stem of each plant were cut and prepared for analysis using the methods of Fritts et al. (1989). Stem sections cut at an oblique angle in the field were recut at a transverse angle. Specimens were polished with a power sander using sequentially finer grades of sandpaper until vascular cells were discernible under magnification. Entire cross sections were examined for locally absent and double rings and then the rings were counted. Once *Sarcobatus* plants become established in disturbed areas, reproduction occurs primarily as sprouting from underground stems that spread laterally from mature plants. This cloning of nurse plants was observed in the subpile soil area. The density of new *Sarcobatus* plants, mostly likely clones, were counted within a 6-meter radius of the three larger nurse plants. The results (Table 2–2) show that both species reach a mature size and begin reproduction in fewer than 4 yr. Phytoremediation appears

*Table 2–2. Canopy Measurements and Annual Growth Rings of Volunteer Sarcobatus vermiculatus and Atriplex canescens Growing in Tailings Subpile Soils.*

| Plant Number[a] | Height (m) | Long Diameter (m) | Short Diameter (m) | Canopy Area[b] ($m^2$) | Clone Density[c] (100 $m^{-2}$) | Annual Growth Rings |
|---|---|---|---|---|---|---|
| SAVE1 | 1.35 | 2.64 | 2.03 | 5.68 | 1.8 | 4 |
| SAVE2 | 1.47 | 2.31 | 2.16 | 5.76 | 3.5 | 4 |
| SAVE3 | 1.45 | 2.97 | 1.83 | 6.19 | 14.2 | 4 |
| ATCA1 | 1.02 | 1.47 | 1.32 | 1.55 | NA | 4 |
| ATCA2 | 0.89 | 1.52 | 1.01 | 1.07 | NA | 4 |

[a]Plant numbers include the genus/species acronyms given in Table 2–1.

[b]Canopy volume was calculated as the area of an ellipse—pi*(long diameter/2)*(short diameter/2)—multiplied by plant height. This overestimate of the volume suffices for comparative purposes.

[c]Seedlings with a 6-meter radius of nurse plants were assumed to be clones.

to be a viable option and is attractive at this site because it will simultaneously improve the surface ecology, which has been severely degraded, but a pilot study on a small portion of the site is required to answer questions of efficacy, safety, and cost.

## 2.4 Overview of Nitrogen Cycling in Terrestrial Ecosystems

Nitrogen (N) is an essential macronutrient for the growth of higher plants. Nitrate ($NO_3^-$) and ammonium ($NH_4^+$) in soils and ground water are the most common plant-available forms of N in arid and semiarid ecosystems (Coyne et al. 1995). Utilization of $NO_3^-$ by higher plants involves the uptake, storage, translocation, and incorporation of N into organic forms. Most N uptake is through roots, although foliar uptake may also occur. N taken up from soil by the roots of terrestrial plants is either in the $NO_3^-$ form or the $NH_4^+$ form. $NO_3^-$ and $NH_4^+$ are taken in through the epidermis of plant roots and into the symplast of cortical and endodermal cells by way of a combination of passive diffusion and active transport which requires expenditure of energy.

Once in the plant, $NO_3^-$ is reduced to ammonia ($NH_3$) or $NH_4^+$ either in the root or after it is transported up the xylem into the leaves. $NO_3^-$ may be stored in cell vacuoles for a period of time before it is reduced. Reduction of $NO_3^-$ is driven by photochemical energy captured through photosynthesis. The $NH_3$ or $NH_4^+$ is converted to amides and, through reactions catalyzed by transferases, amides are converted to amino acids. The amino acids are the building blocks for complex nitrogenous compounds in the plant protoplasm including proteins, chlorophyll, growth regulators, alkaloids, nucleosides, nucleotides, and nucleic acids.

Some N bound in live plant protoplasm is lost as $NH_3$ through stomates to the atmosphere. However, most N is returned to the soil either by death and decay of plant tissue or removed by grazing animals. Most N in terrestrial ecosystems resides in soil organic matter. Bacteria and fungi decay dead plant protoplasm (litter) producing amino acids and other soil organic residues. This soil organic matter is eventually converted to $NH_4^+$ and $NH_3$ by amnifying bacteria. N in plant biomass ingested by grazing animals is excreted in urine or feces and then rapidly hydrolyzed to $NH_4^+$.

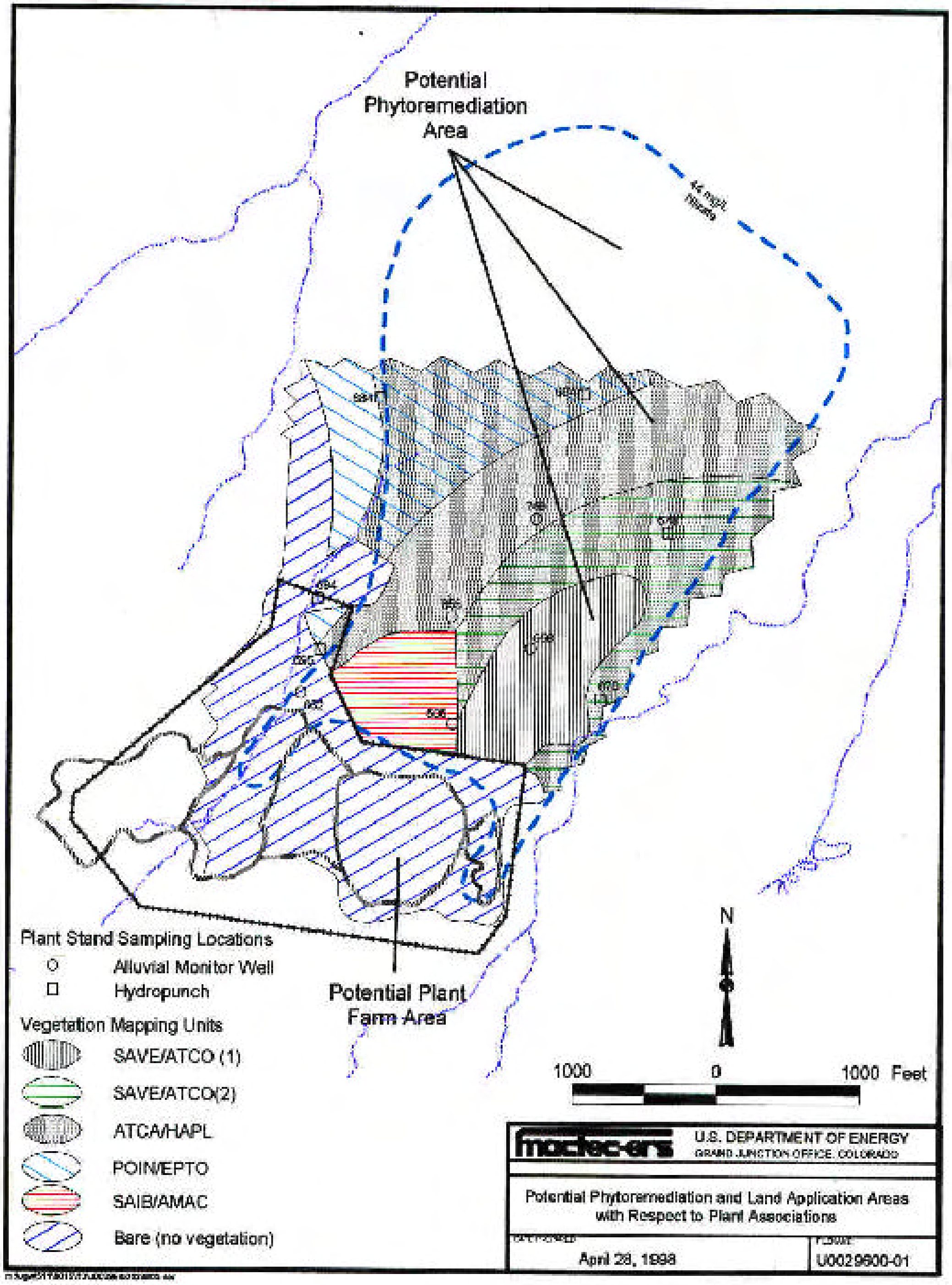


*Figure 2–2. Potential Phytoremediation and Land Application Areas with Respect to Plant Associations*

# 3.0 Feasibility of Using Plants to Remediate Soil and Ground Water

This section explores the feasibility of using native plant farming and phytoremediation to recover ammonium from subpile soils and nitrate from the alluvial aquifer at the Monument Valley site. The feasibility assessment relies on our current understanding of conditions at the site (Section 2.0), a review of current literature, and expertise of staff at the University of Arizona's Environmental Research Laboratory. The feasibility assessment is also the basis for identifying data needs (Section 4.1).

## 3.1 Native Plant Farming

Nitrate in the alluvial aquifer could be recovered to irrigate a native forage farming operation on areas disturbed during remediation of surface contamination. The operation could produce forage for livestock growers in the area until nitrate concentrations in the alluvial aquifer drop below the 44 mg/L MCL, in approximately 10 yr. To accomplish this, fourwing saltbush (*Atriplex canescens var. angustifolia*), the most valuable native shrub in the local range, would be grown in widely-spaced rows under drip irrigation using nitrate-rich water recovered from the plume. After plants are established, a grazing and harvesting program would be implemented to allow utilization of the plants by sheep and cattle. Most of the harvest would be transported off-site, to be used as dried forage elsewhere, resulting in a net removal of nitrogen from the site. Plants would be sown densely to develop a closed canopy within rows, with the area between rows seeded with a mixture of cool-season and warm-season grasses to hold the soil and provide additional livestock forage. Deep watering will be used to encourage deep-rooting of the shrubs during their establishment phase. The plant community, after irrigation ceases, would resemble native range in good condition.

The feasibility of recovering nitrogen from the alluvial aquifer for a native plant farming operation rests on several issues:

- suitability of the remediated soils for irrigation,
- successful establishment of *Atriplex canescens*,
- water requirements of *Atriplex canescens*,
- biomass production and nitrogen uptake by *Atriplex canescens*,
- capacity of the *Atriplex canescens* pasture to support grazing,
- potential for phytotoxicity and soil salinization from irrigation water, and
- sound management practices to control water infiltration, nitrogen leaching, and soil salinization.

### 3.1.1 Land Suitability for Irrigation

Classification of irrigation suitability in arid regions considers soil texture, soil depth, soil water retention, soil permeability, soil chemistry (salinity, sodicity, and alkalinity), percent coarse fragments, and topography. Soils in the remediated area at Monument Valley range from a loamy sand, with about 70 percent fine sand, 25 percent silt, and less than 5 percent clay, to a sand with greater about 90 percent fine sand, less than 5 percent silt, and virtually no clay (DOE 1998; Section 4.6.2). Given this range of soil textures, the field capacity should fall between about 7 and 15 percent volumetric water content (e.g., Brady 1974). The permeability of these soils averages about $1.0 \times 10^{-4}$ centimeters per second (DOE 1998; Section 4.6.1). These soils are deep, have very few coarse fragments, and slopes do not exceed 8 percent. Salinization would not be expected for these deep, coarse-textured soils *under normal irrigation practices*. Overall, based on an arable land classification system used by the Navajo Nation and the U.S. Bureau of Indian Affairs (Appendix A), the soils in the remediated areas do not fall in the highest class, primarily because of the sand texture, but are suitable for irrigation of a native forage crop (e.g., Glenn et al. 1998b). The U.S. Department of Agriculture recommends a check for excessive concentrations of boron, heavy metals, pH, and lime; these parameters will be measured in the pilot stage of the project.

### 3.1.2 Revegetation with *Atriplex canescens*

*Atriplex canescens* is the most widespread and valuable saltbush species in western North America, extending from Mexico into Canada and from sea level to 3,000 meters elevation (Benson and Darrow 1981). It has been used in numerous revegetation projects in the western United States with a track record of good performance on disturbed desert soils including strip-mines (Wagner et al. 1978), copper mine spoils (Sabey et al. 1990), open pit uranium mines (Reynolds et al. 1978) and oil well reserve pits (McFarland et al. 1987). The University of Arizona's Environmental Research Laboratory developed planting methods for *Atriplex canescens* that gave 98 to 100 percent survival over the establishment year at the Tuba City, Arizona, UMTRA site (Glenn et al. 1998a). The University of Arizona also demonstrated that this species can be established using saline water sources on ash piles at Arizona Public Services' Four Corners Generating Station (Fitzsimmons et al. 1998). *Atriplex canescens* is a key pioneer species in desert ecosystem and, once established, it encourages the development of a more diverse flora and fauna (Booth 1985). It is also a preferred species for grazing by livestock and wildlife (Wood et al. 1995).

### 3.1.3 Water Requirements of *Atriplex canescens*

Table 3–1 gives estimates of monthly evapotranspiration for *Atriplex canescens* ($ET_{Atriplex}$). The estimates are based on the Blaney-Cridle formula for potential evapotranspiration ($ET_o$) (Jensen 1973) using mean monthly temperature and hours of effective daylight at Tuba City, Arizona, (Green and Sellers 1964) multiplied by crop coefficients developed for *Atriplex nummularia* at Tempe, Arizona (Glenn et al. 1998b).

The total disturbed area where tailings and contaminated soils were removed is 28 hectares (ha). For the purposes of this estimate, we assume a 530 meter by 530 meter area, and an *Atriplex* planting consisting of 177 rows, 3 meters apart. During the first 2 yr we can assume that the plant canopy will be approximately 1 meter in width, hence the planted area will equal 1 meter width by 530 meters per row times 177 rows, or 93,810 square meters ($m^2$). In latter years the plant canopy may increase to as much as 1.5meters diameter depending on irrigation rates. If irrigation is restricted to the amount calculated for a 1 meter canopy diameter, the plants will be under deficit irrigation (receiving less than they can utilize) after the second year and, therefore, would have no appreciable discharge past the root zone.

N that has been returned to the soil as $NH_4^+$ and $NH_3$ is either taken up again by higher plants, used as an energy source by nitrifying bacteria, forming $NO_3^-$, or lost through volatilization or leaching (Coyne et al. 1995; Barbour et al. 1987). A combination of high temperatures and dry soil can result in substantial volatilization of $NH_3$. The potential for leaching of $NH_4^+$, $NH_3$, and $NO_3^-$ is a function of the soil water balance which depends to a great degree on vegetation condition. Low transpiration rates for vegetation in poor condition may cause deep infiltration of precipitation and leaching of N compounds back towards the ground water. However, very little, if any, leaching would be expected where vegetation in good condition returns precipitation to the atmosphere.

*Table 3–1. Estimates of Monthly Evapotranspiration for Atriplex canescens*

| Month | Ave. Temp. | $ET_o$ | $ET_{Atriplex}$[a] |
|---|---|---|---|
| | (°C) | (cm) | (cm) |
| March | 8.0 | 9.7 | 1.6 |
| April | 12.4 | 12.0 | 12.6 |
| May | 16.9 | 15.2 | 27.5 |
| June | 22.0 | 17.4 | 38.0 |
| July | 25.3 | 19.2 | 46.2 |
| August | 24.2 | 17.7 | 39.1 |
| September | 20.3 | 14.3 | 23.2 |
| October | 13.6 | 11.1 | 8.4 |
| Total | - | - | 196.6[b] |

[a]$ET_{Atriplex} = 4.64(ET_o) - 43.1$, $r^2 = 0.87$, $P<0.001$ (from Glenn et al. 1998b).
[b]Equivalent to 1.97 $m^3/m^2$ over a 210 day growing season.

Based on these evapotranspiration and canopy area values for *Atriplex*, we estimate maximum irrigation requirements as follows:

- Total maximum annual irrigation $= 1.97\ m^3/yr/m^2 \times 93,810\ m^2$
  $= 1.85 \times 10^5\ m^3/yr$ ($4.89 \times 10^7$ gallons/yr)

- Maximum monthly irrigation rate (July) $= 15.0$ liters/day/$m^2 \times 93,810\ m^2$
  $= 1.41 \times 10^6$ liters/day ($3.8 \times 10^5$ gallons/day)

The water requirement estimate represents the maximum irrigation application for high productivity. *Atriplex* can be established on as little as 5 centimeters (cm) of supplemental irrigation with 100 percent survival; as little as 2.5 percent of the estimated water requirement would be sufficient (in theory) to establish the planting. Productivity would be proportional to the amount of water applied through the growing season. The calculations and projections in this and subsequent sections are based on research conducted on *Atriplex* at other sites in Arizona. They are given as examples, but crop coefficients and irrigation schedules are site specific and will be developed as part of the pilot project at Monument Valley.

### 3.1.4 Fate of Nitrogen in Irrigated Desert Ecosystems

Nitrate or ammonia applied to an actively growing crop in proportion to crop needs will be primarily incorporated into root and shoot tissues as organic nitrogen compounds (Fuller 1975). Nitrate is usually in low levels in native desert soils due to rapid uptake by plants or denitrification. Ammonium is usually undetectable in desert soils as it is rapidly absorbed by plants, volatilized to ammonia or oxidized to nitrate through microbial action. Even intensely irrigated and fertilized crops do not discharge nitrogen to ground water in desert irrigation districts so long as crop nitrogen demands are not exceeded (Fuller 1975). In practice, however, nitrogen leaching often occurs in irrigation districts because crops are routinely overfertilized (Cameron and Haynes 1986, Haynes 1986), and leached nitrate can contaminate drinking-water aquifers (California Department of Food and Agriculture 1995). Again, if nitrate loading rates are in proportion to crop needs, there should be little direct loss of nitrate below the root zone. If only enough water is applied to meet crop water demands, there will be little water discharged beyond the root zone to carry away nitrate. Any excess nitrate applied in the irrigation water will remain in the root zone and available for future plant uptake. Monitoring data during the first 2 yr of crop production can help fine-tune irrigation management practices to prevent discharge past the root zone.

Over time, decomposition of roots and leaf litter from the *Atriplex* crop will increase soil organic matter content. Native desert soils generally contain well under 1 percent organic matter. The organic matter content may rise as high as 2.5 percent with the addition *Atriplex* litter, although most irrigated desert soils are much lower due to high microbial activity (Fuller 1975). On decay, organic nitrogen in plant litter enters the soil nitrogen cycle. Although plants cannot directly utilize organic forms of soil nitrogen, they rapidly take up nitrate and ammonia. The accumulation of high levels of soil organic matter will not depress nitrate uptake by crops (Fuller 1975). Organic nitrogen substances in the soil represent a pool from which available mineral forms of nitrogen are slowly released by microbial decomposition. This requires an energy source; the carbon provided by *Atriplex* litter. As long as the carbon:nitrogen (C:N) ratio in the soil and litter is above 30:1, nitrogen will continue to be either recycled by the microorganisms or taken up by plants (Fuller 1975).

Nitrogen use in desert irrigation systems is illustrated by two case studies. A University of Arizona study of *Atriplex canescens* litter decomposition in saline, sandy soils, found that tissue C:N ratios averaged 35:1 and that N was retained while C was lost from the soil (Olsen et al. 1996). Pascual et al. (1998) found that adding high levels of six types of nitrogenous organic waste materials, including municipal sludge, to an arid soil stimulated microbial activity and soil respiration and resulted in immobilization of nitrogen in the soil. In another study, *Atriplex canescens* and *Artemisia tridentata* (big sagebrush) were grown in the greenhouse to test their tolerances as reclamation shrubs for copper mine spoils (Sabey et al. 1990). The study used soils amended with high levels of nitrogen-rich municipal sewage sludge. The sludge enhanced the growth of *Atriplex* 38 to 300 fold over controls, depending on application rate. The study concluded that rates up to 60 tons/ha of sludge containing 1,400 kilograms per hectare (kg/ha) N would be safe in a one time application. Our proposed rate of 176 kilograms per hectare per year (kg/ha/yr) is much lower (see Section 3.1.5).

Nitrate leaching can be a problem if fields are chronically overfertilized, or used for disposal of animal wastes without a crop to absorb the nitrogen. Animal waste is sometimes placed on fields during the winter fallow in Canada to fertilize the next summer's crop. Under these conditions, rain and snow may leach most of the nitrogen into the water table during winter. The result is that almost no nitrogen is left in the soil for the next summer's crop (Paul and Zebarth 1997). Overseeding a winter crop in this case can reduce the potential for contaminating the aquifer (Ball-Coelho and Roy 1997). At Monument Valley we do not anticipate pumping and irrigating the *Atriplex* crop with plume water during winter dormancy, although the plume water could be pumped and stored for use in spring.

At Monument Valley, forage production will result in a net loss of N from the system over time. Leaching of nitrate into groundwater should not be a problem given good irrigation management practices. Other processes such as denitrification, volitilization, and grazing will result in continual losses of nitrogen from the soil system over time. Microbes will denitrify nitrate to $N_2$, especially near the bottom of the root zone where oxygen may be limiting. Volatilization of ammonia will also occur especially in alkaline soils (Fuller 1975). Nitrogen will be removed from the system primarily by livestock grazing or harvesting if the crop is baled and transported off-site. If the crop is grazed by sheep, as expected, some of that nitrogen will be returned to the soil in manure and urine but most will be removed as mutton. Overall, the long-term trend resulting from pumping nitrate-rich water from the alluvial aquifer for irrigation of a *Atriplex* crop will be a reduction in the amount of nitrogen in the aquifer-soil-plant system.

### 3.1.5 Estimating *Atriplex* Biomass Production and Nitrate Uptake

Nitrogen uptake by *Atriplex canescens* can be estimated using measurements of biomass production, water use efficiency (WUE), and protein content. Glenn et al. (1998b) measured biomass production of *Atriplex nummularia* over 3 yr in outdoor drainage lysimeters in Tempe, Arizona. WUE was determined by dividing the annual biomass harvest (dry weight) by the annual volume of evapotranspiration. WUE did not vary significantly by year or by water source. Mean WUE was 1.57 grams dry shoot biomass per liter of irrigation. Assuming that WUE for *A. nummularia* and *A. canescens* are similar (both are $C_4$ shrubs from the same genus) then, based on the amount of water applied, the 1.57 value can be used to estimate biomass production of *A. canescens* at Monument Valley. Using this approach, the estimated maximum annual harvest over the 28 ha area (93,810 $m^2$) follows:

- Total maximum annual irrigation = $1.85 \times 10^5$ $m^3$/yr (from Section 3.1.3)

- WUE = 1.57 grams dry shoot biomass/liter irrigation water
  = 1.57 kg dry shoot biomass/$m^3$ irrigation water.

- Maximum annual harvest = 1.57 kg/$m^3$ WUE × $1.85 \text{x} 10^5$ $m^3$/yr irrigation
  = 290,450 kg dry shoot biomass/yr.

- Productivity = 10,373 kg/ha/yr × 1 metric ton/1,000 kg
  = 10.4 metric tons/ha (28.2 tons/acre).

Glenn et al. (1998b) also analyzed the nutrient content of *A. nummularia* (Table 3–1). Protein content in shoots (stems and leaves) was 10.4 percent. Given an N content of protein of approximately 16 percent, then,

- N content per unit biomass production = 0.104 kg protein/kg dry weight × 0.16 kg N/kg protein
  = 0.017 kg N/kg dry weight, and

- Maximum annual N uptake = 290,450 kg dry weight/yr × 0.017 kg N/kg dry shoot biomass
  = 4,938 kg N,
  = 176 kg N/ha/yr

Assuming the N content of shoots and roots is similar, as it is in many crops, then our estimate of the maximum annual N uptake from an *A. canescens* crop at Monument Valley is 9,875 kg. These are simplified calculations that do not take into account changes in productivity due to factors such as plant age. In general, *Atriplex* are known to be long-lived shrubs and agronomic experiments have shown that they can be grazed or harvested for many years (Osmond et al. 1980), but the irrigation schedule should be adjusted annually to account for changes in net productivity over time. During the pilot phase, a method for determining water and nitrogen demand based on soil-moisture levels and crop productivity will be developed.

### 3.1.6 Forage Value and Grazing Capacity of an *Atriplex canescens* Crop

The forage value of *Atriplex canescens* in a range setting has been demonstrated in a number of studies (e.g., Zartman et al. 1980). Leaf protein content of *A. canescens* is similar to alfalfa. Zartman et al. (1980) state that since the protein content of fourwing saltbush is comparable to major plant forage species like alfalfa and it can survive under saline and arid conditions, it should be considered as an alternate forage species.

The University of Arizona compared the value of *Atriplex barclayana*, similar to *A. canescens*, with conventional grass hay as the forage component in sheep-fattening diets. Lambs were fed mixes containing 30 percent *Atriplex* or other halophytes, or grass hay, from weaning up to final slaughter weight (80 kg per animal). The halophytes or hay supplied the total forage component of the diets. *Atriplex* and grass hay produced equal weight gains and the carcass quality was excellent. Other work has shown that *Atriplex* can be cut, dried, and baled similar to alfalfa. Hence, the planting at Monument Valley can be successfully utilized as sheep forage, either harvested and used off-site or grazed directly on-site.

The following example shows how much forage production could be achieved. A mature, 60 kg range-fed sheep requires 1.8 kg/day of dry matter intake for weight maintenance. *Atriplex* can make up at least 30 percent of the dry matter intake (Swingle et al. 1996), or 0.54 kg/day. When the *Atriplex* stand matures (after the second year of irrigation), approximately 50 percent of the net annual biomass production of the 290,450 kg can be removed by sheep, leaving enough standing biomass to regenerate a crop the following year. This production can support 268,935 sheep-days of grazing assuming 30 percent of a sheep's diet consists of *Atriplex*. If the crop is grazed for 155 days/yr when not under irrigation, the *Atriplex* crop could supply 30 percent of the diet for 1,735 grazing sheep, a large number. A more realistic way to utilize the crop may be to cut and bale a large portion of the annual production for wider distribution in addition to grazing of local animals. At 45 kg/bale, the annual production would be 3,227 bales of *Atriplex* hay if it were all baled.

### 3.1.7 Potential Adverse Effects of Nitrogen, Sulfate, and Salinity in Irrigation Water

This section considers the potential adverse environmental effects of irrigating an *Atriplex canescens* crop with water from the alluvial plume.

*Nitrogen*

Nitrogen is generally regarded as a limiting nutrient for plant growth; in natural or agricultural settings it is rarely present in amounts high enough to cause direct phytotoxicity. However, the alluvial plume at the Monument Valley site presents some special circumstances. Nitrate levels in the alluvial plume are as high as 1,200 parts per million (ppm). The University of Arizona previously grew *Atriplex canescens* in a greenhouse trial using water from Tuba City UMTRA wells (Baumgartner et al. 1996). Nitrate levels of 400, 1,060, and 2,120 ppm (92, 244 and 488 ppm as N) were tested. There were no significant differences in growth or tissue levels of N in *Atriplex* plants grown with the different water sources. Based on these results, *Atriplex* phytotoxic effects or high tissue levels from the alluvial nitrate plume at Monument Valley are not expected.

*Sulfate*

The mean and maximum sulfate concentrations measured in the alluvial plume are 755 mg/L and 3,540 mg/L, respectively (DOE 1998; Section 5.3). Baumgartner et al. (1996) tested the growth response of *A. canescens* to a range of sulfate levels in irrigation water, as high as 3,381 mg/L. No significant biomass responses were observed. At the extreme, *A. canescens* has been successfully grown on processed oil shale with sulfate levels as high as 42,336 mg/L (Richardson and McKell 1980). Although sulfur is an essential nutrient and excess sulfate can enhance plant growth (Mahler 1989), Baumgartner et al. (1996) measured no significant change in biomass of *Atriplex canescens* in response to varying sulfate levels.

*Salinity*

The impact of soil and water salinity is dependent on many factors: type and amount of salts present, soil texture, water application and infiltration rates, and the type of crop utilizing the saline water (Ayers and Wescott 1985). The mean and maximum total dissolved solids (TDS) measured in the alluvial plume were 1,506 mg/L and 5,800 mg/L, respectively (DOE 1998; Section 5.3). The mean TDS is within the range of a “slight to moderate” restriction on use for traditional crops such as wheat and vegetables (450 to 2,000 mg/L); the maximum TDS in the plume falls in the “potentially severe restriction” on use for traditional crops (>2,000 mg/L) (Ayers and Wescott 1985). However, these agricultural guidelines also state that “a salinity problem exists if salt accumulates in the crop root zone to a concentration that causes a loss in yield.”

*Atriplex canescens* has a very high physiological tolerance for salt; biomass production actually increases as salinity increases up to a point (Osmond et al. 1980). Richardson and McKell (1979) found no significant effect on the leaf biomass of fourwing saltbush when irrigated with water with an electrical conductivity as high as 38 decisiemens per minute (dS/m) (TDS of approximately 30,400 mg/L). Doria and Aldon (1993) found that 99 percent of fourwing saltbush greater than 18.5 cm high survived an 8 week irrigation with 100 percent sea water. Sea water typically has a TDS of 32,000 mg/L, more than 40 times the average TDS of the alluvial plume at Monument Valley.

The types of salt ions present in the alluvial aquifer will affect plants and soil differently. "Salt" is a broad term which describes a chemical compound composed of a cation and an anion other than $H^+$ and $OH^-$ or $O^{2-}$ (Chang 1988). Common constituents include cations sodium ($Na^+$), calcium ($Ca^{2+}$), and magnesium ($Mg^{2+}$) and anions chloride ($Cl^-$), carbonate ($CO_3^{2-}$), and sulfate ($SO_4^{2-}$). Table 3–2 gives the mean and range for concentrations of these constituents in the alluvial aquifer.

Soil salinity can also influence soil structure. The ratio of Na to Ca and Mg, called the Sodium Absorption Ratio (SAR), provides clues as to how the soil and ions will interact. The SAR of the alluvium aquifer ranges from a low of 11.5 to a high of 31. If the electrical conductivity of the irrigation water is greater than 2 dS/m and 5 dS/m with an SAR of 11 and 31 respectively, there should be no effect on infiltration (Ayers and Wescott 1985; Hanson et al. 1993). An adjusted SAR will need to be derived based on Ca and carbonate ($CO^3$) levels in the soils. The adjusted SAR accounts for the potential dissolution or precipitation of lime ($CaCO^3$), which will either increase or decrease the SAR (Hanson et al. 1993).

*Table 3–2. Ionic Concentrations in Alluvial Aquifer*

| Ion | Mean mg/L | Range mg/L |
|---|---|---|
| Calcium | 142.5 | 9.2 – 559 |
| Chloride | 24.6 | 5.2 – 106 |
| Magnesium | 115.3 | 6.3 – 600 |
| Potassium | 8.5 | 0.96 – 50.1 |
| Sodium | 115.2 | 21 – 251 |
| Sulfate | 755.3 | 26.7 – 3540 |

from DOE 1998; Section 5.3

The sandy soil texture (Section 3.1.1) and its uniformity to a depth of 4 feet is advantageous with respect to salinity. Large macropores in sand provide good drainage (Jury et al. 1991), and if the water table is at least 2 meters below the surface, then excessive salt accumulation should not occur with proper water applications (Ayers and Wescott 1985). Another advantage of sand is a low cation exchange (Miller and Donahue 1995). Cation adsorption to soil colloids is the mechanism for soil structure changes. If Na is the dominant cation (SAR is greater than 15), then its large hydrated radius can force the clay colloid structure apart potentially resulting in dispersed particles. Colloid dispersion can negatively impact a system by reducing infiltration. The opposite is true if Mg or Ca are the dominant cations. Their presence actually results in flocculation of soil particles, thereby often improving internal drainage (Miller and Donahue 1995).

Increases in soil salinity over time could cause a slight to moderate reduction in infiltration (Hanson et al. 1993), but only in soils with a clay content greater than 10 percent. Only the subpile soil area contains appreciable silt and clay fractions. Salt accumulation in this area can be monitored. It is anticipated that no reduction in infiltration will occur due to salinity because of the likelihood of high Ca content in the soil and the sandy soil texture. The overall uniformity in soil texture over the native plant farm area decreases the likelihood of "uncertainties of ionic concentration in the soil solution" (Osmond et al. 1980) and benefits the management of soil salinity.

### 3.1.8 Management of Recharge, Soil Nitrogen, and Soil Salinity

*Recharge*

The irrigation system will be designed and managed to supply water at a rate so that the crop matures under deficit irrigation—all the water added will be consumed by the crop. Due to the high salt tolerance of *Atriplex*, a leaching fraction is not required. Management of recharge will be especially important to prevent leaching from the ammonium-contaminated subpile soil, a possible source of alluvial aquifer nitrate. A soil water monitoring program using neutron hydroprobe data will be used to optimize irrigation rates as the crop matures during the first 3 yr of the project. These data will be used to modify the irrigation schedule as needed to match the consumptive water use requirements of the crop to avoid adding excess water and causing recharge of nitrate.

*Nitrogen*

If the crop is irrigated with high-nitrate plume water, there may be a net accumulation of nitrate in the root zone over time. Nitrate could ultimately reach levels injurious to plants. Phytotoxic levels of nitrate will be determined in the greenhouse study (Section 4.0). It will be important to determine the appropriate nitrate content of irrigation water pumped from the alluvial plume to avoid nitrate buildup. Blending water from different sources may be necessary. An estimate of the optimum nitrate concentration in irrigation water, based on the nitrate uptake calculations (Section 3.1.5) follows:

- Nitrogen requirement in water supply = 9,875 kg N / $1.85 \times 10^5$ $m^3$ water (Section 3.1.5)
  = $5.34 \times 10^{-2}$ kg/$m^3$ N
  = 53.4 mg/L N

- Nitrate requirement in water supply = 53.4 mg/L N × 4.35 mg $NO_3^-$/mg N
  = 232 mg/L $NO_3^-$

Nitrogen incorporated into shoot and root tissues will either be exported from the site as mutton or baled hay, or returned to the soil in plant litter, sheep manure and urine. Microbial and plant nitrogen cycles will be enhanced due to a combination of high nitrate inputs and high soil moisture and carbon levels from irrigation and litter production.

*Salinity*

The alluvial plume contains less than 500 mg/L sodium chloride (DOE 1998; Table 5–8). The study by Glenn et al. (1998b) found that, up to a leachate salinity of 39,201 mg/L TDS, *Atriplex nummularia* did not show yield reductions. From this we can calculate a theoretical required leaching fraction to control salts,

- Irrigation salinity/drainage fraction = 500 mg/L / 39,201 mg/L
  = 0.012

- Drainage requirement = 0.012 × 197 cm/yr water requirement
  = 2.5 cm/yr irrigation water above consumption.

This small amount can be supplied by natural rainfall (mean annual precipitation = 16.8 cm).

Assuming no leaching and disregarding uptake of salts by *Atriplex*, the total salt storage in the root profile after 10 yr of irrigation can be estimated as,

- Total salt storage after 10 yr = 1.97 $m^3$ irrigation/$m^2$/yr × 500 mg/L salt × 10 yr
  = 9.85 kg/$m^2$ salt in root profile over 10 yr.

However, *Atriplex* plants scavenge soil salts; plant tissues contain 15.1 percent salt content at harvest (Glenn et al. 1998b). Over 10 yr, the amount (theoretically) removed by the *Atriplex* crop would be

- Total salt used by *Atriplex* after 10 yr = 290,450 kg/yr shoot biomass × 15.1% salt × 10 yr
  = 438,580 kg salt.

- Salt used per $m^2$ area = 438,580 kg salt / 93,810 $m^2$ planted area
  = 4.7 kg/$m^2$ salt.

Some salt scavenged by *Atriplex* will be returned to the soil in the litter fraction, some will be removed from the site by grazing animals or by baling and exporting the harvest, and some will return to the soil via animal manure and urine. At any rate, based on the *A. nummularia* study, the accumulation of salt in the root zone will be substantially less than levels that would cause growth reduction (Glenn et al. 1998b). On retiring the *Atriplex* farm, the salts in the root zone will continue to be harvested (depleted) by the *Atriplex* plants; very little would be leached into deeper soil layers by precipitation unless the area is overgrazed. Therefore, there appears to be little likelihood that the salt will represent a problem requiring further remediation, either at the surface or in the aquifer.

## 3.2 Phytoremediation of the Alluvial Aquifer and Subpile Soils

Nitrate levels in the alluvial aquifer, as high as 1,200 mg/L, exceed EPA's MCL for UMTRA sites (Section 2.1). Residual ammonium in subpile soils may be a continuing source of alluvial aquifer nitrate (Section 2.2). Phytoremediation of these areas would involve managing native vegetation growing over the alluvial nitrate plume and in subpile soils for the purpose of extracting nitrate and ammonium.

### 3.2.1 Alluvial Plume Phytoremediation

The term phreatophyte refers to plants that extract water and nutrients from a permanent ground water supply. Two native phreatophytes, *Sarcobatus vermiculatus* (black greasewood) and *Atriplex canescens* (fourwing saltbush), grow in the alluvial plume at Monument Valley (Section 2.3.1); the former is considered an obligate phreatophyte while the latter is a facultative phreatophyte. The *Sarcobatus* and *Atriplex* populations are currently in poor condition because of heavy grazing and possibly herbicide applications (Section 2.3.2). The success of phytoremediation will be dependent on (1) protecting *Sarcobatus* and *Atriplex* populations growing in the plume from grazing; and (2) accelerating recovery and expansion of these populations by planting the plume area.

Evidence from rooting depth literature, photograph comparisons, and observations of plant succession at the site support the premise that phytoremediation may contribute significantly to cleanup of nitrate in the alluvial aquifer. *Sarcobatus* and *Atriplex* populations already cover a large portion of the plume area (Figure 2–2). The rooting-depth literature indicates that the plume is potentially within reach of *Sarcobatus* and *Atriplex* roots (e.g., Nichols 1993; Charles et al. 1987; Branson et al. 1981) providing a way for plants to extract nitrate directly from the plume. A comparison of recent and old photographs suggests that the *Sarcobatus* population may be a consequence of milling activities, that the population has spread over the past 15 yr, and that plants growing in the plume area are much larger than plants growing outside the plume area, apparently a response to nitrate fertilization. Furthermore, *Sarcobatus* and *Atriplex* plants established and grew rapidly in an area now protected from grazing that had been disturbed during surface remediation only 4 yr ago (Section 2.3.2). Planting and protecting *Sarcobatus* and *Atriplex* in other areas of the plume may accelerate population expansion and greatly increase productivity and nitrate uptake.

A simple calculation provides a first-order estimate of nitrate uptake by phreatophytes. If a high productivity phreatophyte community (protected from grazing) consisting of *Sarcobatus vermiculatus* and *Atriplex canescens* covered half of the 44 mg/L plume, an area of approximately 50 ha, it could significantly increase the remediation of nitrate in addition to what can be accomplished by the irrigated *Atriplex canescens* planting. Assuming an evapotranspiration rate of 0.3 meters per yr for a stand of

*Sarcobatus* (Nichols 1994), and using the nitrogen content and WUE values obtained for *Atriplex canescens* as representative of the phreatophyte community (Section 3.1.4.2), then the productivity and nitrate uptake of 50 ha of phreatophytes would be approximately

- Productivity = 1.57 kg dry-weight shoot biomass/$m^3$ water × 0.3 $m^3$ water/$m^2$/yr
  = 0.47 kg biomass/m2/yr
  = 235,000 kg dry-weight shoot biomass/yr

- Nitrate uptake = 0.017 kg N/kg dry-weight shoot biomass × 235,000 kg dry-weight shoot biomass
  = 3,995 kg/yr of N taken into the shoots,
  = 17,378 kg/yr of $NO_3^-$ taken into the shoots.

This compares to the estimate of 4,938 kg/yr of N (21,480 kg/yr $NO_3^-$) taken up into the shoots of a 28 ha irrigated *Atriplex canescens* crop. The pilot study will estimate actual and potential rates of water use and nitrogen uptake by the phreatophyte community at Monument Valley.

### 3.2.2 Subpile Soil Phytoremediation

Phytoremediation of ammonium and nitrate in subpile soil is also feasible. High ammonium and nitrate occurred in one hand-augured soil boring in the northern portion of the New Tailings Pile area (Section 2.2). While ammonium is not on EPA list of contaminants of concern, ammonium in subpile soil may generate nitrate that could enter the alluvial system. *Salsola iberica* (Russian thistle), an exotic annual weed, currently grows in the subpile soil area. In the fall of 1997, the extent of elevated soil ammonium was very apparent from the relative size and abundance of *Salsola* plants; most of the population consisted of small scattered plants, however, many large *Salsola* grew in the area reported to have high soil ammonium.

The *Atriplex* farming operation will be managed to accelerate plant extraction of ammonium from the subpile soil area. This will be accomplished by managing the irrigation system within the subpile soil area of the native plant farm to enhance ammonium uptake, create a favorable soil water balance, and prevent ground water recharge leaching of nitrogen.

The pilot study will explore two approaches for dealing with the high-ammonium part of the site: irrigate with clean well water until the ammonium is utilized, or irrigate with the same nitrate-enriched water that the rest of the site will receive. The choice of action will depend upon the availability of clean water, the size of the ammonium-contaminated parcel, and the results of soil nitrate monitoring. In general, plants take up either the ammonium ion or nitrate with high efficiency. However, halophytes such as *Atriplex canescens* typically have twice the affinity for ammonium than nitrate and take up ammonium preferentially when both are present in equal concentrations (e.g., Morris 1980). The presence of ammonium may actually depress the capacity of *Atriplex* for nitrate uptake. This may affect the efficiency with which *Atriplex* plants in the ammonium-contaminated portion of the site extract nitrate from the soil and irrigation supply.

If the high ammonium part of the site is irrigated with nitrate-enriched water, we expect that plants will preferentially remove the soil ammonium rather than nitrate in the irrigation supply. This will lead to a diminution of the ammonium level in the root zone and an increase in nitrate level. Since the plants will be deficit-irrigated, there will be little discharge past the root zone. Depending upon how much ammonium is present, after several seasons the ammonium will be gone and *Atriplex* plants will begin to utilize nitrate present in the irrigation water and stored in the root zone. If levels of nitrate in irrigation water are moderated, it may be possible to remediate the ammonium-contaminated portion of the site by irrigating with the same plume water as will be applied to the rest of the site; ammonium in the soil will initially be replaced by nitrate which will eventually be absorbed by the *Atriplex* crop.

Finally, it may be desirable to have a closer plant spacing (extra rows of plants) in the ammonium contaminated part of the site, to speed remediation. If the ammonium-contaminated soil covers an appreciable area, however, it may be preferable to irrigated this portion of the site with nitrate-free water initially, until the ammonium is removed by the plants, to avoid loading a large area of the surface soil with excess nitrate.

# 4.0 Pilot Study Data Needs and Design

Section 3.0 demonstrates the potential for remediating nitrate and ammonium in the alluvial aquifer and subpile soils at the Monument Valley site by planting and managing native vegetation, in combination with other treatment options. Remediation using native plants would be highly desirable as it would improve the surface ecology and range value of the site, which was severely degraded by uranium milling and subsequent activities to remove the surface contamination. A combination of (1) irrigating a native forage farm with nitrate-contaminated water from the alluvial aquifer; (2) phytoremediation of alluvial aquifer nitrates with native phreatophytes; and (3) phytoremediation of residual ammonium in subpile soils with native forage species, could remediate the site within 20 yr. However, the feasibility of phytoremediation will require site-specific information. This section summarizes data needs and describes experimental plans for field and greenhouse studies.

## 4.1 Summary of Data Needs

The following is a summary of site-specific data needed to fully evaluate the native plant farming and phytoremediation alternatives for Monument Valley.

### 4.1.1 Native Plant Farming

- Feasibility will be tested initially using a 0.4 ha, drip-irrigated pilot farm planted with *Atriplex canescens* at 3-meter spacing between rows. The farm will be irrigated at four rates determined as percentages of local potential evapotranspiration, in order to determine productivity, water use, and nitrogen uptake as a function of water application. Nitrate-contaminated water from the plume will be used as the irrigation source.

- Irrigation system capacity and design.
  The estimated maximum annual water requirements for high productivity of a 28 ha *Atriplex canescens* farm is $1.85 \times 10^5$ $m^3$/yr ($4.89 \times 10^7$ gallons/yr); the maximum daily requirement is $1.41 \times 10^6$ liters/day ($3.8 \times 10^5$ gallons/day) (Section 3.1.3). However, *Atriplex canescens* can be established on as little as 2.5 percent of this. The final design of the irrigation system will depend on water delivery rates for the alluvial plume.

- Nitrate concentration in irrigation water.
  The estimated optimum nitrate concentration in irrigation water for *Atriplex canescens* is 232 mg/L (Section 3.1.8). Higher levels could cause soil nitrate buildup. Nitrate concentrations in the alluvial plume vary from 44 mg/L to 1,200 mg/L. Blending water from different parts of the plume to achieve the optimum concentration is an option. This will require volume-weighted estimates of nitrate concentrations in the plume and strategic placement of extraction wells.

- *Atriplex canescens* crop water requirements.

  The estimated maximum irrigation rate for the *Atriplex canescens* crop (Section 3.1.3) is based on data for *Atriplex nummularia* at a different site. Development of a long-term irrigation management plan will require water requirement data for *A. canescens* at Monument Valley.

- *Atriplex canescens* productivity.
  Productivity (biomass production rate) of the *Atriplex canescens* crop is needed to determine nitrogen uptake and potential harvest. The current productivity estimate (Section 3.1.5) relies on data for *Atriplex nummularia* at a different site.

- *Atriplex canescens* WUE.
  WUE (dry-weight biomass production per unit water transpired) of the *Atriplex canescens* crop is needed to estimate productivity and nitrogen use for a given irrigation rate. Again, the current WUE estimate relies on data for *Atriplex nummularia* at a different site (Section 3.1.3).

- Nitrogen content of *Atriplex canescens* biomass.
  The total nitrogen content of *Atriplex canescens* plant tissues for a range of nitrate concentrations in irrigation water will be needed to estimate nitrate uptake given the productivity of the crop.

- Grazing and/or harvest capacity of *Atriplex canescens* forage.
  Section 3.1.6 indicates that up to 50 percent of the *Atriplex* crop can be harvested annually, either grazed or cut and baled, without impacting the next year's production. Annual production should be monitored and harvest rates modified as needed to assure high sustained yields.

- Forage management and animal product safety.
  Methods must be developed for utilizing the increased forage production that are consistent with Navajo resource management practices and regulation. The safety of forage for animals and the safety of the animal products for humans must be established and included in a public education program.

- Soil water balance, nitrate, sulfate, and salinity monitoring.
  If the irrigation rate surpasses water use by the *Atriplex* crop, nitrates and salts could pass below the root zone and eventually recharge the alluvial aquifer. Conversely, if recharge is controlled, theoretically, soil nitrates, sulfates and other salts could build up in the root zone causing adverse environmental effects (Section 3.1.7). Recharge of soil nitrates and salts should be monitored and irrigation management practices modified as needed.

### 4.1.2 Alluvial Aquifer Phytoremediation

- Mature phreatophyte productivity.
  Phytoremediation of the alluvial plume will rely on two native phreatophytes, *Sarcobatus vermiculatus* and *Atriplex canescens*. The existing populations have been decimated by overgrazing and possibly herbicide spraying (Section 2.3.2). The productivity of mature *Sarcobatus* and *Atriplex* plants growing in the plume area, both grazed and protected from grazing, is needed to evaluate nitrate and water uptake rates for a range of possible management practices.

- Establishment, growth, and survival of phreatophyte transplants.
  *Sarcobatus* and *Atriplex* populations already cover a large portion of the alluvial plume area. However, it may be possible to increase the distribution and abundance of these populations and accelerate nitrate extraction by planting and irrigating *Sarcobatus* and *Atriplex* seedlings (Section 3.2.1). Data on establishment, growth, and survival of *Sarcobatus* and *Atriplex* transplants in both grazed and protected areas are needed to assess the added value of a large-scale plantings versus simply protecting the existing populations.

- WUE and total water use by a *Sarcobatus* and *Atriplex* community.
  The productivity of the phreatophyte community determined in the field can be used to estimate the transpiration rate and the total water use by the phreatophyte community if WUE is known. WUE can be determined in the greenhouse.

- Nitrogen content of *Sarcobatus* biomass.
  Nitrate uptake by *Sarcobatus vermiculatus* can be estimated from productivity if the nitrogen content of *Sarcobatus* tissues is known.

- Fractionation of alluvial water and vadose zone water in the transpiration stream.
  Estimation of discharge from WUE assumes that uptake of vadose zone water is insignificant. Isotope ratios in the transpiration stream can be used to estimate the fractions of water supplied by the alluvial plume and by precipitation stored in the vadose zone.

### 4.1.3 Subpile Soil Phytoremediation

- Extent of elevated ammonium in subpile soils.
  A major unknown is the extent of elevated ammonium in the subpile soil. Ammonium distribution, soil texture, electrical conductivity, sodium absorption ratio, and initial nutrient levels are needed to develop an appropriate irrigation plan.

- The subpile soil ammonium area lies within the proposed *Atriplex* farm.
  Because *Atriplex* preferentially removes ammonium from soils high in both ammonium and nitrate, irrigation of the subpile soil with alluvial plume water could cause a buildup of soil nitrate (Section 3.2.2) to a point that *Atriplex* is adversely affected. Ammonium and nitrate monitoring data are needed to document ammonium removal rates and soil nitrate levels.

## 4.2 Pilot Study Design

Three components of the pilot study are planned (1) a greenhouse study of plant water use, nitrogen uptake, and phytotoxicity; (2) a native plant farm operation irrigated with nitrate plume water; and (3) phytoremediation of nitrate in the alluvial aquifer and ammonium in subpile soils.

### 4.2.1 Greenhouse Study

The University of Arizona is conducting a separate greenhouse study (not funded by DOE) that will provide plant physiological data that will be used to interpret field study results. The greenhouse study, when coupled with data from the phytoremediation and native plant farming studies, will be used to estimate crop water use, nitrogen uptake, and possible phytotoxicity. The greenhouse study will also generate contaminant accumulation data for *Sarcobatus* and *Atriplex* that will be useful for ecological risk assessments at Monument Valley and other UMTRA sites.

A four-block experiment using approximately 80, 8-liter drainage lysimeters filled with two soil types will be set up in a greenhouse experiment at the University of Arizona's Environmental Research Laboratory. Two native species, *Sarcobatus vermiculatus* and *Atriplex canescens*, will be tested. The experiment will measure growth response, water use, nitrogen uptake and incorporation into plant tissues, and forms of nitrogen in plant tissues, in response to increasing levels of nitrate in the water supply. The two soil types will be (1) sandy soil typical of most of the site; and (2) soil collected from the ammonium-contaminated portion of the subpile soil. The experiment will provide preliminary information on the ability of the plants to grow and extract nitrogen from water with varying levels of nitrate, and the ability of plants to grow and extract nitrogen from the ammonium-contaminated soil. The experiment will be run in water with a NaCl content typical of the site ground water (ca. 500 ppm). A separate experiment will be conducted in which both plant types are irrigated in four replicates each with two water supplies (1) tap water plus plant nutrients; and (2) tap water plus plant nutrients and a mix of potentially toxic elements found in the Monument Valley ground water, using the levels equivalent to the highest levels encountered in the ground water. The elements and levels to be tested are As (0.01 ppm), Ba (0.4 ppm), Mn (0.1 ppm), Mo (0.17 ppm), Se (0.0318 ppm), V (0.7 ppm), and Fl (1.0 ppm). Other elements of potential concern were below detection levels. The plants will be irrigated with test solutions for approximately 60 days, then the concentration of each element will be determined in leaf and stem tissues, and compared with risk guidelines recommended for livestock forage crops developed by the National Academy of Sciences.

Five levels of ammonium, nitrate, and sulfate, and background levels of sodium, chloride, arsenic, barium, selenium, fluoride, and boron, will be applied via irrigation water. Application levels are given below. The control application will consist of distilled water plus quarter-strength Hoaglands solution.

| Constituent | Application Amount (mg/L) |
|---|---|
| Ammonium | 2, 20, 200, 400, 800 |
| Nitrate | 7, 69, 687, 1,373, 2,747 |
| Sulfate | 5, 53, 533, 1,065, 2,130 |
| Sodium | 3,771 |
| Chloride | 3,035 |
| Arsenic | 0.4 |
| Barium | 10.0 |
| Boron | 5.0 |
| Selenium | 0.5 |
| Fluoride | 40 |

Plant response to the irrigation applications will be measured by comparing the Relative Growth Rates of the plants using initial and final dry weights, as well as the canopy volume and stem lengths. Constituent levels will be measured in the leachate throughout the experiment and in the soil and plants at the start and culmination of the experiment. Soil, plant, and water analyses will be conducted at the

University of Arizona's Soil, Water, and Environmental Science Laboratory following EPA standards. The weighing lysimeters will be used to measure soil water balance and evapotranspiration.

### 4.2.2 Native Plant Test Farm

An irrigated planting of *Atriplex canescens* in the area where tailings and contaminated soils were removed will serve several purposes:

- satisfy DOE's obligation to revegetate areas left denuded after completion of the surface remediation,
- remediate and develop an agricultural use of the alluvial nitrate plume,
- recover ammonium from subpile soils, removing a likely ground water nitrate source,
- produce a high quality native plant forage for local land users,
- compensate local land users for loss of grazing rights to the area overlying the alluvial plume, if the phreatophyte phytoremediation alternative (Section 4.2.3) is selected, and
- reclaim the potential rangeland vegetation of the site after irrigation ceases.

This work plan includes tasks for designing the *Atriplex* farm (Section 5.0). Designing the planting, irrigation, and maintenance of the farm will depend, in part, on water and land use decisions made by DOE and the Navajo Nation. The *Atriplex* farming operation may continue for several years if it is selected as a key remediation process or, if other remediation alternatives are selected, irrigation and maintenance may last only as long as it takes to revegetate the area. The final design will also be influenced by the following factors:

- the number of alluvial aquifer wells and pumping rates,
- predicted effects of pumping on ground water hydrology and phreatophyte ecology,
- actual nitrate utilization rates as determined by the pilot study,
- effects of irrigating with plume water on the soil water balance and soil chemistry as determined by the pilot study,
- the extent of high subpile soil ammonium concentrations and determined by the pilot study,
- the balance of potential benefits and adverse effects on land management practices in the area, and
- the cost of developing this agricultural use of the plume versus other remediation techniques (DOE 1998; Section 8.0).

A 0.4 ha pilot farm will be constructed to test the feasibility of native plant farming. The assumption is that the *Atriplex* farm will be used for nitrate remediation, will be harvested, and the harvest utilized as forage for sheep off site, with more limited direct grazing of sheep and other livestock on site.

The planting will consist of double rows 3-meters apart with plants spaced 1-meter apart within rows. The wide spacing between rows will provide a corridor to give livestock access to the plants and to allow entry of harvesting equipment. The space between rows will be seeded with a mixture of cool- and warm-season grasses to stabilize the soil and provide additional forage. A seeding rate of 2.35 grams per square meter will be used.

A drip irrigation system is currently proposed because (1) it targets the plants; (2) the infiltration depth can be controlled; and (3) water is conserved. Emitters with a 5 liter per hour capacity will be installed. Filters and acidifiers (if necessary) will be installed to prevent plugging of emitters by sediment or scale.

Routine irrigation, grazing, and harvest management practices will be developed. Soil water content and depth will be monitored at least monthly during the irrigation season (April through October) with a neutron hydroprobe in probe ports installed using a systematic placement in the planted *Atriplex* rows. Soil sampled from the root zone of *Atriplex* during installation of the probe ports initially, and then repeated semi-annually, will be analyzed to monitor the status of nitrate, sulfate, and other salts in response to irrigation. Plant density will be sampled initially to evaluate *Atriplex* seedling emergence and survival. Thereafter, shoot tissues will be sampled at the end of each growing season to estimate shoot productivity, leaf area index, and nitrogen content. Productivity data will be used for forage production estimates and to establish grazing rates (animal unit months). The productivity and nitrogen content data, coupled with WUE data from the laboratory (Section 4.2.1), will be used to estimate nitrogen uptake rates and crop water use.

### 4.2.3 Phytoremediation Field Studies

An irrigated planting of *Atriplex* will be managed to enhance phytoremediation of elevated ammonium in subpile soils (Section 3.2.2). The lateral extent and depth of elevated soil ammonium will be determined by analysis of subpile soil samples. The 1997 subpile soil analysis (DOE 1997, Section 4.5) and the extent of the stand of large *Salsola* will guide the selection of sampling strata. For 3 to 5 yr thereafter, soils in the high ammonium area (Section 4.2.2) will also be analyzed for ammonium, as well as nitrate and other salts, to monitor the response of the ammonium nitrate balance to irrigation. These data are needed to determine whether nitrate concentrations in irrigation water must be moderated for the subpile soil area by blending with clean water (Section 3.2.2).

The alluvial aquifer phytoremediation field study consists of two parts; a mature plant study and a planting study.

*Mature Phreatophyte Study*

The purpose of the mature plant study is to evaluate recovery, from overgrazing and herbicide applications, of existing *Sarcobatus vermiculatus* and *Atriplex canescens* populations growing in the alluvial plume (Section 2.3.2). Mature plants of both species will be selected in different areas encompassing the range of depths to the alluvial plume and the range of nitrate concentrations in the plume. Livestock exclosures, approximately 2 meters by 2 meters, will be erected around each plant. Six replicate exclosures will be erected for each condition. Six control plants (not protected from livestock grazing) adjacent to protected plants will be tagged.

Protected and unprotected plants will be trimmed at the start of the experiment, measured, and tagged. The extent of regrowth will be measured monthly by estimating leaf area index and canopy volume of green tissues. At the end of the growing season, shoot biomass production will be estimated by trimming plants back to the original dimensions. Plant tissues will be analyzed for total nitrogen. The deuterium method will be investigated to estimate the fraction of water supplied by the vadose zone and by the alluvial aquifer. Total water use will be estimated from the growth increment and from the WUE determined in the greenhouse (Section 4.2.1). Nitrate uptake will be estimated from nitrogen concentrations in tissues and shoot production. Effects of varying nitrate concentrations in the aquifer on nitrate uptake will be evaluated in the greenhouse study (Section 4.2.1).

*Phreatophyte Planting Study*

Planting and protecting *Sarcobatus vermiculatus* and *Atriplex canescens* in areas overlying the alluvial plume, where these species are currently sparse, overgrazed, or lacking, may accelerate phytoextraction of nitrate (Section 3.2.1). The purpose of this planting test is to evaluate whether transplanting and irrigating seedlings is a practicable method for expanding these populations over a larger area of the plume.

Containerized seedlings of *Sarcobatus* and *Atriplex* will be grown from local assessions in the greenhouse. The DOE’s ongoing revegetation study at Tuba City, Arizona, indicates that transplanting is more cost effective that direct seeding these species because of greater establishment and survival rates. Seedlings will be planted in three plant communities within the plume area; the SAVE/ATCO(1) (*Sarcobatus vermiculatus / Atriplex confertifolia*), SAVE/ATCO(2), and ATCA/HAPL (*Atriplex canescens / Haplopappus pluriflorus*) associations (see Figure 2–2). Three livestock exclosures will be erected at random locations in each association. Ten seedlings each of the two phreatophytes will be planted in the exclosures on 0.4 meter spacing. Seedlings will be fertilized at 60-day intervals with Osmocote. Seedlings will be irrigated with approximately 100 liters of water per exclosure using irrigation systems consisting of holding tanks and drip lines. Holding tanks will be refilled from a pickup-mounted water tank. Irrigation will continue from April through September for 2 yr. Seedling survival and plant dimensions will be measured periodically for 3 yr.

# 5.0 Task Descriptions and Schedule

| Task No. | Task Description | Start Date | End Date |
|---|---|---|---|
| | <u>University of Arizona Greenhouse Study</u> | | |
| 1. | Set Up Experiment 1.<br>Fill 2-gallon weighing lysimeter buckets with soil from the plume area of the Monument Valley site. Re-pot *Sarcobatus vermiculatus* and *Atriplex canescens* var. *angustifolia* from germination cells into weighing lysimeters and arrange pots on tables according to the experimental design. | 4/27/98 | 9/30/98 |
| 2. | Begin Experiment.<br>Trim all plants to the same starting height. Sample soil and plant tissues to establish baseline concentrations of nitrogen and contaminants. Mix irrigation solutions and apply to lysimeters. | 5/7/98 | 5/7/98 |
| 3. | Monitor Experiment.<br>Record daily leachate amounts and lysimeter weights. Measure weekly leachate volumes and store for later analysis. Subsample aliquots from the weekly cache of leachate and submit for laboratory analyses. Record plant growth (height and canopy dimensions) on a weekly basis. | 5/7/98 | 7/6/98 |
| 4. | Complete Experiment/Analyze Data.<br>Collect final leachate samples and prepare for chemical analyses. Weigh lysimeters and measure final plant height and canopy dimensions. Dry, weigh, and process plant tissues for chemical analyses. Collect final soil samples and submit to the laboratory for analysis. | 7/6/98 | 7/20/98 |
| 5. | Set Up Experiment 2.<br>Plants will be set up as for Experiment 1 and irrigated for approximately 60 days on tap water + nutrients or tap water + nutrients + trace elements. Plant tissues will be analyzed for the accumulation of trace elements in leaves and stems, and a final report will be prepared. | 7/16/98 | 9/30/98 |

| Task No. | Task Description | Start Date | End Date |
|---|---|---|---|
| | <u>Native Plant Farming Pilot Study</u> | | |
| 1. | Develop Public Education Program.<br>In cooperation with DOE and the Navajo Nation, develop a public awareness program to inform residents of the possible beneficial use of nitrate plume water, and of the steps underway to determine the feasibility of this and other remediation options. The information program will also be a forum for discussion of the need for grazing management over the affected area, including the natural vegetation over the plume.<br><br>Residents of the Kane Valley, Halchita, and Monument Valley area understand the potential health risks associated with using the nitrate plume as a drinking water source. Recovery of plume water as a resource for livestock forage production may seem contrary to the perception that the water is poisonous. | 10/1/98 | 9/30/99 |
| 2. | Survey Extent of Arable Acreage.<br>Determine, using aerial photographs and field reconnaissance, the arable portion of the remediated area; the portion that could be used for the native plant farm.<br><br>Part of the mill site and tailings areas remediated under the UMTRA Surface Program consists of rock outcrops. | 8/10/98 | 9/30/98 |
| 3. | Acquire and Test Seed.<br>The Navajo Department of Agriculture acquired a large quantity of *Atriplex canescens* seed that had been confiscated from illegal seed collectors.<br><br>Acquire and germinate samples of the confiscated *Atriplex* seed and determine the ratio of subspecies (*A. canescens* var. *angustifolia* and *A. canescens* var. *occidentalis*), the purity, and the viability of the supply. Develop seeding rates for subspecies based on the ratio of pure live seed. | 8/24/98 | 9/30/98 |
| 4. | Design Irrigation System.<br>A drip irrigation system that conserves water and limits erosion is currently envisioned for the 1-acre *Atriplex* farm pilot study. The final design will be based on several factors: water delivery rate from wells, nitrate concentration in irrigation water, need for water blending, arable acreage, proportion crop grazed versus harvested, soil water retention characteristics, and initial soil chemistry. | 8/24/98 | 9/4/98 |

| Task No. | Task Description | Start Date | End Date |
|---|---|---|---|
| 5. | Prepare Soils and Seedbed.<br>In the 1-acre test plot, rip soils compacted by heavy equipment during the surface remediation of the site; rip along the contour in rows 3 meters apart.<br><br>Preliminary results from DOE's Tuba City revegetation study shows that deep ripping can improve *Atriplex* establishment and growth. | 9/7/98 | 9/30/98 |
| 6. | Install Neutron Hydroprobe Access Ports.<br>Install approximately 20 neutron hydroprobe ports in the ripped rows prior to planting. Use an auger mounted on a bobcat tractor to install the probe ports; use either thin-walled aluminum tubing or schedule 40 PVC pipe. Retain soil profile samples from the 20 probe ports for chemical analyses. | 9/7/98 | 9/30/98 |
| 7. | Install Irrigation System.<br>Assuming the data required to complete the irrigation system design are available and the design is complete by the end of July, install the system in early August prior to sowing of seed. | 9/14/98 | 9/30/98 |
| 8. | Seed *Atriplex* Rows.<br>Develop a seeding rate based on the percent pure live seed, as determined in the greenhouse, to attain an average density of 3 plants per $m^2$. Broadcast seed in ripped rows and cover seed by dragging a length of chain-link fence.<br><br>Planting in pairs of rows one meter apart with pairs separated by a 3-meter corridor will achieve a combination of high productivity (and nitrogen uptake) and access for grazing animals. | 9/14/98 | 9/30/98 |
| 9. | Begin Irrigation and Soil Water Monitoring.<br>Initially, use irrigation rates that match the water requirements for other *Atriplex* farms (Section 3.1.3). Over time, use the neutron hydroprobe monitoring of the soil water to refine irrigation rates. | 9/21/98 | 9/30/98 |
| 10. | Soil Chemistry Monitoring.<br>Analyze soil samples from installation of hydroprobe ports in the 1-acre test plot to establish baseline soil chemistry (nitrogen, sulfate, salinity, and nutrients). Thereafter, monitor soil chemistry semi-annually for the duration of the irrigation project. | 10/1/98 | 10/30/98 |
| 11. | Monitor Vegetation Establishment.<br>Sample *Atriplex* density twice during the 1999 growing season to evaluate seedling establishment and survival rates. Monitor productivity and nitrogen content semi-annually for 3 yr to estimate crop water use and nitrogen uptake. Use these data, as needed, to fine-tune irrigation rates and nitrogen concentrations. | 6/1/99 | - |

| Task No. | Task Description | Start Date | End Date |
|---|---|---|---|
| | <u>Subpile Soil Phytoremediation</u> | | |
| 1. | Characterize Subpile Soils.<br>Analyze soil samples obtained from the subpile soil area and map the extent of subpile soil ammonium (this task is complete). | 8/1/98 | 8/14/98 |
| 2. | Install Subpile Soil Irrigation System, Prepare Soils, and Plant *Atriplex*.<br>Install an irrigation system in the subpile soil area that allows either blending of plume water and “clean” well water, or irrigating exclusively with clean water. Recontour soils as needed. Plant *Atriplex* in the high ammonium area. | 9/7/98 | 9/30/98 |
| 3. | Monitor Soil Ammonium.<br>In addition to monitoring nitrate, sulfate, salinity, and nutrients, also monitor, semi-annually, ammonium depletion in the subpile soil area. | 10/1/98 | 9/30/99 |
| | <u>Alluvial Aquifer Phytoremediation</u> | | |
| 1. | Grow Transplants.<br>*Sarcobatus vermiculatus* and *Atriplex canescens* var. *angustifolia* seed were planted in germination cells at a University of Arizona greenhouse in February and are ready for transplanting. (This task is complete.) | 2/2/98 | 4/30/98 |
| 2. | Select and Fence Test Plot Locations.<br>Select locations for the fenced and grazed paired plots for mature *Sarcobatus* and *Atriplex*. Select locations in at least three of the vegetation associations overlying the nitrate plume: SAVE/ATCO(1), SAVE/ATCO(2), and ATCA/HAPL (Section 2.3). Select and fence test plot locations for transplanted *Sarcobatus* and *Atriplex* in these vegetation associations and also in the SAIB/AMAC association. Erect three replicate plots in each association. (This task is complete.) | 5/11/98 | 5/15/98 |
| 3. | Plant and Fertilize Test Plots.<br>Plant ten seedlings each of *Sarcobatus* and *Atriplex* in small depressions on 0.4 meter spacing in each fenced exclosure. Fertilize seedlings bimonthly with Osmocote. (This task is complete.) | 5/11/98 | 5/29/98 |
| 4. | Irrigate Test Plots.<br>Set up a simple irrigation system consisting of a small reservoir and drip lines at each of 12 transplanted test plots. Hire a resident of Kane Valley to irrigate transplants weekly, 100 liters each, and refill reservoirs with clean water using a pickup-mounted water tank. Continue irrigation for two growing seasons. (Ongoing.) | 5/4/98 | 9/30/98 |

| Task No. | Task Description | Start Date | End Date |
|---|---|---|---|
| 5. | Monitor Plant Establishment, Survival, and Growth.<br>Check plant survival monthly during the first growing season and semi-annually for two additional growing seasons; one growing season after irrigation ceases. Measure plant height and canopy dimensions annually during the first two growing seasons and sample productivity the third growing season. (Ongoing.) | 6/15/98 | 9/30/98 |

# 6.0 References


Ayers, R. S. and D. W. Wescot, 1985. Water Quality for Agriculture, FAO #29. Food and Agriculture Organization of the United Nations, Rome.

Ball-Coelho, B. and R. Roy, 1997. "Overseeding Rye into Corn Reduces $No^3$ Leaching and Increases Yields," *Canadian Journal of Soil Science* 77:443–451.

Barbour, M. G., J. H. Burk, and W. D. Pitts, 1987. *Terrestrial Plant Ecology*, Second Edition. Benjamin/Cummings Publishing Company, Menelo Park, California.

Baumgartner, D. J., E. P. Glenn, R. O. Kuehl, T. L. Thompson, S. E. Menke, J. F. Artiola, M. A. Algharaibeh, and G. S. Moss, 1996. *Plant Response to Simulated and Actual Uranium Mill Tailings Contaminated Groundwater*, Unpublished, Soil, Water and Environmental Science Department, College of Agriculture, University of Arizona.

Benson, L. and R. Darrow, 1981. *Trees and Shrubs of the Southwestern Deserts*, University of Arizona Press, Tucson, Arizona.

Bonham, C. D., 1989. *Measurements for Terrestrial Vegetation*, John Wiley and Sons, New York.

Booth, D., 1985. "The Role of Fourwing Saltbush in Mined Land Reclamation: a Viewpoint", *Journal of Range Management* 38:562–565.

Brady, N. C., 1974. *The Nature and Properties of Soils*, Eighth Edition, MacMillan Publishing Co., Inc., New York.

Branson, F. A., G. F. Gifford, K. G. Renard, and R. F. Hadley, 1981. *Rangeland Hydrology*, Kendall/Hunt, Dubuque, Iowa.

California Department of Food and Agriculture, 1995. *Nitrate and Agriculture in California*, 2nd printing.

Cameron, K.C. and R.J. Haynes, 1986. "Retention and Movement of Nitrogen in Soils.," Chapter 4 in *Mineral Nitrogen in the Plant-Soil System*, Academic Press, New York, 483 pp.

Charles, F. L., J. A. Morgan, and W. C. Bausch, 1987. *Evapotraspiration of Phreatophytes in the San Louis Valley, Colorado*, Technical Report, Colorado Water Resources Research Institute, Fort Collins, Colorado.

Coyne, P. I., M. J. Trlica, and C. E. Owensby, 1995. "Carbon and Nitrogen Dynamics in Range Plants," *Wildland Plants: Physiological Ecology and Developmental Morphology. Society for Range Management*, D. J. Bedunah and R. E. Sosebee (Eds.), Denver, Colorado, pp 59-167.

Chang, R., 1988. *Chemistry*, Third Edition. Random House, New York.

Dodge, N. N., 1985. *Flowers of the Southwest Deserts*, Southwest Parks and Monuments Association, Tucson, Arizona, 136 pp.

Doria, J. R. and E. F. Aldon, 1993. “Fourwing Saltbush Seedling Survival Using Saline Irrigation,” *Arid Soil Research and Rehabilitation* 7:243–251.

Dunmire, W. W., and G. D. Tierney, 1995. *Wild Plants of the Pueblo Province: Exploring Ancient and Enduring Uses*,. Museum of New Mexico Press, Santa Fe, New Mexico, 290 pp.

Elmore, F. H., and J. R. Janish, 1976. *Shrubs and Trees of the Southwest Uplands*, Southwest Parks and Monuments Association, Tucson, Arizona, 214 pp.

Fitzsimmons, K., C. Lovely, and E. Glenn, 1998 (in press). “Establishment of *Atriplex canescens* Accessions Using Saline Wastewater in the Colorado Plateau Desert,” *Arid Soil Rehabilitation and Reclamation*.

Foxx, T. S., G. D. Tierney, and J. M. Williams, 1984. *Rooting Depths of Plants on Low-Level Waste Disposal Sites*, LA–10253–MS, Los Alamos National Laboratory, Los Alamos, New Mexico.

Fritts, H. C., and T. W. Swetnam, 1989. “Dendroecology: a Tool for Evaluating Variations in Past and Present Forest Environments,” *Advances in Ecological Research* 19:111–118.

Fuller, W., 1975. *Management of Southwestern Soils,* University of Arizona Press.

Glenn, E., D. Moore, S. Sanderson, J. Brown, D. Lash, M. Nelson, and J. Waugh, 1998a (in press). “Comparison of Growth and Morphology of *Atriplex canescens* Varieties Occidentalis and Angustifolia,” *Southwestern Naturalist*.

Glenn, E., R. Tanner, S. Miyamoto, K. Fitzsimmons, and J. Boyer, 1998b. “Water Use, Productivity and Forage Quality of the Halophyte *Atriplex nummularia* Grown on Saline Waste Water in a Desert Environment,” *Journal of Arid Environments*, 38:45–62.

Green, C. and W. Sellers, 1964. *Arizona Climate*, University of Arizona Press, Tucson, Arizona.

Hanson, B., S. R. Grattan, and A. Fulton, 1993. *Agricultural Salinity and Drainage*, University of California Irrigation Program, University of California, Davis.

Haynes, R.J., 1986. “Uptake and Assimilarion of Mineral Nitrogen by Plants,” Chapter 6 in *Mineral Nitrogen in the Plant-Soil System*, Academic Press, New York, 483 pp.

Jensen, M. (ed.), 1973. “Consumptive Use of Water and Irrigation Water Requirements,” *ASCE*, New York.

Jury, W. A., W. R. Gardner, and W. H. Gardner, 1991. *Soil Physics*, Fifth Edition. John Wiley and Sons, Inc., New York.

Mahler, R. J., 1989. “Sulfur Effects on Cotton Cultivars Grown in a Greenhouse,” *Journal of Plant Nutrition*, 12(2):187–206.

Mayes, V. O., and B. B. Lacy, 1989. *Nanise’, A Navajo Herbal: One Hundred Plants for the Navajo Reservation*, Navajo Community College Press, Tsaile, Arizona, 153 pp.

McFarland, M., D. Ueckert, and S. Hartmann, 1987. “Revegetation of Oil Well Reserve Pits in West Texas,” *Journal of Range Management* 40:122–127.

Miller, R. W., and R. L. Donahue, 1995. *Soils in our Environment*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Morris, J., 1980. “The Nitrogen Uptake Kinetics of Spartina alterniflora in Culture,” *Ecology* 61:1114–1121.

Nichols, W. D., 1993. “Estimating Discharge of Shallow Groundwater by Transpiration from Greasewood in the Northern Great Basin,” *Water Resources Research* 29:2771–2778.

Nichols, W.D., 1994. “Groundwater Discharge by Phreatophyte Shrubs in the Great Basin as Related to Depth to Ground Water,” *Water Resources Research* 30(12):3265–3274.

Olsen, M., R. I. Frye, and E. Glenn, 1996. “Effect of Salinity and Plant Species on $Co_2$ Flux and Leaching of Dissolved Organic Carbon During Decomposition of Plant Residue,” *Plant and Soil* 179:183–188.

Osmond, C. B., O. Bjorkman, and D. J. Anderson, 1980. *Physiological Processes in Plant Ecology: Toward a Synthesis with Atriplex*, Springer-Verlag, Berlin.

Pascual, J., T. Hernandez, C. Garcia, and A. Garcia, 1998. “Changes in the Organic Matter Mineralization Rates of an Arid Soil after Amendment with Organic Wastes,” *Arid Soil Research and Rehabilitation* 12:63–72.

Paul, J., and B. Zebarth, 1997. “Dentrification and Nitrate Leaching During the Fall and Winter Following Dairy Cattle Slurry Application,” *Canadian Journal of Soil Science* 77:231–240.

Reynolds, J., M. Cwik, and N. Kelley, 1978. “Reclamation at Anaconda's Open Pit Uranium Mine, New Mexico,” *Reclamation Review* 1:9–17.

Richardson, S. G., and C. M. McKell, 1979. “Water Relations of *Atriplex canescens* as Affected by the Salinity and Moisture of Processed Oil Shale,” *Agronomy Journal*, 72:946–950.

Richardson, S. G., and C. M. McKell, 1980. “Salt Tolerance of Two Saltbush Species Grown in Processed Oil Shale,” *Journal of Range Management* 33(6):460–463.

Sabey, B., R. Pendleton, and B. Webb, 1990. “Effect of Municipal Sewage Sludge Application on Growth of Two Reclamation Shrub Species in Copper Mine Spoils,” *Journal of Environmental Quality* 19:580–586.

Swingle, R., E. Glenn, and V. Squires, 1996. “Growth Performance of Lambs Fed Mixed Diets Containing Halophyte Ingredients,” *Animal Feed Science and Technology* 63:137–148.

U.S. Department of Energy, 1998. *Final Site Observational Work Plan for the UMTRA Project Site at Monument Valley, Arizona* in process, prepared by MACTEC–ERS for U.S. Department of Energy.

Voss, E. G. (ed.), 1983. *International Code of Botanical Nomenclature*, Adopted by the 13th International Botanical Congress, Sydney, August 1981. Bohn, Scheltema & Holkema, 472 pp.

Wagner, W., W. Martin, and E. Aldon, 1978. “Natural Succession on Strip-mined Lands in Northwestern New Mexico,” *Reclamation Review* 1:67–73.

Welsh, S. L., N. D. Atwood, L. C. Higgins, and S. Goodrich, 1987. *A Utah Flora*, Great Basin Naturalist Memoirs No. 9, Brigham Young University, Provo, Utah, 894 pp.

Whitson, T. D. (ed.), 1992. *Weeds of the West*, Western Society of Weed Science, Newark, California, 630 pp.

Wood, M., B. Buchanan, and W. Skeet, 1995. “Shrub Preference and Utilization by Big Game on New Mexico Reclaimed Mine Land,” *Journal of Range Management* 48:431–437.

Zartman, R. E., T. D. Miller, J. R. Goodin, and M. Gichuru, 1980. “Effects of Water Quality on Forage Production,” *Journal of Environmental Quality* 9(2):187–190.

# Appendix A

# Irrigation Suitability Land Classification

## Specifications for Land Classes[1]

| Land Characteristics | Class 1 | Class 2 | Class 3 | Class 6 |
|---|---|---|---|---|
| ***Soils***[2] | | | | |
| Texture (Surface 10") | MC,M,MF | Any | Any | All other lands not meeting criteria for arability |
| Moisture Retention-AWHC 0-48" | >6.0" | >4.5" | >2.5" | |
| Effective Depth | >48" | >30" | >20" | |
| Salinity (EC × 103), 0-48" (at irrigation equilibrium) | <4 | <8 | <12 | |
| Sodicity - SAR of Root Zone (0-48") | <13 | <13 | <37.5 | |
| Permeability, 10-48" | 0.2-6.0 in/hr | 0.06-6.0 in/hr | 0.06-20 in/hr | |
| Coarse Fragments, 0-10"[3] | | | | |
| Gravel (% by volume) | <15 | <35 | <55 | |
| Cobbles (% by volume) | <5 | <10 | <15 | |
| Rock Outcrops (distance apart) | >200' | >100' | >50' | |
| Frequency of Overflow (years) | None (<1 in 10) | Rare (1 in 10) | Occasional (2 in 10) | |
| Depth to Calcic Horizon | >20" | >10" | Any | |
| Depth to Water Table | >60" | >48" | >30" | |
| ***Topography and Land Development*** | | | | |
| Slope (percent) | <5 | <8 | <15 | |
| Rock Fragments for Removal (cu yds/Ac) | | | | |
| Cobble | <10 | <35 | <70 | |
| Stone | <10 | <25 | <70 | |
| Surface Grading[4] | None or light | Medium | Heavy | |
| Tree Removal (% canopy) | <10 | <40 | <70 | |
| Reclamation required for Sodicity | None | Moderate | High | |
| ***Drainage*** | | | | |
| Surface Drainage Requirement[5] | 1 | 2 | 3 | |
| Depth to Restrictive Layer (<0.01 inches/hour H.C.) | | | | |
| When W.A.H.C. of the 4 foot to restrictive layer, or 4 foot to 10 foot layer (whichever is least) is > 0.15 inches/hour | >6' | >6' | >6' | |
| When W.A.H.C. of the 4 foot to restrictive layer, or 4 foot to 10 foot layer (whichever is least) is < 0.15 inches/hour | >8' | >8' | >8' | |
| If artificial drainage is required: | | | | |
| Hydraulic Conductivity of zone to be drained[6] | >0.15 in/hr | >0.15 in/hr | >0.15 in/hr | |
| Depth to Drainage Barrier | >6' | >6' | >6' | |

## Notes on Specifications for Land Classes[1]

1. Each individual factor represents a minimum requirement. Two or more interacting deficiencies may result in land being placed in lower class than single deficiencies specify.

2. Specifications for the "Soil" group are representative of conditions after land is developed for irrigation.

3. Less than 15% gravel for class 2 if surface texture is coarse or moderately coarse.
   Less than 35% gravel for class 3 is surface texture is moderately coarse.

4. (a) Land is further downgraded if surface grading reduces effective depth or otherwise permanently reduces soil fertility.
   (b) Degrees of leveling for hummocky areas:
      light: less than 1 foot of cut and fill.
      medium: 1 to 2 feet of cut and fill.
      heavy: 2 to 3 feet of cut and fill.

   (c) Degrees of leveling for gullied areas:
      light: 0-200 cubic yards of earth work per acre.
      medium: 200-400 cubic yards of earth work per acre.
      heavy: 400-800 cubic yards of earth work per acre.
      v. heavy: over 800 cubic yards of earth work per acre.

5. Surface drainage refers to the natural ability to either shed or transmit water. It is not the same as overflow (which refers to the condition of inundation) or internal drainage.

   Category 1: Surface drainage is not limiting.
   Category 2: Surface drainage is limiting, but easily corrected.
   Category 3: Surface drainage is limiting and not easily corrected.

6. Zone to be drained is least of the following:

   1) Four feet to a restrictive layer
   2) Four feet to bedrock
   3) Four feet to a drainage barrier
   4) Four feet to ten feet.