Management Model for Land Application of Wastewater

T.W. Sammis, J.G. Mexal G. Picchioni and D. Saucedo *

Abstract

Applying wastewater to land for remediation has been recommended by the Environmental Protection Agency (EPA) as a method to recycle nutrient and organic matter and conserve water resources. Small communities are selecting primary treatment using a lagoon treatment system and land application as the most cost-effective way of treating municipal wastewater. Managers must balance the irrigation requirements of the vegetation receiving the treated wastewater against the risk of groundwater contamination with nitrogen and against the risk of salinized soils that would effectively kill the biological system. The objective of the research was to develop a water-nitrogen balance irrigation-scheduling model that could be used to schedule irrigation for land application of wastewater from a lagoon treatment system to prevent contamination of the ground water.

The City of Las Cruces constructed a lagoon wastewater treatment plant that has a permit to process 1,500 m^3/d of pretreated industrial wastewater and domestic wastewater from the West Mesa Industrial Park (WMIP). The land application site is a Chahuahuan desert ecosystem where the predominant vegetation consists of winter annuals of flixweed (*Descurainia sophia*)and pinnate tansy mustard (*Descurainia pinnata*), perennials of narrowleaf peppergrass or pepperweed (*Lepidium latifolium*), and shrubs of creosote (*Larrea tridentata*) and mesquite (*Prosopis glandulosa*) The sprinkler system used to apply the wastewater is a fixed system with Senninger #3012-1-3/4 emitters operating at a pressure 310 kPa and a flow 18 l/m. The spacing down the laterals and between laterals is 12 m.

The irrigation scheduling model calculates evapotranspiration (ET) from a volume balance soil water model that reduces potential evapotranspiration by a crop coefficient scaling factor and a soil moisture stress function determined by the plant available water in the soil profile. The model runs on a daily time step. The model predicted 32 kg/ha nitrogen leaching under the creosote plants which occurred in two events where irrigation was over applied. During the rest of the growing season no nitrogen was leach. Nitrogen leaching below the root zone of mesquite was not calculated.

***New Mexico State University Agronomy and Horticulture Department Las Cruces, NM**

Introduction

Applying wastewater to land for remediation has been recommended by the Environmental Protection Agency (EPA) as a method to recycle nutrient and organic matter and conserve water resources. The level of treatment prior to land application (LA) can range from primary treatment using a lagoon to tertiary treatment using standard wastewater treatment facilities. Land application systems that utilize the land as a treatment unit and not just as a disposal area are gaining acceptance in many arid regions. Small communities are selecting primary treatment and land application as the most cost-effective way of treating municipal wastewater. In a LA system, wastewater has been applied to crops, rangelands, forests, and recreation areas, including parks and golf courses, and to disturb lands, such as mine spoil sites (Sopper and Kardos, 1973; Sopper et al., 1982; Bastian and Ryan, 1986; Luecke and De La Parra, 1994). These systems are cheaper to construct and can be operated by personnel with familiarity with common irrigation systems.

The soil and plants act as filters that trap and treat, through various mechanisms, contaminants in the wastewater and allow the treated wastewater (effluent) to drain through the soil profile (Watanabe, 1997). The wastewater provides an effective source of nutrients that the vegetation roots assimilate. The net effect is a beneficial system allowing for both the effective remediation of wastes and the recycling of water, nutrients, and carbon via biomass production (Bastian, 1986). However, the effects of continuous irrigation with sewage effluent on soil and leachate water quality need to be evaluated. As the wastewater infiltrates and moves through the soil profile, waste particles are trapped by the soil. Managing the quantity and frequency of waste loading will permit adequate soil drying, thereby avoiding soil clogging, which can result in anaerobosis (Thomas, 1973). The chemical nature of the soil environment is critical to the reactions necessary for waste remediation. Applying organic matter at appropriate, controlled rates, coupled with the proper soil-water-air environment, results in increased microbial activity and subsequent decomposition of compounds found in the wastewater. Even though LA systems are conventional technology approved by the EPA for many communities, there is little information to guide land managers in arid and semi-arid environments where the wastewater may be the only source of supplemental water. Managers must balance the irrigation requirements of the vegetation against the risk of groundwater contamination with nitrogen and against the risk of salinized soils that would effectively kill the biological system. Light, frequent irrigation can increase surface soil salinity that can limit crop production. On the other hand, over-irrigation can carry nitrate-nitrogen to the groundwater.

The objective of the research was to develop a desert ecosystem irrigation scheduling water balance model that could be used to schedule irrigation for land application of wastewater from a lagoon treatment system to prevent contamination of the ground water.

Description of Wastewater Permit

The City of Las Cruces constructed a lagoon wastewater treatment plant that has a permit to process 1,500 m^3/d of pretreated industrial wastewater and domestic wastewater from the West Mesa Industrial Park (WMIP). The facility is located approximately 4 km west of Las Cruces in Section 2, T24S, R1W, and Section 35, T23S, R1W, Dona Ana County. The West Mesa Industrial Park collects and sends the wastewater to one of two treatment trains, each consisting of a manual bar screen and sewage grinder, two synthetically lined mixing basins (in series), and a synthetically lined holding pond. The wastewater is then land applied to 32 ha with a fixed head sprinkler system. Ground water below the site is at a depth of approximately 100 m. The land application site is a Chahuahuan desert ecosystem where the predominant vegetation consists of winter annuals of flixweed (*Descurainia sophia*)and pinnate tansy mustard (*Descurainia pinnata*), perennials of narrowleaf peppergrass or pepperweed (*Lepidium latifolium*), and shrubs of creosote (*Larrea tridentata*) and mesquite (*Prosopis glandulosa*)

The permit for the land application of the wastewater states that the wastewater application will be conducted so that nitrogen loading will not exceed 25% of the maximum amount of nitrogen expected to be taken up by the existing native vegetation.

Theory of wastewater allowable hydraulic loading rate design (English Units)

The yearly wastewater application rate (Lw(p)) needed in the design of the wastewater irrigation system and the amount NO_3^--N loading to groundwater that will occur using this design can be determined based on the yearly water and nitrogen mass balance equations reported in the design approaches outlined by Metcalf and Eddy, Inc (1990) and WCPF (1989).

The hydraulic loading based on water balance equation is:

$Lw(p) = ET – Pr + Wp$ ………………………………………. ….[Eq.1]

where:

Lw(p) = Wastewater hydraulic loading rate (m/yr) , the volume of wastewater applied per unit area of land per unit time.
ET = Design evapotranspiration rate (m/yr)
Pr = Design precipitation rate (m/yr)
Wp = Design percolation rate (m/yr).

The wastewater nitrogen loading to ground water based on the nitrogen mass balance equation is:

$Ln = U + D + 10\ Wp\ Cp$ ………………………………………… [Eq. 2]

where:

Ln = Wastewater nitrogen loading (kg/ha/yr)
U = Crop nitrogen uptake (kg/ha/yr)
D = Denitrification (kg/ha/yr)
Wp = Percolating water (m/yr)
Cp = Percolate nitrogen concentration (mg/L).

The wastewater nitrogen loading (kg/ha/yr) is calculated from:

$Ln = 10\ Lw\ Cn$ ……………………………………………….....[Eq.3]

where:

Lw = Wastewater applied (m/yr)
Cn = total nitrogen in applied wastewater (mg/L).

Solve for Wp in Eq. 2 yields:

$Wp = (Ln – U- D)/ 10\ Cp$.

Substitute the Wp term in Eq. 1 yields:

$Lw = ET – Pr + (Ln –U – D)/10\ Cp$ ………………………….…[Eq. 4]

The fraction of applied nitrogen removed by nitrification and volatilization (F) can be expressed as:

$F = D/Ln$ ……………..……………………………………… [Eq. 5]

where:

Ln = Wastewater nitrogen loading (kg/ha/yr)

D= Denitrification (kg/ha/yr).

Solve for D in Eq. 5 and substitute in Eq. 4 yields:

$D = F\ Ln$

$Lw = ET - Pr + (Ln - U - F\ \ Ln)/10\ Cp$ …………………………[Eq. 6]

Insert Eq. 3 into Eq. 6 yields

$Lw = ET - Pr + (10\ Lw\ Cn - U - (10\ F\ Lw\ Cn)/10\ Cp$ ………… [Eq. 7]

Simplify Eq. 7:

$Lw = (ET - Pr) + [10\ Lw\ Cn\ (1 - F) - U\ ]/10\ Cp$

$10\ Lw\ Cp = 2.7\ Cp\ (ET - Pr) + 10\ Lw\ Cn\ (1\text{-}F) - U$

$10\ Lw\ Cp - 10\ Lw\ Cn\ (1\text{-}F) = 10\ Cp\ (ET - Pr) - U$

$10\ Lw\ (Cp - Cn\ (1\text{-}F) = 10\ Cp\ (ET - Pr) - U$

$Lw\ (Cp - Cn\ (1\text{-}F) = Cp\ (ET - Pr) - U/10$

$Lw\ (Cp - Cn\ (1\text{-}F) = Cp\ (ET - Pr) - U/10$

$Lw = [Cp\ (ET - Pr) - U/10]\ /\ (Cp - Cn\ (1\text{-}F))$…………………..… [Eq. 8]

Express the unit of Lw in mm/yr and multiply Eq. 8 by '–1' yields:

$Lw = [Cp\ (Pr - ET) + 100\ U]\ /\ (Cn\ (1\text{-}F)\text{-}Cp)$ ………………………[Eq. 9]

The amount of nitrogen taken up by the tree (U) can be expressed in terms of the evapotrnspiration production function and the nitrogen concentration in plant tissues [Cc] in (%):

$U = (a + b\ ET)\ Cc$ ……………………………………………………[Eq. 10]

Plug Eq. 10 into Eq. 9 yields:

$Lw = [Cp\ (Pr - ET) + (100\ (a + b\ ET)\ Cc)]\ /\ (Cn\ (1\text{-}F)\text{-}Cp)$ ……….. [Eq. 11]

where:

Lw = allowable hydraulic loading rate (mm/yr)
ET = design ET rate (mm/yr)
Pr = design precipitation rate (mm/yr)
Cp = total nitrogen in percolating water (mg/L)
Cn = total nitrogen in applied wastewater (mg/L)
Cc = nitrogen concentration in plant tissues (%).
a = intercept of the Evapotanspiration production function (kg/ha)
b = slope of the Evapotanspiration production function (kg/ha/mm)
F = fraction of applied total nitrogen removed by denitrification and volatilization. This fraction will be assumed to be 20%.
100 = conversion factor (unitless).

After the irrigation design criteria are determined from Equation 11, then BMPs and operational models should be developed to implement the design criteria on an operational basis. For the original design equation one must know the water production function for the desert species. For the daily operational models, one must know the climate, soils, and vegetation characteristics of the site. The design model assumes that sufficient water is available from the logon treatment system to not limit plant growth and that nitrogen is also not limiting. Consequently, the hydraulic loading always exceeds the ET of the vegetation when solving equation 11, and if sufficient nitrogen is not applied for plant growth by the wastewater then nitrogen is available from the soil nitrogen pool to make up the difference. The design model also assumes that mineralization is not occurring to generate nitrogen for plant uptake or leaching. The operational model does not make these assumptions.

Description of the Irrigation-Scheduling Biomass Model.

A volume balance model served as the water balance component of the irrigation-scheduling model. Et was determined by using climate data to calculate a reference evapotranspiration (Eto) and a crop coefficient (Kc) for each major vegetation type (Sammis 2004). Crop coefficients for each vegetation type were estimated from the literature for mesquite (Levitt et al 1995) and a separate pot experiment for creosote plants (Saucedo et al 2004). The calculated non-stressed Et for each vegetation type was reduced by a water stress function, which was a function of the proportional available water in the root zone (Abdul-Jabbar et al. 1984). The linear water stress function has an intercept of zero and a slope of 2, yielding a water stress factor of 1 obtained at 50% of allowable soil water depletion. Consequently, for a management allowable depletion greater than 50%, the plant will be under water stress.

Other inputs to the model include maximum rooting depth, root growth rate coefficient, and water holding capacity of the soil and a leaf area density function that reduces Et by the percentage change in leaf area index in the field compared to the leaf area index of the non-stressed plants.

The model, which is a one-dimensional model, calculated the total water balance including the deep drainage, and changes in soil moisture due to irrigation and rainfall as inputs and evapotranspiration as output of the soil profile.

Biomass

Daily net dry matter gain per plant (DM) is estimated as the product of Et and water use efficiency (WUE). The allocation of DM is modeled to leaves, then to reproduction, and lastly to branches and the trunk. The leaf area per tree (m^2 $tree^{-1}$) is modeled by multiplying the total leaf biomass per tree by the specific leaf area, SLA (m^2 kg^{-1}). The plant diameter (mm) and height (m) are modeled by converting trunk biomass to volume based on the wood density and then solving for the tree size with the calculated volume of a cone, and tree radius to height ratio specified as an input parameter. Critical growth stages, expressed in terms of thermal time (i.e. cumulative growing degree days), are used to control seasonal growth duration of each organ in the model.

Nitrogen Dynamics

Because plant growth is significantly affected by nitrogen availability, a nitrogen balance component was added to the existing plant model and a nitrogen stress coefficient was used to adjust the WUE and, consequently, daily dry matter gain. Details of the soil temperature and nitrogen dynamics modules are given by Asare (1990). The inputs for the nitrogen object are initial organic nitrogen, ammonia, and nitrate-nitrogen in the top 30 cm of the root zone and the amount of each component in the rest of the root zone. Also, a denitrification rate coefficient is specified. The fraction of nitrogen in the leaves, branches and reproductive organs for nitrate uptake calculations are also specified as input. The nitrogen-nitrate stress function (NS) is a scaling function from 0 to 1 and is described by eq. 12:

NS=IF(N >nstress,1,((N)^nstress/((nstress/2)^12+(N)^nstress))) ……….[Eq.12]

Where N = The average nitrogen level in the soil water in the root zone in mg N/kg H_20

Nstress= Nitrogen level at which nitrogen limited Et and growth mgN/kg H_20. This variable is an input to the model.

This is a sigmoid type function where the nstress level was set to 12 for creosote. Consequently, the nitrogen stress function starts to decrease Et at a N value of 12 mg N/kg H_20 and has a value of less than 0.01 when N reaches 4 mg N/kg H_20.

The nitrogen subroutine was not use in the mesquite runs because mesquite fixes its own nitrogen and so nitrogen was not a limiting factor. Nitrogen will be taken up by mesquite the same as alfalfa until it becomes a limiting factor, and the plant will then generate its own nitrogen by symbiotic nitrogen fixation.

Model Runs

Currently, the model has to be run separately for each major vegetation type. To minimize nitrogen leaching required by the permit, the vegetation type that has the least nitrogen movement below the root should be used to schedule the irrigation during that time period. The yearly water application rate should not exceed that calculated by equation 11. The over all growth for the desert site is the growth of each individual model run weighted by the percent area of the vegetation type for that model run. The same approach is used to get the weighted evapotranspiration from the site.

Material and Methods

The sprinkler system used to apply the wastewater is a fixed system with Senninger #3012-1-3/4 emitters operating at a pressure 310 k Pa and a flow 18 l/m. The spacing down the laterals is 12 m and the spacing between laterals 12 m. The number of sprinklers per line is 18 and the irrigation rate of the sprinklers is 0.75 cm/h. The irrigation controller program operates 1 to 3 lines at once. The research plot is located between sprinkler line 21 and 19. The irrigation controller was programmed to turn on A19, A20, and A21 at the same time when water was available from the wastewater treatment facility.

Before the irrigation-scheduling model was developed, the irrigations were scheduled to apply 5 mm/day during the growing season. Water application was measured using a water meter on the main line. Rain was measured using a tipping bucket rain gage at the site. Weather data and calculated reference evapotranspiration were retrieved from the weather station at the Nation Weather Site and New Mexico state University and the New Mexico Climate Center Web site (NMCC 2003).

The soil type at the site is classified at as Bluepoint loamy sand (0 to 1431 mm and stratified loamy find sand to loamy sand (457 – 1524mm) (Dona Ana County Soil Survey 1980). Nitrogen content of the irrigation water was analyzed by collecting a water sample from the holding pond and analyzing for nitrate-nitrogen and total nitrogen (TKN). Canopy measurements were taken 27 June 2002 using a spherical denisometer (Forest Densiometers Model –A). Four readings (north, south, east and west) were taken on the plot under mesquite and creosote.

Results

Wastewater application

Wastewater application began on February 5, 2002. The treated plot received varied amounts of effluent throughout 2002 and 2003. This was due to temporal fluctuations in tenant-generated wastewater and the high evaporation losses from the wastewater lagoons through the peak summer months (Figure 1).

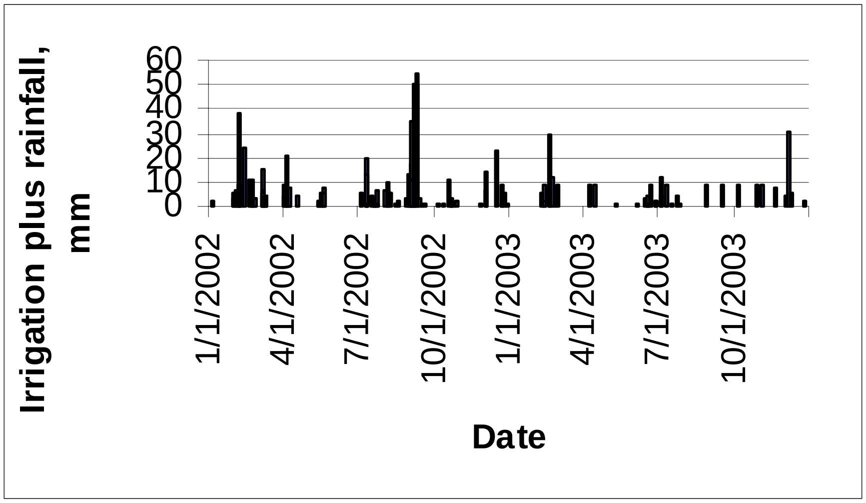

Figure 1. Irrigation plus rainfall applied to the wastewater site.

Generally, the application depth was 10 mm. In late summer, the application of wastewater onto the treated site increased due to one tenant's increase of wastewater discharge. The effluent increased from zero to an average of 50 mm over an 11-day period from August 31 to September 10, 2002. Nitrate nitrogen in the irrigation water for the year averaged less than 0.2 mg/l but the TKN nitrogen averaged 8 mg/l. It was assumed that all this was converted immediately to nitrate nitrogen after entering the soil.

The overhead area occupied by the creosote vegetation canopy was 60% with a standard deviation (SD) of 8% which was slightly larger than the overhead area occupied by the creosote crop coefficient study (50%) used to estimate the crop coefficient. Consequently, the density scaling factor in the irrigation scheduling model was set to one. Mesquite occupied 76% of the area, which would be similar to the overhead area occupied in the pot study to determine the kc for mesquite. (Levitt, et al. 1995).

Because of the low number of creosote and mesquite plants per ground area, the actual project area of the creosote / ground area was 8.7 % and for the mesquite 5.7% base on photographs taken from a airplane in June 2002 and analysised using arceview

Above ground WUE, input into the model was 14 kg/ha/mm. This number was estimated from the crop coefficient pot study and was similar to the slope of the water production function for alfalfa which was 12 kg/ha/mm (Sammis 1981).

Creosote plant model results

The total water applied to the plots was 814 mm in 2002 and 242 mm in 2003, and total Et was 462mm in 2002 and 254 mm in 2003. The non stress Et for the year was 1252 mm in 2002 and 1355 mm in 2004. The steady state design model conditions were not achieved for the two years of operations. Both nitrogen and water were limiting during that time period. Consequently, the design model predicted that under non limiting conditions, the Et would be 1252mm/year and the hydraulic loading could have been 5610mm/year resulting in a nitrogen application of 96 kg/ha/year and a leaching of 23 kg/ha/year of nitrogen.

The daily operation model showed that the creosote plants were under water stress after April 23 2002 when insufficient water was available from the treatment plots to supply enough irrigation water to satisfy the evaporative demands of the plants (Figure 2).

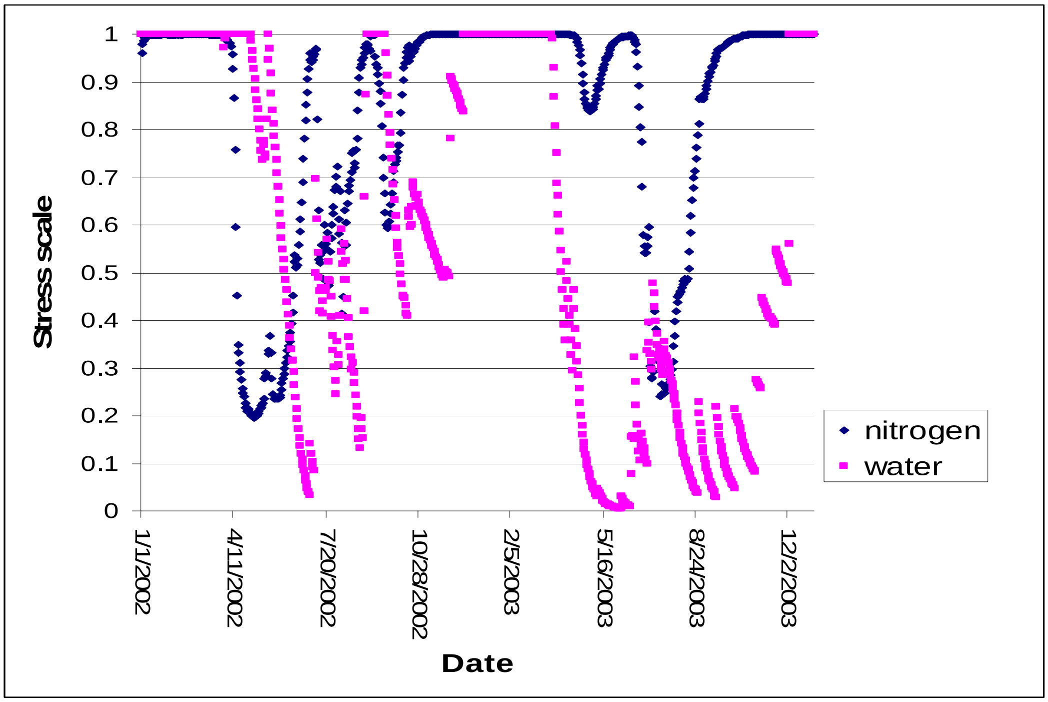

Figure 2. Creosote Nitrogen and Water stress for wastewater irrigated plots.

The assumption in the model was that the soil profile was full at the beginning of the run in January 1, 2002. In 2003 the winter rains filled the root zone but soil water stress again started on March 22. Because the plants were under stress after April 23, 2002 and March 22, 2003, deep drainage was low after those dates except on Sept. 6 –

10, 2002 when the irrigation system was run for 4 straight days when a control valve did not work. Drainage of 11 mm also occurred in Feb 21 2003 (Figure 3).

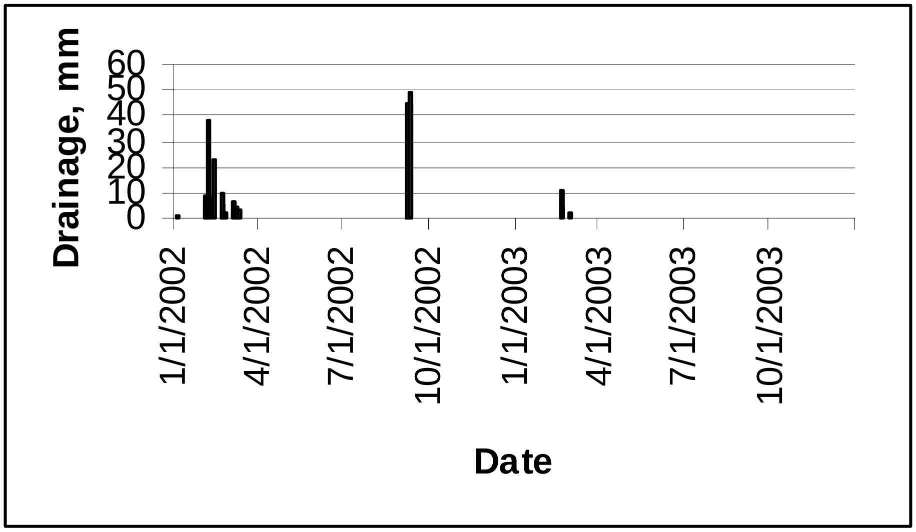

Figure 3. Drainage amount under the creosote plant.

Nitrogen stress also occurred to limited Et and growth because the irrigation wastewater stream had only TKN nitrogen of 8 mg/l. (Figure 2). Generally a logon wastewater treatment plant would have N levels of 40 mg/l which would cause nitrogen to be leached below the root zone (Metcalf and Eddy, Inc, 1990). The logon treatment system receives only industrial waste which accounts for the low nitrogen content. Nitrogen stress generally occurred during the summer months when uptake demand and growth was greatest. Mineralization rates increase during the summer months when temperatures increase, but the mineralization rate was insufficient to supply the nitrogen needed by the creosote plant.

The daily evapotranspiration varied from 3 to 4 mm in/day (Figure 4) during the summer months even though the non stress Et would have been 8 mm/day.

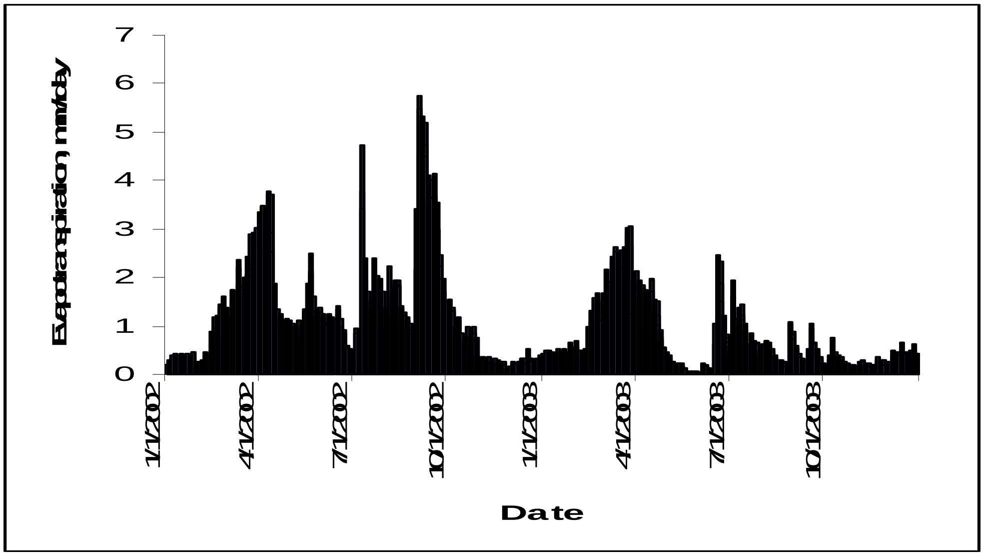

Figure 4. Creosote evapotranspiration rate.

Because nitrogen and water stress existed the amount of nitrogen leached below the root zone was 33 kg/ha for the two years compared to the amount applied of 64 kg/ha. However, all the nitrogen leached occurred on the over irrigation events of Oct 2002 (13 kg/ha) and the end of February 2003 (20 kg/ha). Except when an errors of water application occurs the creosote plant extract all of the available nitrogen in the wastewater stream. Total biomass growth for the 2002 was two 0.64kg/m^2 and 0.35 kg/m^2 in 2003.

Mesquite plant model results

The WUE of the mesquite plant was estimated to be the same as the creosote plant 14 kg/ha/mm**.** The plots received the same amount of water as the creosote plants (Figure 1). The assumption was that nitrogen was not limiting. The mesquite plants were not under water stress until the May in 2002 and 2003 (Figure 5).

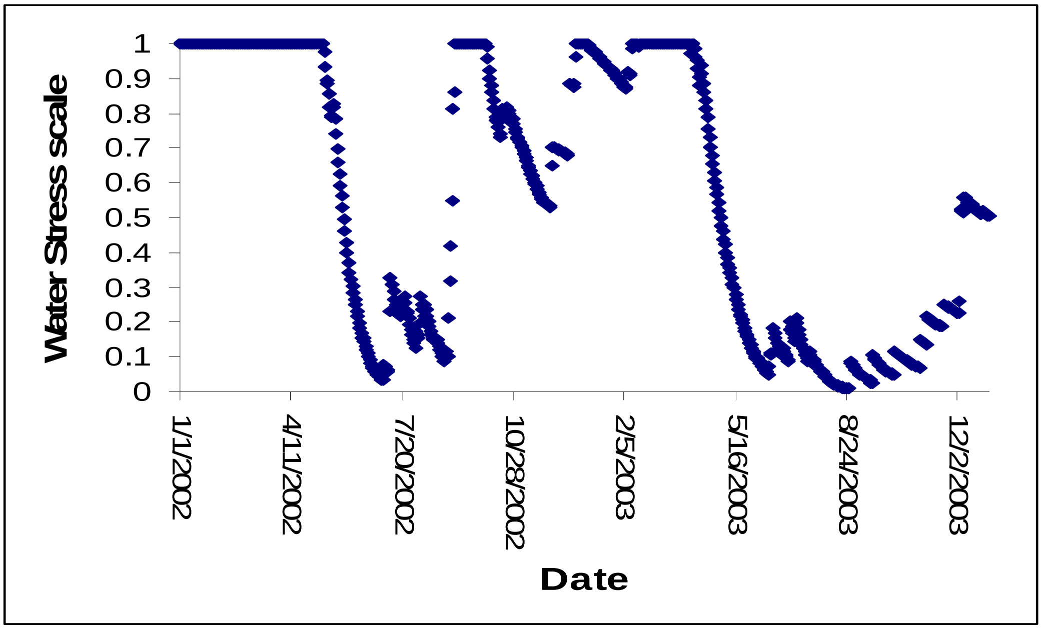

Figure 5. Mesquite water stress for wastewater irrigated plots.

Deep drainage under the mesquite plants was similar to that under the creosote plant (Figure 6). The daily evapotranspiration varied from 5 to 6 mm during the summer higher than the creosote plant because nitrogen was not limiting (Figure 7). The maximum crop coefficient for mesquite under non stress conditions was 1.29 compared to 1.02 for creosote. This also contributed to the slightly higher Et when water was available after a rain or irrigation event. Yearly evapotranspiration calculated by the model was 643 mm in 2002 and 299 mm in 2003 because of the decrease irrigation amounts in 2003 compared to 2002. Consequently, yearly biomass growth was 0.9 kg/m^2 in 2002 and 0.41 kg/m^2 in 2003 greater than the creosote plant growth because the mesquite was not under nitrogen stress. The nitrogen balance for the mesquite plant is still being developed because of its symbiotic ability to produce nitrogen.

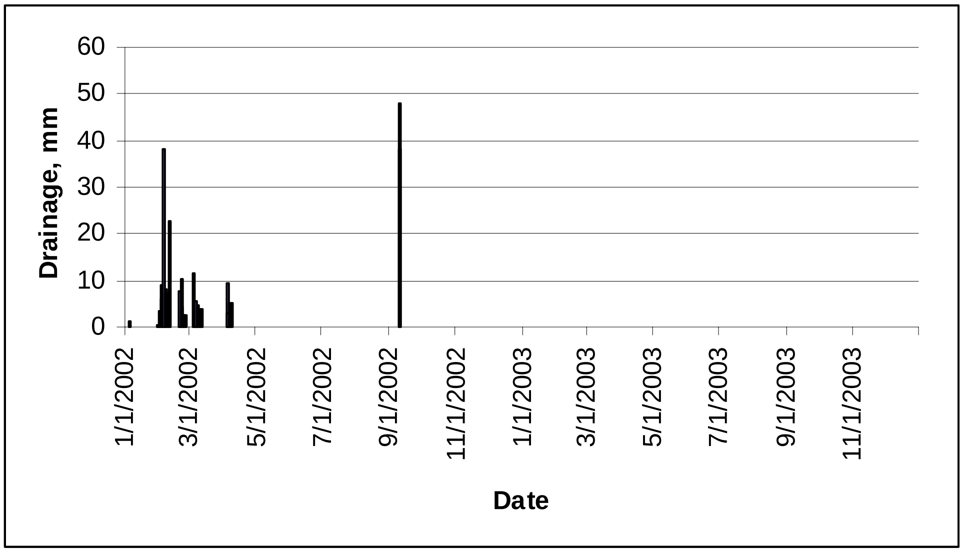

Figure 6. Drainage amount under the mesquite plant.

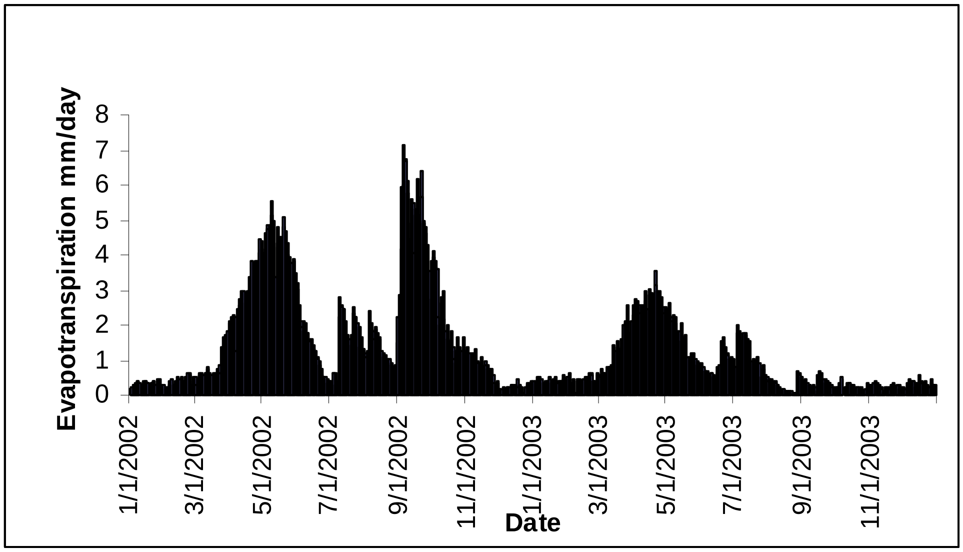

Figure 7. Mesquite evapotranspiration rate.

Conclusion

A preliminary model that simulates the water and nitrogen balance under creosote was developed and a water balance model was developed for mesquite. The model appears to work reasonably well but continued research is underway to verify the growth, nitrogen and water balance components of the models.

References

Asare, D. K. 1990. Modeling nitrogen dynamics in a cultivated soil. M.S. Thesis, New Mexico State University, Las Cruces, New Mexico.

Al-Jamal, M.S., T.W. Sammis, J.G. Mexal, G.A. Picchioni and W.H. Zachritz. 2001. A growth -irrigation scheduling model (GISM) for wastewater use in forest production. Agric. Water Mgt. J. 56:57-79.

Bastian, R.K., and J.A.Ryan. 1986. Design and management of successful land application systems, p. 217-234. In Proceedings. Utilization,treatment, and disposal of waste on land. Soil Science Society of America, Madison, Wisconsin.

Duff, A.B., J.M. Meyer, C. Pollock, P. Felker. 1994. Biomass production and diameter growth of 9 half-sib families of mesquite (Prosopis glandulosa var. glandulosa) and a fast-growing Prosopis alba half-sib family grown in Texas. For.Ecol. Mgt.67 (1-3):257-266.

Killingbeck, K.T. and W.G. Whitford. 1996. High foliar nitrogen in desert shrubs: An important ecosystem trait or defective desert doctrine? Ecology 77(6):1728-1737.

Levitt, D. G., J. R. Simpson and J. L. Tipon. 1995. Water use of two landscape tree species in Tuscon Arizona. J Amer. Soc Hort. Sci. 120(3)409-416.

Luecke, D.F. and C. De la Parra. 1994. From pollution to park. Experiment in Tijuana: a low-tech approach to wastewater management. Calif. Coast and Ocean 10 (1):7-19.

Metcalf and Eddy, Inc. 1991. Wastewater engineering:treatment, disposal, and reuse. McGraw Hill:New York, 815 pp.

Mexal, J.G. and W.H Zachritz II. 1999. A plan for a vegetated land application wastewater treatment system for the city of Las Cruces, NM West Mesa Industrial Park. City of Las Cruces, NM. 30p.

Sammis, T.W. 2004. Penman's equation for potential evapotranspiration. http://weather.nmsu.edu/math/penmans.html

Saucedo,D.,T.W. Sammis, G.A. Picchioni and J.G. Mexal. 2004. Wastewater application and water use of Larrea Tridentate. http://weather.nmsu.edu/westmesa/

Sharifi, M.R., F.C. Meinzer, E.T. Nilsen, P.W. Rundel, R.A. Virginia, W.M. Jarrell, D.J. Herman, and P.C. Clark. 1988. Effect of manipulation of water and nitrogen supplies on the quantitative phenology of *Larrea tridentata* (creosote bush) on the Sonoran Desert of California. Amer. J. Bot. 75:1163-1174.

Sopper, W.E. and L.T Kardos. 1973. Vegetation responses to irrigation with treated municipal wastewater, p. 271-294. In: Sopper, W.E., Kardos, L.T. (eds). Recycling treated municipal wastewater and sludge through forest and cropland. The Pennsylvania State University Press: University Park, PA.

Sopper, W.E., E.M. Seaker, and R.K. Bastian (eds.). 1982. Land reclamation and biomass production with municipal wastewater and sludge. The Pennsylvania State University Press: University Park, PA. 524 pp.

Sammis T. W. 1981. Yield of Alfalfa and Cotton as Influenced by Irrigation. Agronomy Journal 73:323-329

Samani, Z.A. and M. Pessarakli. 1986. Estimating potential crop evapotranspiration with minimum data in Arizona. Transactions of the ASAE 29(2):522-524.

Stephen J. D. and L. G. Klikoff. 1973. Effect of plant moisture stress on carbohydrate and nitrogen content of big sagebrush. J. Range Manage. 26(3):207-209.

Thomass, R.E., 1973. The soil as a physical filter, p. 38-45. In: Sopper, W.E., Kardos, L.T. (eds). Recycling treated municipal wastewater and sludge through forest and cropland. The Pennsylvania State University Press: University Park, PA.

Vallotton, A.D., J.G. Mexal, D.G. Vallotton, C. Erickson, L. Iglesias, B. Jessen, R. Nuñez, G. Picchioni, Z. Samani, and W.H. Zachritz II. 2000. Sustainable use of wastewater for small communities: A model system for short rotation woody crop production, p. 47-71. Westerhoff, P. (ed). The U.S.-Mexican border environment: Water issues along the U.S.-Mexican border. Southwest Center for Environmental Research and Policy Monograph Series No. 2. San Diego State University Press.

W.C.P.F. 1990. Natural systems for wastewater treatment. Manual of Practice FD-16. Water Pollution Control Federation, Alexanderia, VA. 270 p.

Watanabe, M.E. 1997. Phytoremediation on the brink of commercialization. Environmental Science and Technology. 31(4):182-186.

Zachritz, W.H., J.G. Mexal, and T. Sammis. 2001. Land application of wastewater in arid regions: the challenge of balancing plant water requirements and nitrogen uptake. Proc. 2001 Rio Grande Environmental Conf., Weslaco, TX. April 26-28, 2001. CD = rec2001\Paper-Presentersweb\REC 2001 PaperZacharitz_web.htm.