

Management Model for Land Application of Wastewater

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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 anaerobiosis (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 water 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.

Description of Wastewater Permit

The City of Las Cruces constructed a lagoon wastewater treatment plant that has a permit to process 400,000 gallons per day (gpd)[1,500 m³/d] of pretreated industrial wastewater and domestic wastewater from the West Mesa Industrial Park (WMIP). The facility is located approximately 7 miles (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 80 acres (32 ha) with a fixed head sprinkler system. Ground water below the site is at a depth of approximately 350 ft (100 m). The land application site is a Chihuahuan 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 NO₃⁻-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:

$$Lw(p) = ET - Pr + Wp \dots\dots\dots [Eq. 1]$$

where:

Lw(p) = Wastewater hydraulic loading rate (ft/yr), the volume of wastewater applied per unit area of land per unit time.

ET = Design evapotranspiration rate (ft/yr)

Pr = Design precipitation rate (ft/yr)

Wp = Design percolation rate (ft/yr).

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

$$Ln = U + D + 2.7 Wp Cp \dots\dots\dots [Eq. 2]$$

where:

Ln = Wastewater nitrogen loading (lb/acre/yr)

U = Crop nitrogen uptake (lb/acre/yr)

D = Denitrification (lb/acre/yr)

Wp = Percolating water (ft/yr)

Cp = Percolate nitrogen concentration (mg/L).

The wastewater nitrogen loading (lb/acre/yr) is calculated from:

$$L_n = 2.7 L_w C_n \dots\dots\dots [Eq. 3]$$

where:

L_w = Wastewater applied (ft/yr)

C_n = total nitrogen in applied wastewater (mg/L).

Solve for W_p in Eq. 2 yields:

$$W_p = (L_n - U - D) / 2.7 C_p.$$

Substitute the W_p term in Eq. 1 yields:

$$L_w = ET - Pr + (L_n - U - D) / 2.7 C_p \dots\dots\dots [Eq. 4]$$

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

$$F = D / L_n \dots\dots\dots [Eq. 5]$$

where:

L_n = Wastewater nitrogen loading (lb/acre/yr)

D = Denitrification (lb/acre/yr).

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

$$D = F L_n$$

$$L_w = ET - Pr + (L_n - U - F L_n) / 2.7 C_p \dots\dots\dots [Eq. 6]$$

Insert Eq. 3 into Eq. 6 yields

$$L_w = ET - Pr + (2.7 L_w C_n - U - (2.7 F L_w C_n) / 2.7 C_p) / 2.7 C_p \dots\dots\dots [Eq. 7]$$

Simplify Eq. 7:

$$\begin{aligned} L_w &= (ET - Pr) + [2.7 L_w C_n (1 - F) - U] / 2.7 C_p \\ 2.7 L_w C_p &= 2.7 C_p (ET - Pr) + 2.7 L_w C_n (1 - F) - U \\ 2.7 L_w C_p - 2.7 L_w C_n (1 - F) &= 2.7 C_p (ET - Pr) - U \\ 2.7 L_w (C_p - C_n (1 - F)) &= 2.7 C_p (ET - Pr) - U \\ L_w (C_p - C_n (1 - F)) &= C_p (ET - Pr) - U / 2.7 \\ L_w (C_p - C_n (1 - F)) &= C_p (ET - Pr) - U / 2.7 \\ L_w &= [C_p (ET - Pr) - U / 2.7] / (C_p - C_n (1 - F)) \dots\dots\dots [Eq. 8] \end{aligned}$$

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

$$L_w = [C_p (Pr - ET) + 4.4 U] / (C_n (1 - F) - C_p) \dots\dots\dots [Eq. 9]$$

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

$$U = (a + b ET) C_c \dots\dots\dots [Eq. 10]$$

Plug Eq. 10 into Eq. 9 yields:

$$L_w = [C_p (Pr - ET) + (4.4 (a + b ET) C_c)] / (C_n (1 - F) - C_p) \dots\dots\dots [Eq. 11]$$

where:

- Lw = allowable hydraulic loading rate (inch/yr)
- ET = design ET rate (inch/yr)
- Pr = design precipitation rate (inch/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 Evapotranspiration production function (lb/acre)
- b = slope of the Evapotranspiration production function (lb/acre/inch)
- F = fraction of applied total nitrogen removed by denitrification and volatilization. This fraction will be assumed to be 20%.
- 4.4 = 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.

Description of the Irrigation-Scheduling Model.

A volume balance model served as the water balance component of the irrigation-scheduling model. It was determined by using climate data to calculate a reference evapotranspiration (Eto) and a crop coefficient (Kc) for each major vegetation type was used to scale the daily Eto calculated with the equation developed by Penman (Sammis ?). Crop coefficients for each vegetation type were estimated from values in the literature and are only approximations because of limited data.

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.

Currently, the model has to be run separately for each major vegetation type. To minimize deep drainage, the vegetation type that has the least daily evapotranspiration during any portion of the year should be used to schedule the irrigation during that time

period. The yearly water application rate should not exceed that calculated by equation 11.

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 45 psi and a flow 4.85 gpm (18 l/m). The spacing down the laterals is 40 ft (12 m) and the spacing between laterals 40 ft (12 m). The number of sprinklers per line is 18 and the irrigation rate of the sprinklers is 0.29 in/h (0.75 cm/h). The irrigation controller program operates 1 to 3 lines at once. Each line requires 84.3 gpm (18 sprinklers *4.85gpm) and the station demand is 168.6 gpm with two lines open and 253 gpm with three lines open. 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 0.18 in/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 as Bluepoint loamy sand (0 to 17 in and stratified loamy fine sand to loamy sand (18-60 in) (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 densiometer (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. 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). 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 gpd (l/d) to an average of 67,000 gpd (255,000 l/d) over an 11-day period from August 31 to September 10, 2002. This amount of daily discharge was equivalent to a depth of 7.9 cm per day. Nitrate nitrogen in the irrigation water for the year averaged less than 0.2 mg/l but the TKN nitrogen averaged 9 mg/l (Table 1).

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 pot 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 k_c for mesquite. (Levitt, et al. 1995).

The water use efficiency (WUE) of creosote was estimated to be 595 lb/ac-in at 0% moisture. This number was determined by calculating the water use for creosote from January 18 to November 1, 2002 based on the crop coefficient and reference evapotranspiration. To calculate e_t and the change in pot weight per unit area between those dates after the pots had been water to field capacity. The change in weight was due to the growth of the creosote. This calculation is also based on a measured plant moisture content of 82% on a dry weight basis. This WUE value is close to the WUE of *Eucalyptus camaldulensis* which is 535 lb/ac –in (Al Jamal, et al. 2002)

Creosote plant model results

Twenty four inches (60 cm) of irrigation water and seven inches (17.5 cm) of rain water were applied to the site during the year. The creosote plants were not under water stress until May 29 when insufficient water was available from the treatment plant to supply enough irrigation water to satisfy the evaporative demands of the plants (Figure 2). Because the plants were under stress after April 21, deep drainage was low after that date except on Sept. 6 - 10 when the irrigation system was run for 4 straight days when a control valve did not work. The daily evapotranspiration varied from 0 to .25 in/day (Figure 3). Yearly evapotranspiration, calculated by the model, was 18 in and deep drainage was 12 in with 7.1 in of that occurring because of the stuck control valve. With an E_t of 19 inches, a leaf nitrogen content of 2%, and 1.0 % for the stems (Killingbeck and Whitford 1996), the average nitrogen content would be 1.2% and the nitrogen taken up by the plant would have been 136 lb/ac. The total wastewater irrigation applied only 44 lb/ac of nitrogen. The organic nitrogen content in the soil in the top 3 ft is 4,560 lb N/ac (Stephen, et al. 1973) and the mineralization rate can be estimated at 1.5% or 68 lb/ac. If this 68 lb N/ac is added to the 43 lb/ ac from the irrigation water, this would supply enough nitrogen for the E_t to increase to 15.5 in. No nitrogen would have leached below the root zone but rather, the plants would have used all available nitrogen. The model needs a nitrogen stress function to balance the nitrogen and E_t of the creosote plant.

Mesquite plant model results

The WUE of the mesquite plant was estimated to be 414 lb/ ac –in based a study by Duff, et al. (1994). Twenty four in (60 cm) of irrigation water and seven in (17.5 cm) of rain water were applied to the plot during the year. The mesquite plants were not under water stress until April 21 when wastewater was unavailable from the treatment plant to supply irrigation water to satisfy the evaporative demand of the plants (Figure 4). Deep drainage occurred before April 21 and on Sept 9 when the irrigation system control valve was stuck in the open position and the irrigation system filled the root zone to field capacity and 1.9 inches (4.8 cm) went to deep drainage. The daily evapotranspiration varied from 0 to .25 in/d, the same as the creosote plants (Figure 5). Yearly evapotranspiration calculated by the model was 21 in and deep drainage was 10 in. With an E_t of 21 inches and a nitrogen content assumed to be the same as calculated for creosote, the plant nitrogen uptake would have been 104 lb/ac. The total wastewater irrigation was only 44 lb/ac of nitrogen. The organic nitrogen content in the soil in the top 3 ft is 4,560 lb N/ac (Stephen, et al. 1973) and the mineralization rate can be estimated at

1.5% or 68 lb/ac. The total available nitrogen would have been 112 lb/ac. Thus, 8 lb N/ac would have been leached below the root zone. This is considerable less than the 26 lb/ac of nitrogen that would be allowed to leach under the permit for operation of this facility. In this case, the mesquite model would not need a nitrogen component to account for nitrogen stress.

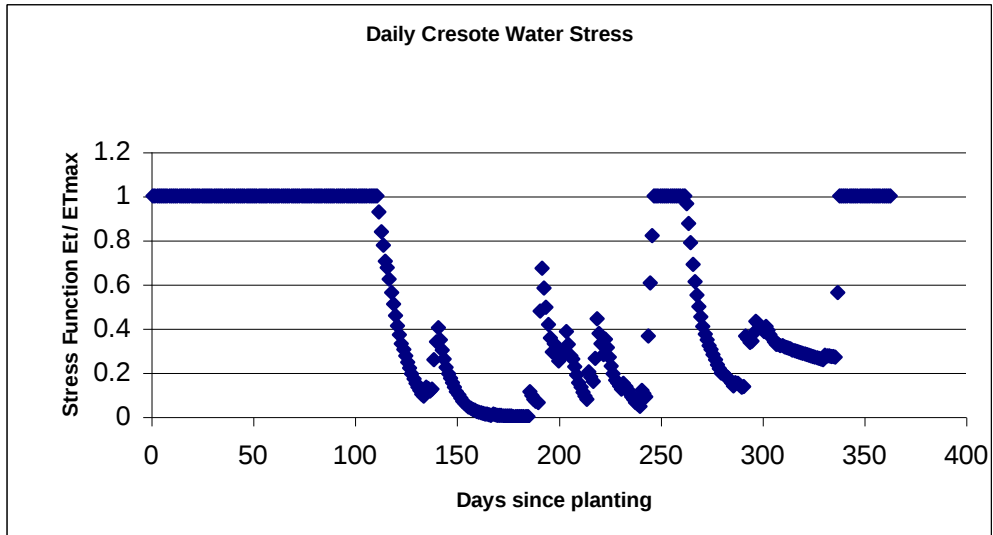


Figure 2

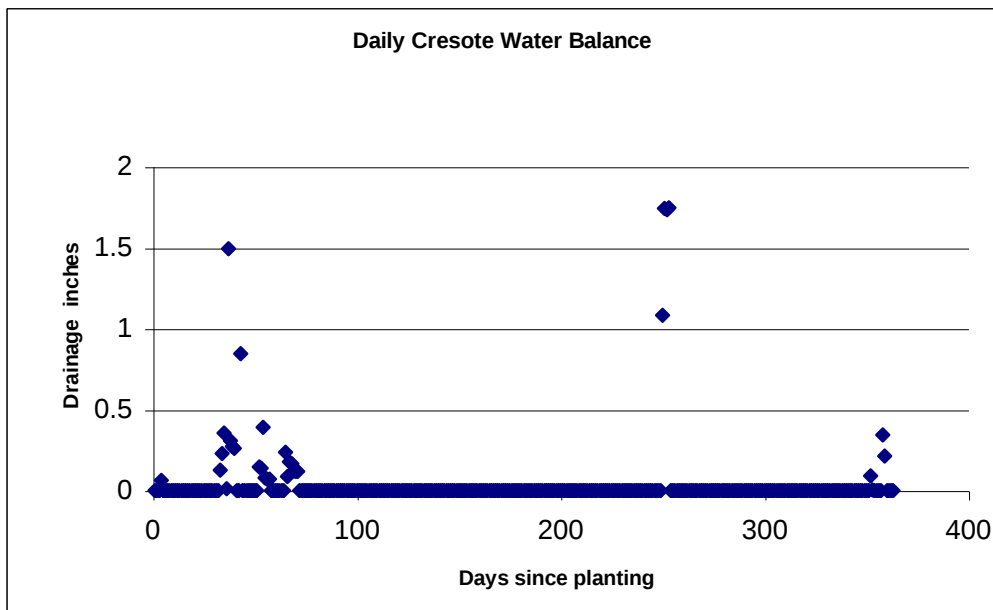


Figure 3

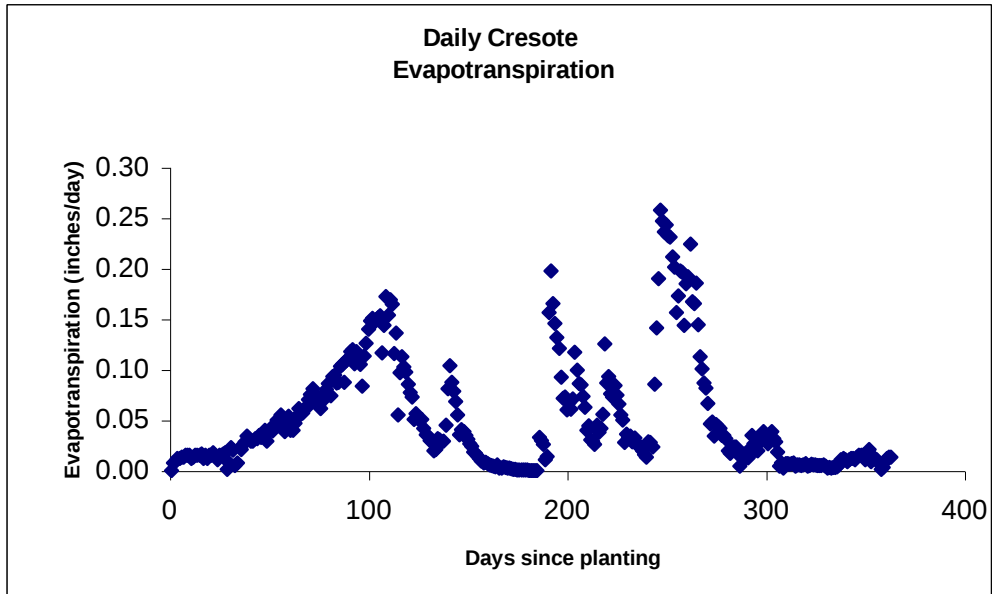


Figure 4

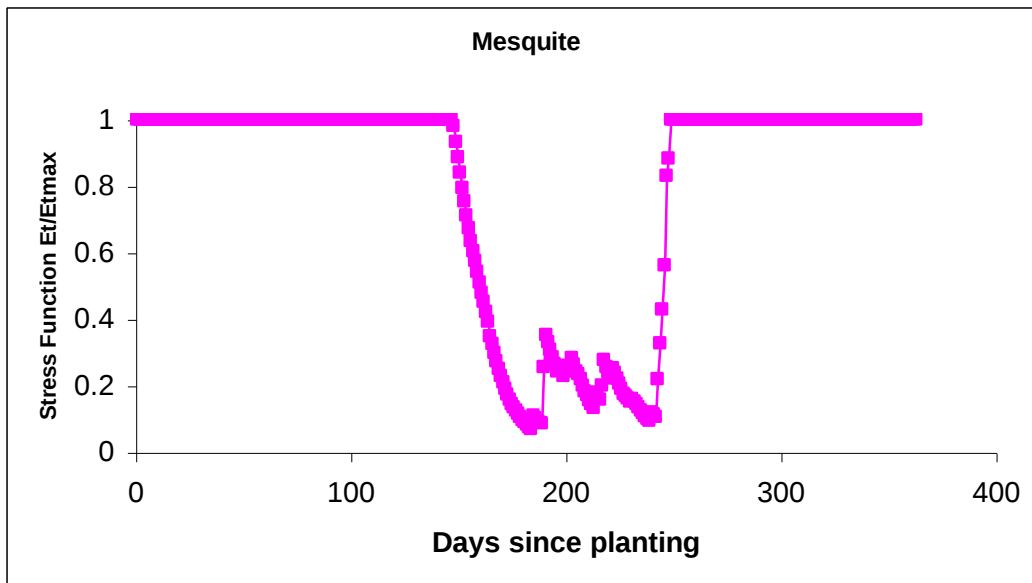


Figure 5

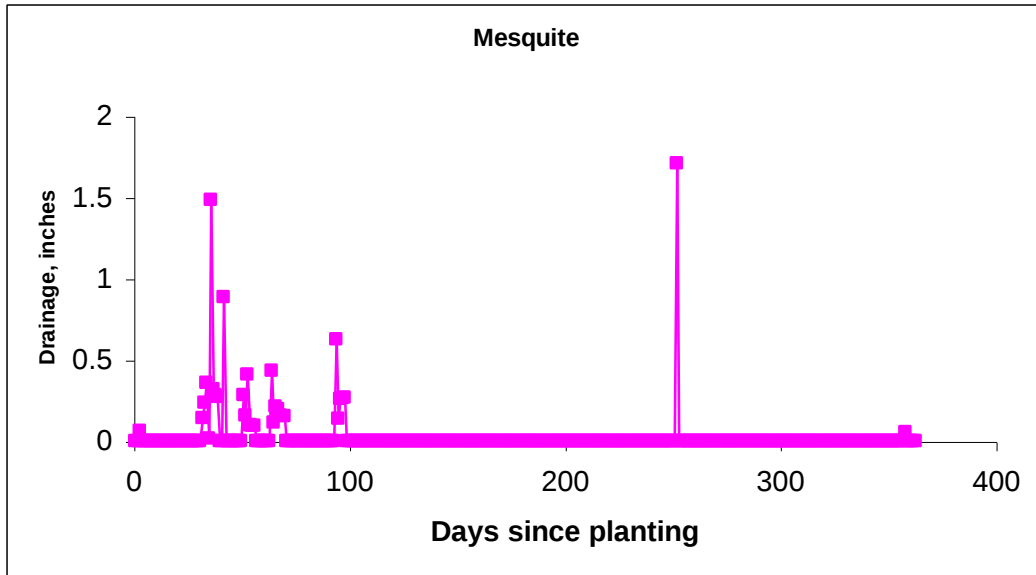


Figure 6

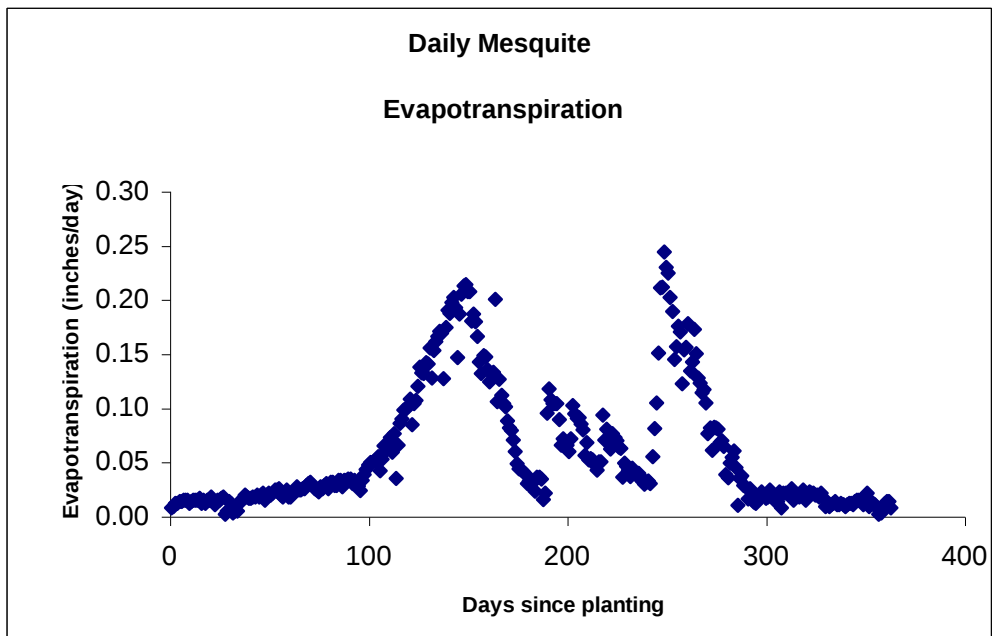


Figure 7.

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