HYDRODYNAMIC MODELING TO OPTIMIZE IRRIGATION EFFICIENCY

Jeffrey J. Anderson[1] J. C. Guitjens[2]

ABSTRACT

The two-dimensional, hydrodynamic model HYDRUS-2D is used to simulate irrigation schedules for an alfalfa crop over the length of a growing season. The objective is to evaluate current practices in order to produce management alternatives that reduce irrigation drainage.

HYDRUS-2D uses a finite element technique that numerically solves the Richards equation for water movement in variably saturated media. The model is calibrated by comparing its output to actual field data collected from an instrumented plot at the Newlands Agricultural Research Center in Fallon, Nevada. The simulation's scope is applied to a vertical cross-sectional study area, 21.95 m in depth by 18.50 m in width, representing half of the spacing between two parallel drains. The soil profile contains one drain and three piezometers below it. An accurate model of the site's layered soil profile is developed by selecting soil parameters that produce acceptable agreement between actual and modeled drain discharge values, as well as, root mean square error between piezometric pressure heads.

The following ratio is used to determine what portion of the water leaving the soil profile is consumed by evapotranspiration,

$$D_{et} / (D_{et} + D_d)$$

where D_{et} is the depth of water used by evapotranspiration and D_d is the depth of drainage water. Optimal results are achieved as the ratio approaches one. Using short, 24-hour intervals indicates how the ratio behaves on a daily basis during irrigation cycles and provides insight into ways to modify standard irrigation practices to create a more efficient management alternative.

---

[1]Jeffrey J. Anderson, Graduate Student, University of Nevada Reno, 1000 Valley Rd. Reno, NV 89512-0013, email: jeferwho@hotmail.com

[2]J.C. Guitjens, Professor of Irrigation Engineering, University of Nevada Reno, 1000 Valley Rd. Reno, NV 89512-0013, email: guitjens@unr.edu

INTRODUCTION

Irrigation is the primary water consumer in Nevada, responsible for using as much as 83.2% of the state's water resources annually (Cobourn, 1992). A large portion of this water is not used beneficially by crops, but instead is lost to canal seepage and deep drainage in the field. Legislative reform, industrial growth, and a swelling population continue to increase the demands on water resources. Since agriculture is not only the largest water user but also returns irrigation drainage, it is critical that more efficient means of canal delivery and irrigation management be developed in order to spread the finite amount of water to an increasing number of concerns. The Bureau of Reclamation has a program aimed at reducing canal seepage, but irrigators receive no organized support to consider technologies that can advance water conservation through management (Guitjens, 1999). This paper is aimed at helping managers by explaining how the HYDRUS-2D software package can be used to quantify the hydrodynamics involved in the irrigation-drainage relationship. It is hoped that managers could utilize the protocol described in this paper to improve their own management decisions.

OBJECTIVES

The objectives are to illustrate the usefulness of HYDRUS-2D for: (1) developing a calibrated, hydrodynamic, irrigation-drainage model which can then be used to (2) evaluate a previous year's irrigation schedule and then employed (3) to generate management alternatives with reduced drainage.

BACKGROUND

The study site which was modeled is located at the Newlands Agricultural Research Center (NARC), part of the Newlands Project in Churchill County of West Central Nevada (Fig. 1). The Newlands Project is one of the oldest irrigation projects authorized under the Reclamation Act of 1902. Water is diverted from the Truckee and Carson Rivers to irrigate about 65,000 acres of the Carson Desert (Clark, 1995). It has been suggested that 35% of the diverted river water is lost to canal seepage before reaching the field, then another 35% of the remaining water is lost to drainage after irrigation (Guitjens, 1999). Early in the history of the project irrigation began raising the water table which eventually encroached on the root zone, decreasing yields. To maintain an unsaturated root zone it was necessary to install a network of ditch drains throughout the project; the drains conduct water from the fields, through a series of ditches to low lying wetlands which include the Stillwater National Wildlife Refuge.

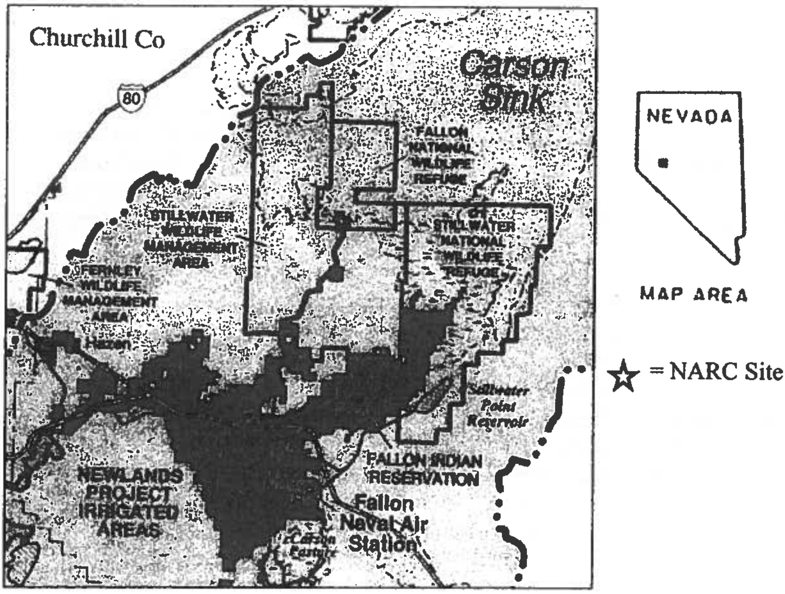


Fig. 1. Fallon Area with NARC Site (Trionfante and Peltz, 1994)

The infiltration through the saline soils of the Carson Desert fills the marshes with drainage water of poor quality. The water's concentration increases from 240 mg/L prior to irrigation to 600 - 3,000 mg/L after drainage, a 2.5- to 12.5-fold increase (Rowe et al., 1991). For comparison, water with concentrations greater than 1000 mg/L may be harmful to sensitive crops and is considered unfit for human consumption (Hoffman, 1994). To intensify the problem Operating Criteria and Procedures (OCAP) were implemented between 1977-88. The goal of these court ordered rules is to ensure the efficient management of water for the Newlands Irrigation Project by maximizing the use of the Carson River while reducing the contribution of the Truckee River. The execution of the OCAP increased project efficiency by decreasing the quantity of water delivered to the distribution system. Consequently the amount of water reaching the wetlands decreased, this ultimately led to a 50% reduction in wetland size, and a four- to seven-fold increase in average dissolved-solids concentrations in the drainwater (Hoffman, 1994).

The highly concentrated drainwater is believed to be responsible for the large loss of emergent and submergent vegetation in the Stillwater and Carson Lake wetlands. The loss of these primary producers, has had a negative effect on higher trophic levels, both in terms of loss in nesting and cover habitat, and in the loss of food supply. During the past three decades, Federal and State wildlife biologists have observed that migratory waterfowl have decreased in kind and number while disease has increased in the population (Hoffman, 1994; Clark, 1995).

In 1990 the Truckee-Carson-Pyramid Lake Water Rights Settlement Act was passed by Congress and enacted to restore wetland ecosystems, like the Stillwater National Wildlife Refuge. The act authorized the purchase of water rights from agriculture lands to be used to dilute the saline waters which had been created in the wetlands (WHSRN, 1999). By 1995, over 10,000 acre-feet of water had been purchased for transfer to the refuge, these purchases continue from willing farmers (Clark, 1995).

The purchase of agricultural water rights, coupled with the water needs of a growing population and industrial sector puts the future of farming in Churchill Country in question. Experience indicates that the Stillwater wetlands will flourish when supplied with adequate freshwater to dilute saline drainwater. Agriculture can survive and contribute to this goal by focusing on water conservation through drainage reduction. Ayers and Meek (1994) showed that the salt mass discharge decreased in rough proportion to decreased drainwater volumes, thus improving irrigation efficiency ultimately reduces the salt load reaching the wetlands. Improved efficiency will also conserve fresh water, which could be used for dilution if it is allowed to enter the wetlands directly.

METHODS

Study Area

Figure 1 shows that NARC is located in the Lahontan Valley, part of the Carson Desert of West Central Nevada. The region is a mid-latitude desert with cold winters and hot summers. Mean annual precipitation is roughly 13 cm per year with the majority falling during the winter months, temperature ranges from -32°C to 41°C with an average of 10.4°C and the elevation is approximately 1,190 m (Newton, 1998).

Hydrogeologic Setting: The Quaternary sediments (Fig. 2) in the Carson Desert were derived from the surrounding fault block mountains composed predominantly of Late Tertiary olivine-basalts, rhyolites, andesites, rhyodacites, many of which occur as tuffs (Willden and Speed, 1974).

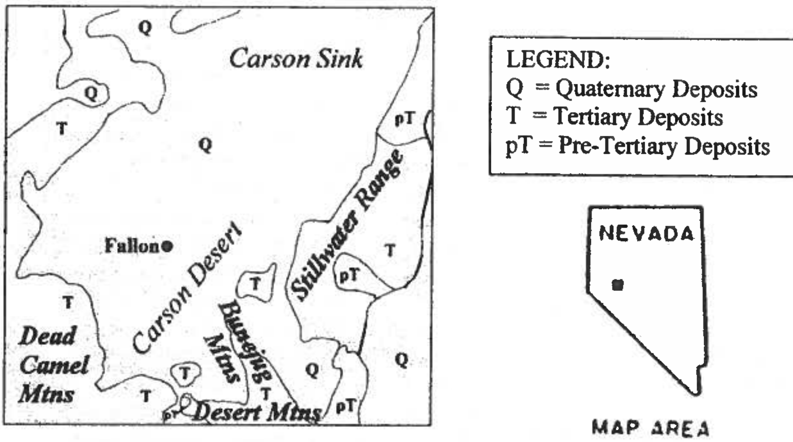


Fig. 2 Geologic Map of Fallon Area (modified from Willden and Speed, 1974 and Faulkner, 1996)

Glancy (1986) divided the subsurface into four distinct aquifers (Fig. 3) based on differences in water-chemistry and variations in the hydraulic properties of the aquifer materials. A shallow alluvial aquifer extends from the land surface to a depth of about 50 feet, an intermediate-depth alluvial aquifer extends from 50 feet to depths of between 500 to 1,000 feet, and a deep-alluvial aquifer underlies the intermediate aquifer. The fourth aquifer is a mushroom shaped basalt formation which exists within the alluvial aquifers and is exposed to the surface at Rattlesnake Hill. All four aquifers respond to stresses independently over the short term due to their varying hydrologic characteristics. Over the long term these units are hydrologically interdependent revealing an interconnected nature of their transmissive zones, thus the subsurface can be thought of as an aquifer system over the long term. Due to the lack of precipitation, recharge to the aquifer system is mainly accomplished by the infiltration of irrigation water and canal seepage.

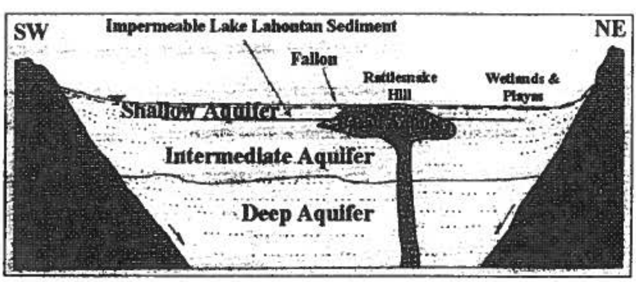
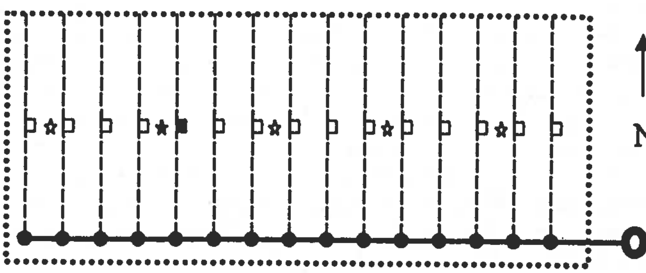


Fig. 3. Hydrogeologic cross-section of study area (Faulkner, 1996)

Site Description: Field data were collected at NARC from a 22-acre field equipped with a series of 15 lateral, tile drains installed two meters below the ground surface and 37 meters apart (Fig. 4). Raised dirt borders exist above each drain lateral and allow flood irrigation events to occur from north to south. Borders are absent near the main drain to allow excess water to runoff toward the east. During 1992 alfalfa was grown in the field and pressure head data were collected from piezometers near the midpoint of each drain. Flows were monitored from each of the lateral drains through an access hole. Bore logs from five locations across the length of the field show a layered soil profile containing various mixtures of sand, silt and clay (Mathis 1995). Guitjens (1992) described the soil's available water storage capacity as ranging in general from 9 to 13%, although in very sandy areas the capacity dropped to between 4 and 6%. Pohll (1993) conducted slug tests to determine the effective hydraulic conductivity of the profile to be approximately 3.23×10^{-3} m/day with a variance of 1.72×10^{-5} m^2/day^2. No information on the conductivity of individual layers is available to date. Pohll and Guitjens (1994) show that a small (0.001) regional gradient exists across the field, although it is dominated by the local gradient to drains in the time immediately following an irrigation event. Precipitation, irrigation amounts, Class-A pan evaporation, and wind data were also collected, however, no measurement of surface runoff between borders was made.



Field Boundary
Drain Lateral
Main Drain
Piezometer Nest
Drain #5 Piezometer Nest
Soil Bore Location
Soil Bore #4 Location
Access Hole
Sump

Fig. 4. Site Plan of NARC

Modeling Procedure

The modeling procedure requires the adoption of a systematic protocol; Fig. 5 illustrates the protocol used in this study.

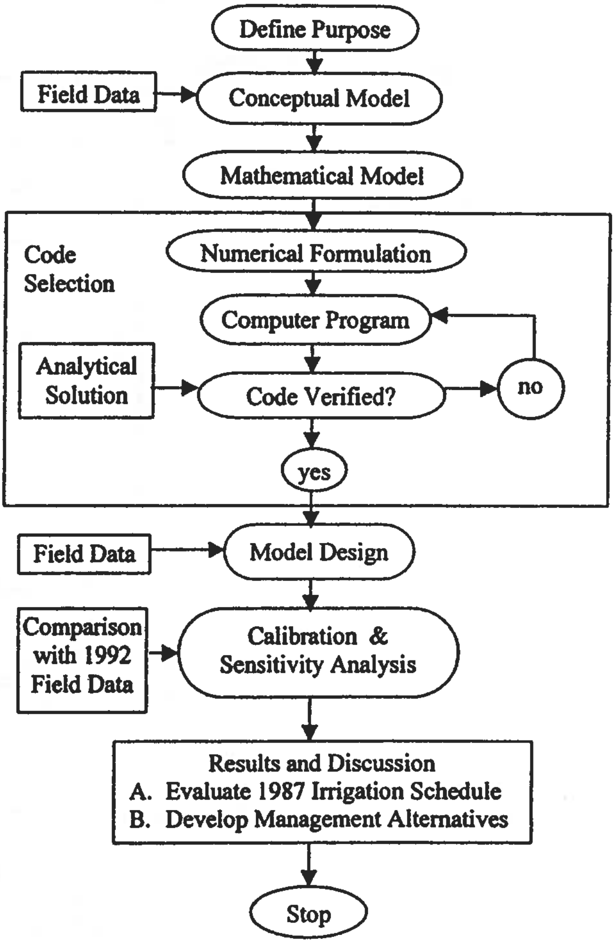


Fig. 5. Flow Chart of Modeling Protocol
(Adapted from Anderson and Woessner, 1992)

Conceptual Model: Once the purpose of the project is determined a conceptual model (Fig. 6) summarizes the key elements, present in the field and acts as a link to the computer model.

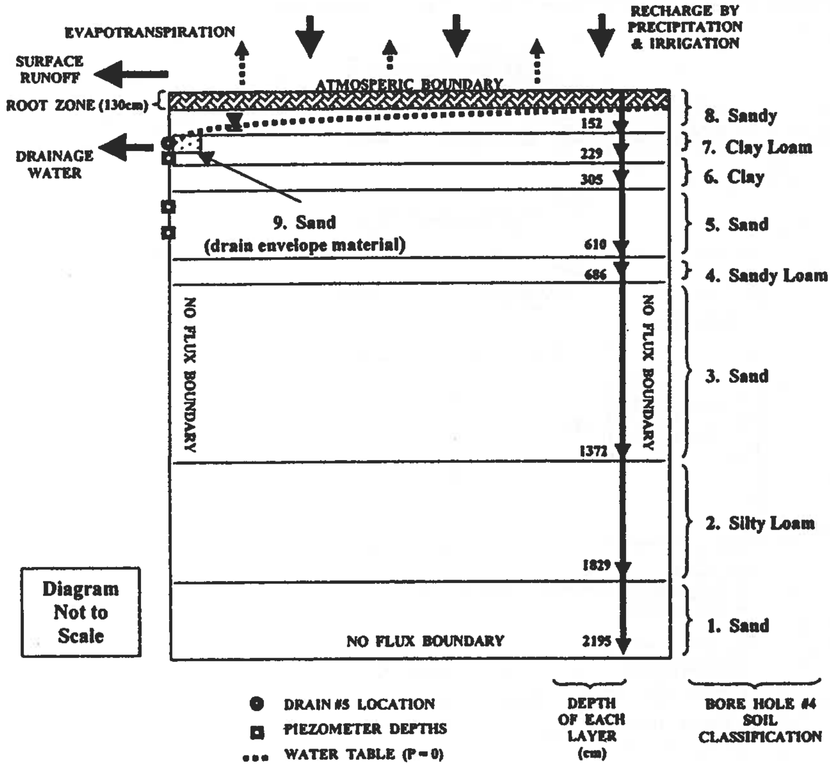


Fig. 6. Conceptual Model of the Area of Interest

The area of interest is limited to a vertical cross-section adjacent to drain #5 with the dimensions of 21.95 m in depth by 18.50 m in width. This cross-section represents a half drain spacing and assumes a mirror image to the left of the drain. Drain #5 extends from 190-200 cm below the surface. Below the drain there are three piezometers at the depths of 216 cm, 320 cm and 412 cm, respectively. Nine different subregions are included, the main horizons (1-8) match the materials and depths described in the log from bore hole #4 (Mathis, 1995). The ninth sub-region represents the drain envelope material that is commonly laid around tile drains at the time of installation. The alfalfa root zone is set to a depth of 130 cm.

Recharge is accomplished by precipitation and irrigation events. Water leaves the profile as either evapotranspiration (ET) at the atmospheric boundary or drainage through the tile drain. Surface runoff occurs when the HYDRUS-2D simulation is unable to accept the full precipitation-irrigation event within a 12-hour period of model time. The vertical sides and bottom are all no flux boundaries. Note that the small regional gradient described by Pohll and Guitjens (1994) has been left out of the conceptual model since HYDRUS-2D is not designed to handle this. This simplification is considered allowable since the local gradient towards the drain would dominate the regional gradient during the irrigation season. The local gradient during the irrigation season is towards the drain, and a local water-divide exists at the mid-point between drains. The slope of the local gradient increases when moving radially toward the drain (Schwab et al., 1996). ET is assumed to occur only during daylight hours, while drainage may occur 24 hours each day. The ET of the alfalfa crop is quantified by multiplying a variable crop coefficient (Rashedi, 1983) by the reference ET, which is derived from Class A pan evaporation data and pan coefficients which are a function of wind speed and relative humidity (Doorenbos and Pruitt, 1977).

Mathematical Model: The two-dimensional, isothermal Darcian flow of water in variably saturated rigid porous medium can be described using the following formulation of Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K^A_{i}\frac{\partial h}{\partial x_j} + K^A_{iz}\right)\right] - S \qquad (1)$$

where θ is the volumetric water content (cm^3/cm^3), h is the pressure head (cm), S is a sink term for evapotranspiration (cm^3/hr), x_i (i=1,2) are the spatial coordinates (cm), t is time (hrs), K^A_{ij} and K^A_{iz} are components of a dimensionless anisotropy tensor $\mathbf{K}^A$, and K is the unsaturated, hydraulic conductivity function (cm/sec) given by,

$$K(h,x,z) = K_s(x,z)\, K_r(h,x,z) \qquad (2)$$

where K_r is the relative conductivity and K_s the saturated hydraulic conductivity (cm/hr). HYDRUS-2D version 1.0 (Simunek et al., 1996), a finite element code which solves (1), was used for this project. This program has been verified widely and was not modified for this research.

Model Design: HYDRUS-2D includes a geometry module that was used to create the exterior and interior boundaries (Fig. 7). MESHGEN, the HYDRUS-2D finite element mesh generator, was used to create a grid with 3,989 points, 7,774 triangles and 11,762 edges (Fig. 8). The density of the grid was increased in the area near the drain, by increasing the number of points on the line defining the drain envelope (Fig. 9).

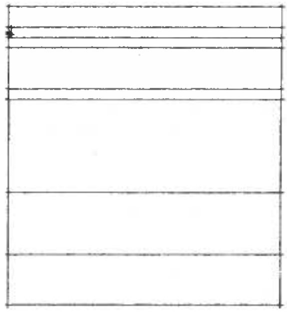


Fig. 7. Profile Showing Boundaries Created in HYDRUS-2D Geometry Module (1,850 cm wide x 2,195 cm deep)

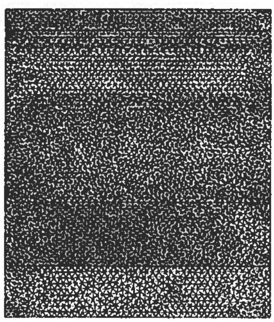


Fig. 8. Finite Element Grid Generated by the MESHGEN Module.

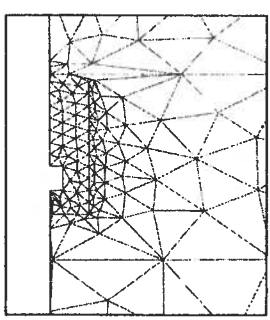


Fig. 9. Enlargement of the Grid in the Vicinity of the Drain (notice the increased density within the drain envelope boundary)

The boundary module was used to define the boundary types. The surface is an atmospheric boundary, the drain a seepage face, while the sides and bottom of the profile are no flux boundaries. The 130 cm root distribution of the conceptual model varied between 115-150 cm in the computer model due to the irregular way the mesh elements fit together. The initial pressure head was set to zero at a depth of 130 cm and increased linearly to 2,065 cm at the bottom of the profile. In order to obtain the gradient towards the drain, the profile was allowed to drain for 120 hours before any irrigation was simulated. The piezometer locations were made observation nodes in the mesh, this provided pressure head values to compare simulation output to field data.

Calibration: The model used for calibration implemented the irrigation schedule and ET field data from the 1992 growing season to create a time variable boundary table with 243 entries. All precipitation-irrigation events and daily ET amounts are entered in HYDRUS-2D as a unit width, hourly flux with the units cm/hour. Daily totals for recharge and ET were divided by 12 hours, to create an hourly flux which would apply, or remove, the correct amount of water during daylight hours only. If the HYDRUS-2D simulation was unable to accept the total amount of recharge in that 12-hour period, the difference was assumed to be surface runoff and the recharge amount was less than the application amount according to the irrigation schedule.

The 1992 season was selected for calibration since piezometer and drainflow data had been collected during that period. Modeled pressure heads were compared to field values, collected from the drain #5 piezometer nest using a root mean square error (RMSE) technique,

$$RMSE = [1/n\ \Sigma(h_m - h_s)_i^2\ ]^{0.5} \qquad (3)$$

where, n is the number of field piezometer readings, h_m is the field measured pressure head and h_s is the simulated pressure head. Simulation and field measured drain flows were also compared as part of the calibration process. The model simulated 3,000 hours, from April 13th to August 10th, which represents the time when piezometer and drain-flow data were collected. Table 1 summarizes how the model time was discretized, note the default settings were used for the time step control. The iteration criteria that were used are shown in Table 2, only maximum number of iterations was increased from the default settings, as this gave the program a greater flexibility in reaching convergence.

Table 1. Time Discretization Summary

Initial Time (hours)	0
Final Time (hours)	3000
Initial Time Step (hours)	0.1
Minimum Time Step (hours)	0.001
Maximum Time Step (hours)	1.0

Table 2. Iteration Criteria Summary

Maximum Number of Iterations	20
Water Content Tolerance	0.0001
Pressure Head Tolerance	0.1
Lower Optimal Iteration Range	3
Upper Optimal Iteration Range	7
Lower Time Step Multiplication Factor	1.3
Upper Time Step Multiplication Factor	0.7

Initial soil types, matching the descriptions used in the log for soil bore #4, were chosen from the entries in the HYDRUS-2D, soil catalog. Each soil type in the catalog has default values, within an accepted range, for its hydraulic properties. The model was calibrated by varying the soil type of the horizons until the RMSE for pressure head was minimized.

HYDRUS-2D incorporates the use of Feddes Parameters (Feddes et al, 1978) to determine root water uptake. Using the default Feddes' values the actual ET values did not match the values calculated by the conceptual model. Since the conceptual technique is specific to alfalfa, the Feddes' parameters were adjusted until the modeled ET equaled the conceptual figures. Changes in the Feddes' parameters are summarized in Fig. 10 and Table 3.

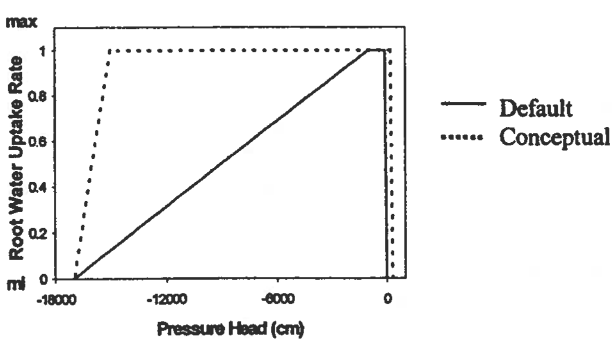


Fig. 10. Comparison of Default Feddes' Parameter Values with the Values which Allowed the Conceptual ET to be Obtained in the Model.

Table 3. Data Table Used to Create Fig. 10, where: P_0 is the pressure head below which roots start to extract water from the soil, P_1 is the pressure head value below which roots start to extract water at the maximum possible rate, P_2 is the pressure head below which roots can no longer extract water at the maximum rate, P_3 is the pressure head at which root water uptake ceases, also known as the wilting point. All values in cm.

	Conceptual	Default
P_0	300	0
P_1	200	-100
P_2	-15000	-1000
P_3	-17000	-17000

The calibration results are shown in Fig. 11 and Fig. 12. The average RMSE for pressure heads (15.0 cm) was obtained using the soils shown in Table 4, these match the soil bore log closely. The average of the 14 collected field drain flows was 4.2 L/min, within an order of magnitude of the modeled average of 8.7 L/min. Some error in flows was expected due to the difference in the way field values were derived, compared to the model. The field drainflow was measured from the access hole (see Fig. 4) at the end of a drain #5, which collected water over the entire drain-lateral length. In contrast, the two-dimensional model calculated the seepage face flux only along a unit drain length. To compare field data with the modeled results an assumption was made that the seepage face flux represented the average flux for a unit length. Soil heterogenuity makes it improbable that infiltration rates would be constant on a field-scale, hence the flow into the drain along each unit length would vary and it is possible that the modeled cross-sectional flux would not be representational of the average. Since the field measures 162 m from north to south a small deviation from the average seepage face flux would lead to a sizeable error in the modeled drain flow.

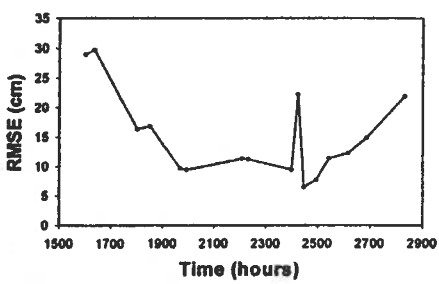


Fig. 11. RMSE comparing modeled & field pressure heads

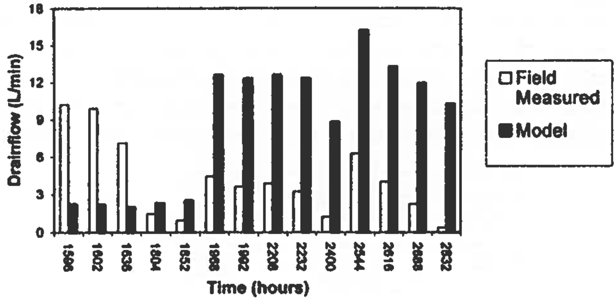


Fig. 12. Comparison of modeled and field drain flows

Table 4. List of Soil Material and Parameters Used in Calibrated Model. Q_r = residual water content, Q_s = saturated Water Content, K_s = saturated hydraulic conductivity

Layer	Soil Type	Q_r	Q_s	K_s (cm/hr)
1	Sand	0.045	0.43	29.7
2	Silt Loam	0.034	0.46	0.25
3	Sand	0.045	0.43	29.7
4	Sandy Loam	0.065	0.41	4.4208
5	Sand	0.045	0.43	29.7
6	Clay	0.070	0.36	0.02
7	Clay Loam	0.100	0.39	1.31
8	Sandy Loam	0.065	0.41	4.4208
9	Sand	0.045	0.43	29.7

Figure 12 shows the modeled drainflow is generally greater than the field flow, especially at later time. In water balance terms this indicates that either the ET schedule values were not large enough or that the modeled recharge was over estimated. The ET schedule is considered reliable since it was based on direct Class A pan measurements and alfalfa crop coefficients developed specifically for the study site (Rashedi, 1983). The weakness seems to be in the amount of water allowed to infiltrate within the model. The geometry of the field allows water to run off the south end of an irrigation border. Anecdotal evidence supports the notion that the entire amount of water that was applied according to the irrigation schedule would not have entered the profile, unfortunately no measurements of surface runoff exist to adjust the irrigation amounts. The sensitivity analysis (Fig. 15) shows that an average drainflow of 4.8 L/min can be obtained in the model when the irrigation amount is reduced to 90% of the original amount. A 10% reduction in the irrigation amounts only produced a slight increase in the RMSE for pressure heads (from 14.5 cm to 17.5 cm).

Sensitivity Analysis: Additional simulations were run to check the sensitivity of the calibrated model to changes in ET and irrigation amounts. Figures 13-16 show the effects of using 90%, 80% and 70% the original values for ET and irrigation.

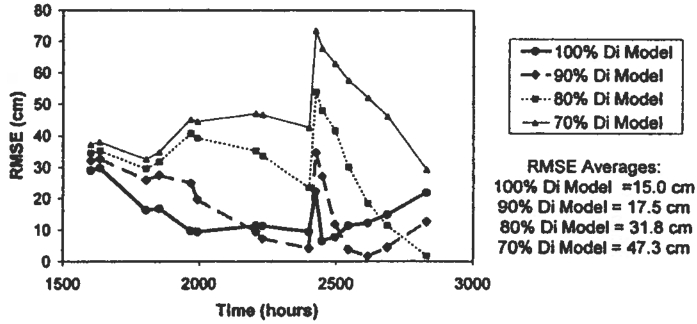


Fig. 13. RMSE for four D_i levels

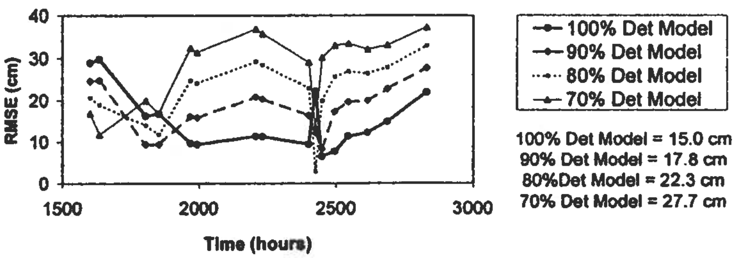


Fig. 14. RMSE for four D_{ct} levels

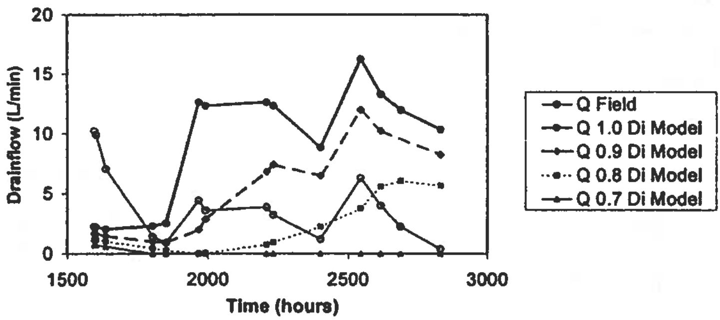


Fig. 15. Observed Drain Discharge Compared to Simulated Values for Four D_i Levels

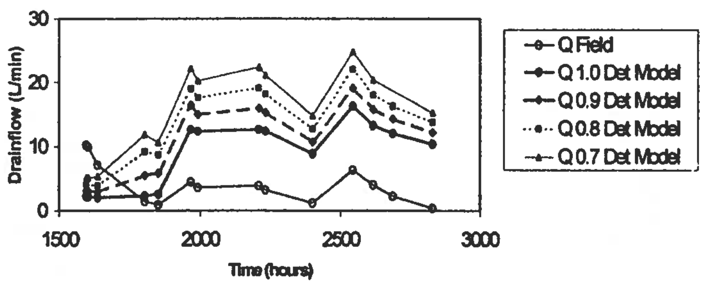


Fig. 16. Observed Drain Discharge Compared to Simulated Values for Four D_{et} Levels

Results and Discussion: Once a calibrated model is obtained it can be used to evaluate the efficiency of a previous year's irrigation schedule. This is done by inputting the appropriate time variable boundary information including an irrigation schedule, precipitation records and Class A pan based ET data. For this research 1987 was chosen because during that year half of the NARC field was sprinkler irrigated while the other half was flood irrigated. Simulating each of these schedules allows comparison between two common methods of irrigation. The simulations each modeled 5,316 hours, representing a full growing season from February 26th to September 30th. The actual atmospheric flux used in each simulation are shown in Fig. 17.

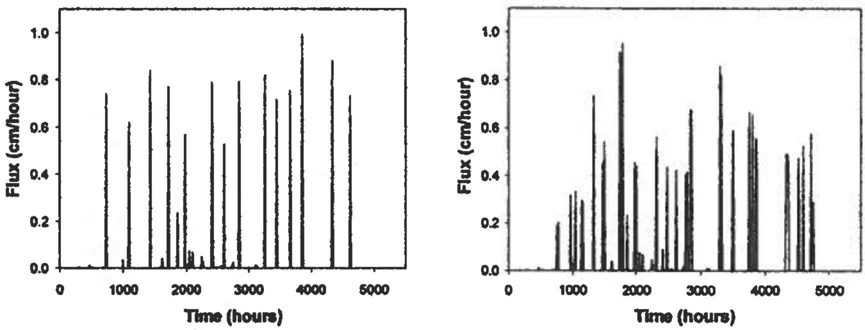


Fig.17. Atmospheric Fluxes for Simulations of the 1987 Flood (left) and Sprinkler (right) Irrigation Schedules.

For the purposes of this research, efficiency is judged with the following ratio,

$$D_{et} / (D_{et} + D_d) \qquad (4)$$

where D_{et} is the depth of water used by evapotranspiration and D_d is the depth of drainage water. The ratio only is valid when no surface runoff occurs. The quantity D_{et} represents the water used beneficially by the plant, while $(D_{et} + D_d)$ delineates the total amount of water depleted from the soil. Optimal results are achieved as the ratio approaches one. Using short, 24-hour intervals indicates how the ratio behaves on a daily basis during irrigation cycles and provides insight into ways to modify standard irrigation practices to create a more efficient management alternative.

The cumulative atmospheric fluxes from the irrigation schedules were compared with the cumulative fluxes crossing the boundary within each simulation. The flood simulation accepted the entire amount (134.6 cm) of water that was applied. In contrast, at four separate times the sprinkler simulation profile did not accept all of the applied water and surface runoff occurred (Fig. 18). The total depth of water applied using the sprinkler schedule was 238.8 cm, of which 6.6 cm went to runoff.

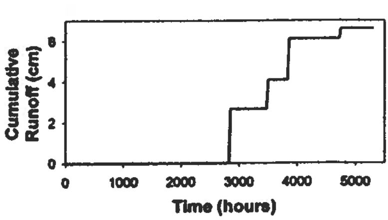


Fig. 18. Cumulative Surface Runoff Occurring During the 1987 Sprinkler Irrigation Simulation.

Before the efficiency of a simulation can be calculated and graphed on a daily basis the HYDRUS-2D output file *v_mean.out* must be modified. Using a spreadsheet program D_i, D_{et} and D_d for each iteration can be calculated by multiplying *vAtm, vRoot* and *vSeep* respectively by the time elapsed since the last iteration. Adding each D_i value to the ones before it provides a cumulative total of D_i for each time step. The same is done with D_{et} and D_d. To calculate the efficiency ratio on a daily basis the only values that are important are the cumulative totals for each 24-hour increment. Manually separating these values is time consuming, but a short FORTRAN program speeds the process greatly. The program used to sort the data for the irrigation efficiency graphs included in this paper follows in Fig. 19. The program requires an input file *24sort4* which includes the following columns: time, cumulative D_i, cumulative D_{et} and cumulative D_d. The output file *sort4* will contain the cumulative values of D_i, D_{et} and D_d for each 24-hour period. To find daily values for D_i, D_{et} and D_d take the difference between each day's cumulative total and use these daily values to calculate $D_{et}/(D_{et} + D_d)$. Daily $D_{et}/(D_{et} + D_d)$ for the flood and sprinkler irrigation simulations are shown in Fig. 20 and 21.

```
Real Time, CDi, CDet, CDd
        Open (10, File='24sort4.txt', status='old')
        Open (20, File='sort4.txt', status='old')
    P=1.0
    Do 100
    Read (10,*,end=101) Time, CDi, CDet, CDd
    Check = (P*24.0)-Time
    If (Check .LE. 0.2) then
        Write (20,*) Time, CDi, CDet, CDd
        P=P+1.0
    End if
    100 continue
    101 Close (10)
        Close (20)
    End
```

Fig. 19. FORTRAN Program Used to Sort Data

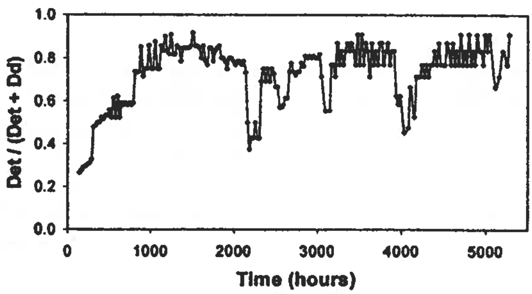


Fig. 20. Fraction of Removed Soil Water Going to ET for 1987 Flood Irrigation Simulation

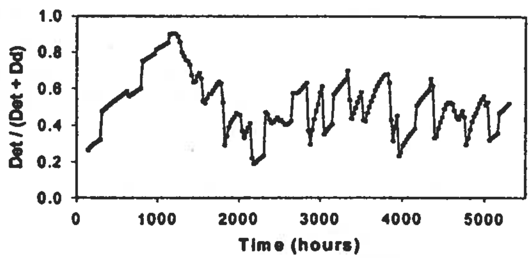


Fig. 21. Fraction of removed soil water going to ET for 1987 sprinkler irrigation simulation

The average value of $D_{et}/(D_{et} + D_d)$ for the flood simulation (0.73) was higher than for the sprinkler simulation (0.51), indicating that in this case the flood schedule was more efficient than the sprinkler schedule. Due to the surface runoff the sprinkler irrigation was actually less efficient than 0.51. A better measure of efficiency when runoff occurs is the water use efficiency (E_u),

$$E_u = W_u / W_d \qquad (5)$$

where W_u is the water benefically used and W_d is the water delivered to the area being irrigated (Schwab et al, 1996). Therefore, with W_u equal to D_{et} and W_d equivalent to $(D_{et} + D_d)$ plus the depth of runoff, the E_u for the sprinkler simulation equalled 0.48.

The aim of a management alternative is to increase the efficiency of an irrigation schedule without adversely affecting the plant's yield. Various strategies for increasing the efficiency have been tried, each one attempts to reduce the application of water in order to prevent drainage. To be sure that plant stress is not reducing yield the *cum_Q.out* file should be examined to be sure that *CumQRP* (cumulative potential root-water uptake) and *CumQRP* (cumulative actual root-water uptake) are equal, if they are than the model is allowing the calculated reference ET to occur.

The management alternative that has shown the greatest success is based on meeting the ET requirements of the plant. A weekly irrigation was applied to meet the ET requirements of the upcoming week. ET and natural precipitation values from 1987 were used. The natural precipitation was included in the model, but was in addition to the amount of water applied to meet the ET requirement. A second management alternative modeled a 90% efficiency based on the depth of weekly irrigation equal to $D_{et}/0.9$ for that week. The results of these management alternatives appear in Fig. 22.

The average value of $D_{et}/(D_{et} + D_d)$ for the simulation that matched the ET requirements was 0.85 while the $D_{et}/90\%$ simulation averaged 0.78. The natural precipitation reduced the expected efficiency of each simulation due to increased drainage. This drainage may be helpful for leaching salts out of the root zone. Figure 23 shows how the average efficiency of the $D_{et}/90\%$ simulation was increased from 0.78 to 0.84 when the natural precipitation was removed from the model.

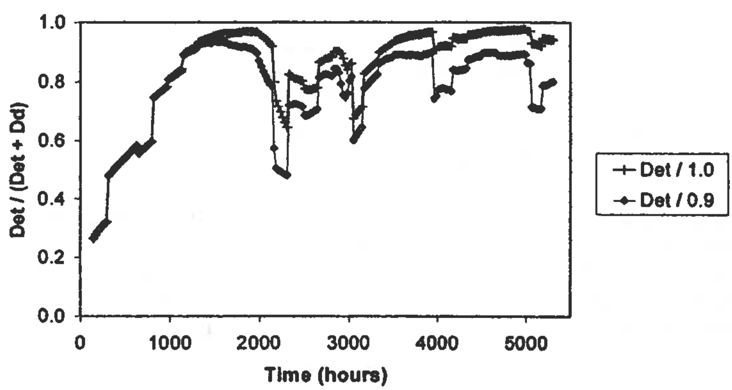


Fig. 22. Fraction of Removed Soil Water Going to ET for Two Management Alternatives. $D_{et}/1.0$ corresponds to a schedule that matches ET requirements, $D_{et}/0.9$ corresponds to a schedule with a 90% efficiency.

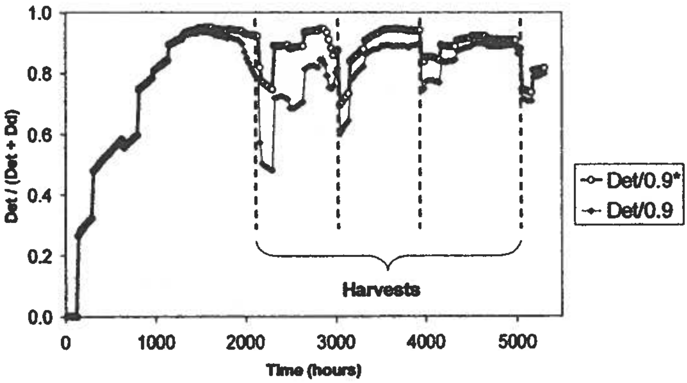


Fig. 23. Fraction of Removed Soil Water Going to ET for Two Management Alternatives. $D_{et}/0.9$ corresponds to a schedule with a 90% efficiency and natural precipitation, $D_{et}/0.9$* corresponds to the same schedule without natural precipitation.

Each management alternative shows a similar pattern of decreased efficiency, first during the initial hours of the simulation (t<1,600 hrs) and then after each alfalfa cutting. Cuttings occurred on May 21st (2,148 hours), June 26th (3,012 hours), August 3rd (3,924 hours) and September 18th (5028 hours). Figure 24 shows the daily drainage for the $D_{et}/1.0$ model. The greatest drainage occurs at the beginning of the simulation. This early drainage may be a remnant of the initial conditions imposed on the profile and the drainage that occurs while the initially flat water table takes on a sloped form. Therefore, it is possible that the early inefficiency may result from model limitations and may not be duplicated in the field where this sloping water table rises following irrigation rather than falling from a flat water table. After 1,600 hours the initial drainage is complete (Fig. 24) and the efficiency remains relatively high with the exception of short periods of inefficiency during four post-harvest periods (Fig. 23). The inefficiency after the first two cuttings matches closely with an increase in drainage. By reducing irrigation before harvest D_d may also be reduced. The same is not true about the third and fourth cuttings where drainage is minimal and continues to decline after harvest. Here the apparent inefficiency is the result of a small drainage term dominating a smaller post-harvest ET term.

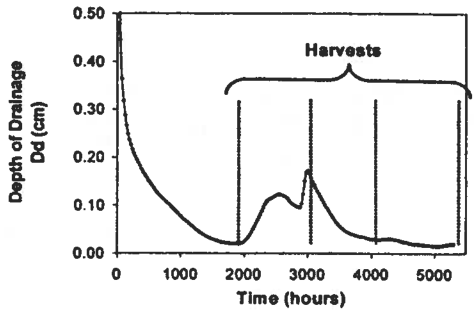


Fig. 24. Depth of Water Going to Drainage During each 24-hrs, Harvests are Shown as Vertical Lines.

CONCLUSION

A two-dimensional, hydrodynamic model of a half drain spacing was developed using HYDRUS-2D. The model was calibrated to pressure head and drainflow data collected in 1992 at the NARC. A RMSE of 15.0 cm was achieved between field and modeled pressure head by adjusting the soil type and hydraulic properties of layers in the profile. This RMSE is in close agreement with the values obtained in previous work (Newton, 1998 and Guitjens, 1999). The modeled versus field drainflow showed less agreement, due in part to modeled results being compared to the average across the length of the drain and in part to overestimates in the recharge due to lack of surface runoff measurements. Future work will attempt to calibrate drainflow by reducing the time allowed for infiltration to more closely approximate the hydrodynamics of an irrigation event. The calibrated model was useful for evaluating the 1987 flood and sprinkler irrigation schedules, showing that both schedules over watered. Management alternative schedules were developed based on the ET requirements of alfalfa and resulted in an increased efficiency of between 12-37%.

REFERENCES

Anderson, M.P. and Woessner, W.W. 1992. Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic Press, San Diego, CA, 381 p.

Ayars, J.E. and Meek, D.W. 1994. Drainage load-flows relationships in arid irrigated areas. Trans. ASAE, 37: 431-437.

Clark, J. 1995. Stillwater National Wildlife Refuge, Refuge Reporter, Retrieved May 20, 1999 from the World Wide Web: http://www.gorp.com/gorp/resource/us_nwr/nv_still.htm

Cobourn, J., Johnson, W., Ford, J., Reid, M., and Allen, N. 1992. Nevada's water future: making tough choices, A Guide for Public Policy Dialogue, Sponsored by University of Nevada, Cooperative Extension.

Doorenbos, J. and Pruitt, W.O. 1977. Crop water requirements. Irrigation and Drainage Paper No.24, FAO United Nations, Rome, 144 p.

Faulkner, B.R. 1996. Soil chemistry and hydrodynamics of irrigation with drainwater, Nevada, University of Nevada, Reno Masters Thesis, 78 p.

Feddes, R.A., Bresler, E., and Zaradny, H. 1978. Simulation of Field Water Use and Crop Yield, Simulation Monographs, Pudoc, Wageningen, The Netherlands, 188 p.

Glancy, P.A. 1986. Geohydrology of the basalt and unconsolidated sedimentary aquifers in the Fallon area, Churchill County, Nevada, USGS Water-Supply Paper 2263. 62 p.

Guitjens, J.C., 1992. Interpreting spatial yield variability of irrigated spring wheat. Trans. ASCE. 35(1):91-95.

Guitjens, J.C. 1999. Modeling management alternatives for efficient water use and drainage reduction. USCID 17th Congress, Spain Trans. 1B-Q48 (R3.06):79-94.

Hoffman, R.J. 1994. Detailed study of irrigation drainage in and near Wildlife Management Areas, West-Central Nevada, 1987-90, Part C. Summary of irrigation-drainage effects on water quality, bottom sediment and biota. USGS Water-Resources Investigations Report 92-4024C. 32 p.

Mathis, A.C. 1995. Influence of the subsurface distribution of salts and trace elements on the quality of irrigation drainage water at Fallon, Nevada, University of Nevada, Reno Masters Thesis, 185 p.

Newton, B. 1998. Simulating hydrodynamics of irrigation drainage. University of Nevada, Reno, Professional Paper, 68 p.

Pohll, G.M. 1993. Modeling regional flow and flow to drains, University of Nevada, Reno Masters Thesis, 120 p.

Pholl, G.M. and J.C. Guitjens. 1994. Modeling regional flow and flow to drains, Journal of Irrigation and Drainage Engineering. 120(5):925-938.

Rashedi, N. 1983. Evapotranspiration crop coefficients for alfalfa at Fallon, Nevada, University of Nevada, Reno Masters Thesis, 155 p.

Rowe, T.G., Lico, M.S., Hallock, R.J., Maest, A.S. and Hoffman, R.J. 1991. Physical, chemical and biological data for Stillwater, Frenley and Humboldt Wildlife Management Areas and Carson Lake, West-Central Nevada, 1987-1989. USGS Open-File Report 91-185.

Schwab, G.O., Fangmeier, D.D., and Elliot, W.J., 1996. Soil Water Management Systems, 4th ed., Wiley and Sons, New York. 371 p.

Simunek, J., Sejna, M., and van Genuchten, M.Th. 1996. The HYDRUS_2D Software Package for Simulating Water Flow and Solute Transport in Two-Dimensional Variably Saturated Media, Version 1.0, USSL, Riverside, CA, 167 p.

Trionfante, J. and Peltz, L. 1994. Hydrologic features of the Truckee and Carson River Basins and adjacent areas, Western Nevada and Eastern California, USGS, Open File Report 93-368, map.

WHSRN-USA. Stillwater Nevada, USA Hemispheric Reserve. Retrieved May 21, 1999 from the World Wide Web: http://wetlands.ca/wi-a/whsrn/stilwater.html.

Willden, R. and Speed, R.C. 1974. Geology and mineral deposits of Churchill County, Nevada, Bulletin 83 of Nevada Bureau of Mines and Geology, University of Nevada, Reno, 95 p.