Comparison of Water Balance Predictions Made with HYDRUS-2D and Field Data From the Alternative Cover Assessment Program (ACAP)

Preecha Apiwantragoon[1], Craig H. Benson[1], and William H. Albright[2]
[1]*University of Wisconsin, papiwantrago@wisc.edu, benson@engr.wisc.edu, Madison, WI, USA*
[2]*Desert Research Institute, bill@dri.edu, Reno, NV, USA*

ABSTRACT

A comparison is made between water balance predictions obtained from HYDRUS-2D and field measurements from a test section simulating a capillary barrier. The predictions from HYDRUS-2D deviate appreciably from the field data. Differences between the measurements and predictions are related to errors in predicting surface runoff (SRO) and evapotranspiration (ET), and uncertainties in the hydrologic properties of the soils. Greater differences between the measured and predicted SRO were obtained when hourly meteorological data were used as input instead of daily data. Increasing the saturated hydraulic conductivity until the measured and predicted surface runoff were essentially equal allowed more water to enter the soil profile and resulted in more realistic changes in soil water storage (SWS) during the wetter portions of the record. However, calibration to the SRO data also resulted in large over-predictions of ET, and much lower SWS than was measured in the field. Adjusting the vegetation parameters had little effect on the predictions. Zero percolation was predicted by the model for all cases. In contrast, approximately 50 mm of percolation was measured in the field.

INTRODUCTION

Alternative covers employing a water balance approach are being considered for capping waste containment facilities located in semi-arid and arid climates in lieu of conventional covers employing barriers with low saturated hydraulic conductivity (e.g., clay layers and/or geomembranes). Alternative covers are being used because they are often less costly to construct and are believed to be less susceptible to damage caused by weathering.

Design of alternative covers generally includes simulating the hydrology of the cover with an unsaturated flow model that accounts for interactions between the soil, plants, and atmosphere. One of the models used by designers is HYDRUS-2D (Simunek et al. 1999), which uses the finite element method to solve a modified form of Richards' equation:

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

In Eq. 1, θ is volumetric water content, t is time, x_i is a spatial coordinate (i = 1, 2), K is the unsaturated hydraulic conductivity, K_{ij}^{A} and K_{iz}^{A} are anisotropy factors, and S is a sink term for plant water uptake. Although HYDRUS-2D includes rigorous algorithms to simulate the processes controlling unsaturated flow, limited study has been undertaken to evaluate the accuracy of HYDRUS-2D for alternative cover design (e.g., see Scanlon et al. 2002). Model accuracy is particularly important in alternative cover design and assessment, because alternative covers generally are required to meet strict percolation criteria (< 1-3 mm/yr).

The US Environmental Protection Agency (USEPA) currently is conducting a long-term field study referred to as the Alternative Cover Assessment Program (ACAP). One of the purposes of ACAP is to evaluate and improve tools used to design and assess alternative covers, such as HYDRUS-2D. Data from 24 large-scale test sections being monitored by ACAP are available for this purpose (Albright and Benson 2002). A detailed description of the test sections can be found in Roesler et al. (2002).

This paper describes a comparison made between predictions from HYDRUS-2D and field data collected from an ACAP test section. Input to the model was selected to be as representative of on-site conditions as practical. Field meteorological data and laboratory-measured hydrologic properties of the cover soils were used as input whenever possible.

TEST SECTION

The field data are from an ACAP test section located in Marina, CA. Marina has a semi-arid to sub-humid coastal climate with 460 mm of precipitation each year on average. The cover profile consists of a 1220-m thick layer of sandy clay used for water storage over a 300-mm layer of poorly graded sand that forms a capillary break. A root barrier was placed between the sandy clay and the sand. The test section is vegetated with a mixture of grasses native to the Marina area (blue wild rye, California brome, creeping wild rye, and pacific hairgrass).

The hydrology of the cover is monitored using a large-scale (10 m by 20 m) lysimeter that permits direct measurement of all water balance quantities except evapotranspiration (ET), which is computed as the residual of the water balance. Benson et al. (2001) provides a detailed description of the lysimeter and Roesler et al. (2002) describes the water balance computations. Surface runoff and percolation are monitored by measuring the rate at which water accumulates in collection basins. Soil water content is measured using low frequency (40 MHz) time domain reflectometry (TDR) probes and soil water potential is measured with thermal dissipation sensors. Soil water storage is computed by integrating the water content profiles. Meteorological data are obtained from a weather station mounted on the test section.

MODEL SET-UP

HYDRUS-2D was used to simulate the hydrology of the capillary barrier at Marina. One-dimensional simulations were conducted, vapor flow and heat transfer were assumed to be negligible, both soil layers in the cover were assumed to be uniform, homogeneous, and isotropic, and hysteresis was ignored.

Unsaturated hydrologic properties of the cover soils were described using the van Genuchten and van Genuchten-Mualem equations (van Genuchten 1980). Hydrologic properties used as input for many of the simulations are summarized in Table 1. These parameters are based on laboratory tests conducted on 15 undisturbed samples collected during construction of the test section (Gurdal et al. 2003). Geometric means were used for the saturated hydraulic conductivity (K_s) and α. Arithmetic means were used for θ_r, θ_s, and n. The pore interaction factor was assumed to be 0.5 for both soils.

Soil	Saturated Hydraulic Conductivity (cm/s)	θ_r	θ_s	α (m^{-1})	n
Sandy Clay	6.8×10^{-8}	0.00	0.34	0.04	1.4
Sand	3.6×10^{-3}	0.07	0.39	5.30	2.8

Table 1. Hydrologic properties of the cover soils

The vegetation input to HYDRUS-2D consisted of potential transpiration demand, a root density function, and a water stress function. Potential transpiration (PT) was computed from potential evapotranspiration (PET) using the Ankeny-Ritchie-Burnett equation (Fayer 2000), which is based on leaf area index (LAI). PET was computed using the modified Doorenbos-Pruitt equation, as implemented in UNSAT-H (Fayer 2000). The root density function was derived from a database compiled by Winkler (1999). The water stress function in Feddes et al. (1978) was used with the following matric suctions: anaeorbiosis point = 3.6 m, optimal point = 3.6 m, limiting point = 26.9 m, and wilting point = 450 m. The wilting point was estimated from the lowest water contents measured in the root zone during the growing season and the water retention curve for the sandy clay. A root growth rate of 7.5 mm/d was assumed, and the root depth was limited to the interface between the sandy clay and sand layers.

Initial conditions were assigned using water contents measured in the field (0.23 for sandy clay, 0.18 for sand). An atmospheric boundary condition was applied at the surface. Meteorological data used for the atmospheric boundary are summarized in Roesler et al. (2002). A seepage face boundary was applied at the base of the profile, as recommended in Scanlon et al. (2002) for modeling lysimeters. Mesh size was selected iteratively so that the cumulative mass balance remained less than 1%. The vertical spacing was <0.1 mm at the boundaries and layer interfaces, and was as large as 50 mm at interior points. The minimum time step was set at 10^{-10} d and the water content and pressure head tolerances were set at 10^{-6} and 10^{-3} m.

BASE CASE PREDICTIONS

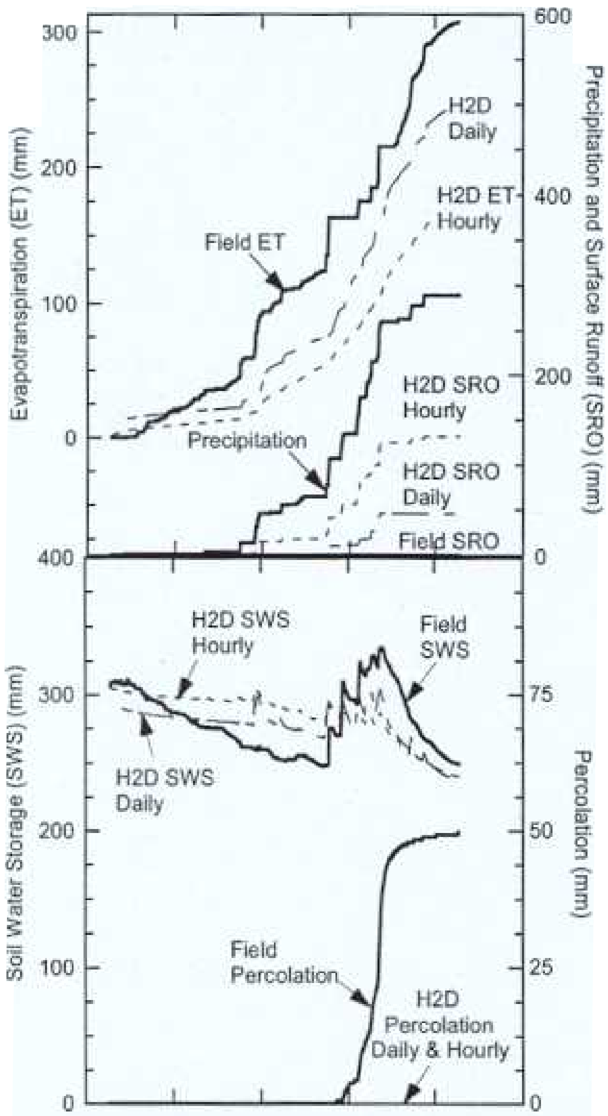


Figure 1. Base case predictions and measured evapotranspiration (ET), surface runoff (SRO), soil water storage (SWS), and percolation. Daily and hourly meteorological data used as input.

Simulations were conducted using hourly and daily meteorological input along with the other aforementioned input parameters. Results of these simulations are referred to herein as 'base case' predictions. Water balance quantities predicted with HYDRUS-2D and measured in the field for the base case are shown in Fig. 1 (predictions with HYDRUS-2D are marked as H2D). Both hourly and daily data were used because Scanlon et al. (2002) indicate that runoff predicted with HYDRUS-2D (and similar models) is sensitive to the temporal discretization of the input.

Surface runoff (SRO) was over-predicted appreciably for both hourly and daily input, mainly during intense precipitation events. Hourly input resulted in larger over-predictions of SRO because precipitation is applied with greater intensity when hourly data are used (precipitation is uniformly distributed throughout the day with daily input, resulting in lower intensity). Scanlon et al. (2002) also found that SRO increased in some cases when hourly input was used instead of daily input.

Evapotranspiration (ET) generally was under-predicted, especially during wetter periods. ET predicted using daily input was closer to that measured in the field. Daily input results in more infiltration (less SRO), making more water available for ET.

Similar patterns of soil water storage (SWS) were predicted with daily and hourly input, and they generally follow the seasonal variations observed in the field (Fig. 1). However, the changes in soil water storage are smaller than those observed in the field, largely due to the under-predictions of infiltration and ET. The relatively large decrease in SWS predicted early in the record using daily input is due to a short-term over-prediction of ET at the beginning of the record.

No percolation was predicted using hourly or daily input, whereas 49.8 mm of percolation was measured in the field. The most likely cause of the under-prediction of percolation is due to the over-prediction of SRO, which prevented the SWS from reaching a point that would result in appreciable drainage. Khire et al. (1997) also report that errors in SRO affect predictions of percolation, as well as all other subsurface processes.

SURFACE RUNOFF CALIBRATION

Attempts were made to improve the predictions by adjusting K_s of the sandy clay until the predicted SRO resembled the field-measured SRO (which was nil). Matching the field-measured SRO required increasing K_s of the sandy clay from 6.7×10^{-8} cm/s to 4.0×10^{-4} cm/s (i.e., nearly four orders of magnitude). All other parameters were the same as those in the base case simulations. Water balance predictions made with HYDRUS-2D using hourly meteorological input and the calibrated K_s are shown in Fig. 2.

Calibrating the model resulted in larger changes in SWS and higher ET, largely due to additional water entering the soil profile (Fig. 2). Higher K_s also allowed water to be removed by ET more readily (i.e., water could move to the surface more readily with higher K_s). However, the predictions made with the calibrated model generally are poorer than those using base-case input. ET tends to be grossly over-predicted, and SWS is grossly under-predicted. The under-prediction of SWS is largely due to the over-prediction of ET. The changes in SWS are an exception. The changes in SWS predicted with the calibrated model during the wetter months are closer to the changes in SWS observed in the field.

Despite the higher K_s, the calibrated model predicted no percolation, which is likely due to the large under-prediction in SWS. That is, the soil never became wet enough to result in appreciable drainage.

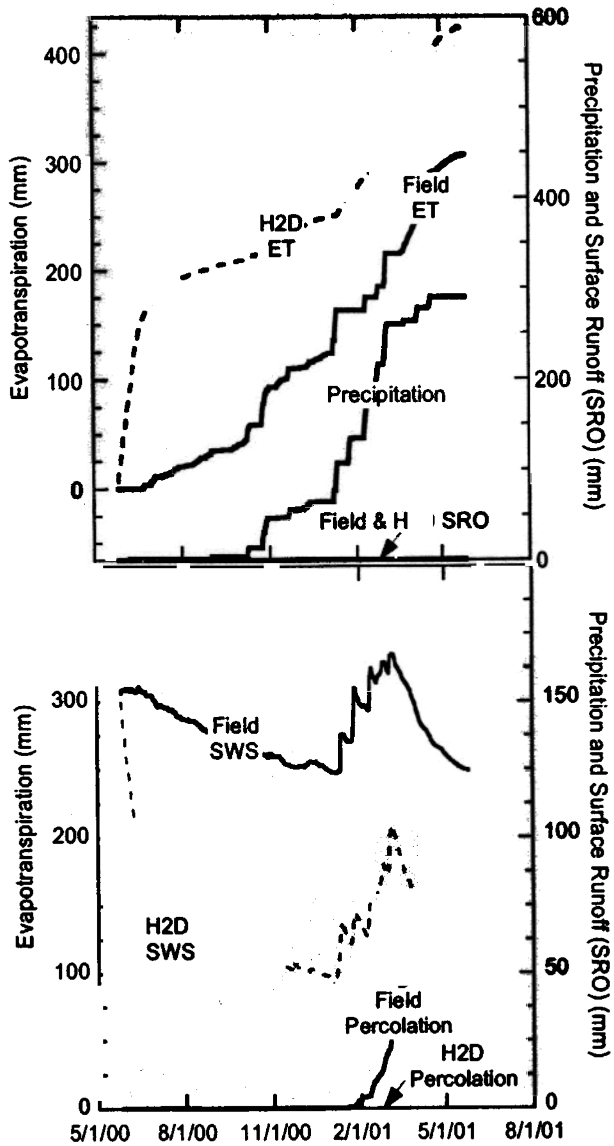


Figure 2. Field data and water balance predictions from HYDRUS-2D calibrated by adjusting K_s until the predicted and measured SRO matched.

PROPERTIES OF VEGETATION

Attempts were made to reduce the over-prediction of ET obtained early in the record by adjusting the wilting point and maximum root depth of the vegetation, both of which are not known with certainty. The wilting point was varied from 450 m (base case) to 150 m and the maximum root depth was reduced from 1.22 m to 0.75 m. In addition, a simulation was conducted where transpiration was set to zero during the first growing season (May – Dec. 2000). Adjusting these parameters had negligible effect on the water balance predictions.

CONCLUSIONS

Water balance predictions made with HYDRUS-2D and field measurements from a test section simulating a capillary barrier cover have been compared in this paper. Predictions made with HYDRUS-2D deviated appreciably from the field data. The differences appear to be related to errors in predicting surface runoff (SRO) and evapotranspiration (ET) and uncertainties in the hydrologic properties of the soils. Greater differences between the measured and predicted SRO were obtained when hourly meteorological data were used as input instead of daily data.

Adjustments were made to the model by increasing the saturated hydraulic conductivity (K_s) until the measured and predicted SRO matched and by varying the parameters describing the vegetation. Increasing K_s allowed more water to enter the soil profile, and resulted in more realistic changes in soil water storage (SWS) during the wetter portions of the record. However, increasing K_s also resulted in large over-predictions of ET, and much lower SWS than was measured in the field. Adjusting the vegetation parameters had little effect on the predictions.

Zero percolation was predicted by the model for all cases, despite the adjustment of K_s. In contrast, approximately 50 mm of percolation was measured in the field. This discrepancy suggests that percolation rates predicted by HYDRUS-2D (and other similar models) can only be considered as estimates, and should be interpreted with caution.

ACKNOWLEDGEMENT

Funding for ACAP has been provided by the United States Environmental Protection Agency (USEPA) through the Superfund Innovative Technology Evaluation (SITE) program. Steve Rock of USEPA is the project manager. Support for construction and instrumentation of the ACAP test sections was also provided by site owners. The findings and opinions in this article are solely those of the authors. Endorsement or approval by USEPA or the site owners is not implied and should not be assumed.

REFERENCES

Albright, W., Benson, C., 2002. Alternative Cover Assessment Program, 2002 Annual Report, Publication No. 41182, Desert Research Institute, Reno, NV, USA.

Fayer, M., 2000. Unsaturated Soil Water and Heat Flow Model: v 3.0, Theory, User Manual, and Examples, Report No. 13249, Pacific Northwest National Laboratory, Richland, WA, USA,

Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of field water use and crop yield, John Wiley & Sons, New York.

Gurdal T., Benson, C., Albright, W., 2003. Hydrologic Properties of Final Cover Soils from the Alternative Cover Assessment Program, Geo-Engineering Report No. 03-02, University of Wisconsin, Madison, WI, USA.

Khire, M., Benson, C., Bosscher, P., 1997. Water balance modeling of earthen landfill covers, J. of Geotechnical and Geoenvironmental Eng., 123(8), 744-754.

Roesler A., Benson, C., Albright, W., 2002. Field Hydrology and Model Predictions for Final Covers in the Alternative Cover Assessment Program - 2002, Geo-Engineering Report No. 02-08, University of Wisconsin, Madison, WI, USA.

Scanlon, B., Christman, M., Reedy, R., Porro, I., Simunek, J., Flerchinger, G., 2002. Intercode comparisons for simulating water balance of surficial sediments in semi-arid regions, Water Resour. Res., 38(12), 59-2 – 59-26.

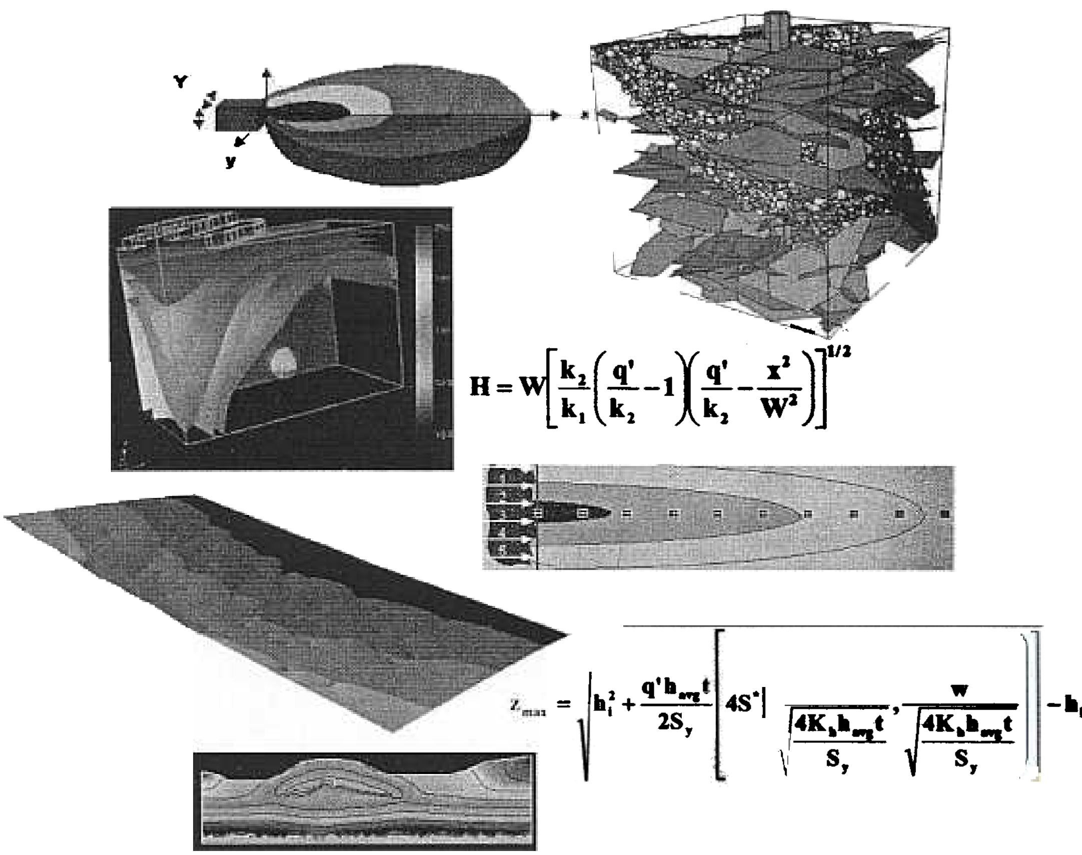
Simunek, J., Sejna, M., van Genuchten, M., 1999. The HYDRUS-2D Software Package for Simulating the Two-Dimensional Movement of Water, Heat, and Multiple solutes in Variably-Saturated Media, v. 2.0, US Salinity Lab., Agr. Res. Serv, US. Dept. of Agric., Riverside, CA, USA.

van Genuchten, M., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, 892-898.

Winkler, W., 1999. Thickness of Monolithic Covers in Arid and Semi-arid Climates, MS Thesis, University of Wisconsin, Madison, WI, USA.

MODFLOW and More 2003
Understanding through Modeling

Proceedings
Volume II
(pages 439-885)



Organizing Committee
Eileen Poeter, *IGWMC, Colorado School of Mines*
Chunmiao Zheng, *University of Alabama*
Mary Hill, *U.S. Geological Survey*
John Doherty, *Watermark Computing, Australia*

September 16-19, 2003

INTERNATIONAL GROUND WATER MODELING CENTER (IGWMC)
COLORADO SCHOOL OF MINES