Water Balance At An Arid Site: A Model Validation Study of Bare Soil Evaporation

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SUMMARY

This report contains results of model validation studies conducted by Pacific Northwest Laboratory (PNL) for the Department of Energy's (DOE) National Low Level Waste Management Program (NLLWMP). The model validation tests consisted of using unsaturated water flow models to simulate water balance experiments conducted at the Buried Waste Test Facility (BWTF) located at the Department of Energy's Hanford site, near Richland, Washington. The BWTF is a lysimeter facility designed to collect field data on long-term water balance and radionuclide tracer movement. It has been operated by PNL for the NLLWMP since 1978. An experimental test case, developed from data collected at the BWTF, was used to evaluate predictions from different water flow models.

The major focus of the validation study was to evaluate how the use of different evaporation models affected the accuracy of predictions of evaporation, storage, and drainage made by the whole model. Four evaporation models were tested including two empirical models and two mechanistic models. The empirical models estimate actual evaporation from potential evaporation; the mechanistic models describe water vapor diffusion within the soil profile and between the soil and the atmosphere in terms of fundamental soil properties, and transport processes. The two empirical models were a method documented by Nimah and Hanks (1973), and a method proposed by Beese, van der Ploeg and Richter (1977). The vapor diffusion models used were based on the work of Hammel, Papendick and Campbell (1981). The two vapor diffusion models differed in whether they accounted for water content and temperature gradients (non-isothermal), or just water content gradients (isothermal) to describe vapor flow. In addition to examining the effects of using different evaporation submodels, the sensitivity of model predictions to rainfall distribution, and to the presence or absence of evaporation on rain days was also examined.

The accuracy of the models was evaluated by simulating water flow in one of the 7.6-m deep soil lysimeters of the BWTF from April 6, 1979 (Day 96) to April 30, 1980 (Day 462). Model predictions were then compared to data collected at the BWTF during this period. The primary data used for comparison were the change in the total water stored in the 7.6-m profile, however, water

flow at 1.5 m and 7.6 m (shallow and deep drainage rates, respectively), and estimates of evaporation were also examined.

The water flow models that included the diffusion-type evaporation submodels performed best overall. This was primarily because they include water vapor flow, which allowed better predictions of spring and summer drying of the soil profile. Their predictions of storage and evaporation also showed less sensitivity to the question of rain-day evaporation. The isothermal-diffusion evaporation model seemed to perform better than the nonisothermal model, which was contrary to expectations because the nonisothermal model is believed to more rigorously describe the transport processes controlling evaporation. The differences between the nonisothermal and isothermal were not great; however, the results presented here imply a need to examine our understanding of the evaporation process more closely.

The empirical models performed poorly in their description of evaporation and profile water storage during summer months. These models do not contain an explicit description of water vapor flow. Apparently this is an important mechanism for delivering water to the soil surface for evaporation during the summer. The empirical models performed better when describing winter evaporation when the soil was relatively wet and actual evaporation was close to potential evaporation (PE). During this period the flow model containing the Beese, van der Ploeg and Richter (1977) evaporation submodel (hereafter referred to as the Beese submodel) performed best of the two empirical models.

The Nimah and Hanks (1973) model showed the greatest sensitivity to rain-day evaporation. All models showed some sensitivity to this, however, the effect may have been exaggerated because we were modeling sandy soil where soil drying immediately following a rain is often rapid. Our results show that the effect of evaporation during rain-days must be considered when developing models.

The predictions of drainage were supported quite well by the experimental data. This indicates that the method used to estimate hydraulic conductivity needed for the Darcian submodel was adequate. This important result supports recommendations for these procedures that were made previously based on laboratory results.

Our results indicate that an explicit description of water vapor flow is needed to accurately predict soil water balances where evaporation is the dominant process at the soil surface. Our results also indicate that more work is needed on modeling the effect of temperature gradients on water flow. Because long-term simulations are needed for waste management decisions, multi-year simulations need to be performed to check for error propagation.

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INTRODUCTION

In 1979, the Department of Energy created the National Low Level Waste Management Program (NLLWMP), which is responsible for identifying and developing technology that supports the creation of disposal facilities for low-level radioactive waste. The primary technique currently used to dispose of low-level waste is shallow land burial (SLB), defined as burial of waste in shallow trenches (<20 m) excavated out of surface soils and sediments. Therefore, the majority of research supported by the NLLWMP has been related to SLB technology.

The NLLWMP established the Transport Assessment--Arid Task at Pacific Northwest Laboratory (PNL) in 1979. The primary focus of this task has been the assessment and development of modeling technology used to predict the transport of water and radionuclides through unsaturated sediment (i.e., unsaturated zone transport). Transport of materials through unsaturated soil is expected to be the dominant pathway for contaminant migration at most SLB sites.

The Transport Assessment--Arid Task has supported experimental work in three major areas related to modeling technology: 1) site characterization, 2) site monitoring, and 3) model validation. Techniques to characterize sites are needed to collect input data for modeling; techniques to monitor sites are needed to collect field data during SLB operations that can be used to verify and update the predictions of unsaturated zone transport models; model validation is necessary to evaluate the accuracy of the model and is therefore an essential process in the development of transport models used in the licensing process for burial sites.

The accuracy of a model is measured by comparing the model prediction against some recognized standard. The standard may be an analytical solution to the transport equation, it may be a simple mass balance check, or it can be an experimental data set describing the experiment being simulated. This report presents a summary of results from model validation studies conducted in the Transport Assessment--Arid Task. Our model validation studies involved the simulation of field experiments; specifically, the simulation of water flow in

unvegetated soil. The analysis consisted of comparing model predictions of water flow in an unvegetated lysimeter to field measurements taken in the lysimeter over a period of one year. The emphasis of the study was to quantify the sensitivity of predictions made by a water flow model to the choice of evaporation model, the inclusion of rain-day evaporation, and the annual rainfall distribution. Four evaporation models were used in this study that represent the major classes of evaporation models found in current literature.

BACKGROUND

Future SLB sites constructed for the disposal of low-level radioactive waste will have to be licensed by the Nuclear Regulatory Commission (NRC). The licensing process and technical requirements for SLB sites are outlined in the regulatory rule 10 CFR Part 61, recently issued by NRC (1982). This rule requires that predictions of future site performance be made as part of a site licensing process. For a license application to be approved and disposal operations to begin, the site performance predictions must provide a "reasonable assurance" that adequate safety will be provided to site operators and the general public.

Site performance will be predicted using a suite of computer models that quantify the movement of radionuclides out of the burial trenches and along various transport pathways, which could culminate in radiation exposure to site operators and/or the general public. The pathways to be modeled are somewhat site specific, however 10 CFR Part 61 (NRC 1982) explicitly requires that transport along the water pathway be evaluated at all sites.

Transport along the water pathway results from the flow of soil water through the buried waste. As the water passes through the waste zone, radionuclides are dissolved into the soil solution and carried away from the waste trench. This process has the obvious potential for contaminating the soil surrounding the SLB site as well as ground and surface water supplies. Modeling radionuclide transport along the water pathway requires predicting the interaction of several complex hydrologic and geochemical processes (Jones and Gee 1984). The Transport Assessment--Arid Task has concentrated its model validation efforts on the hydrologic (i.e., water flow) processes.

WATER FLOW PROCESSES ACTIVE AT AN SLB SITE

The water flow processes that control unsaturated zone transport are shown in Figure 1. These are the processes that need to be addressed by water flow models. They are runoff, infiltration, evaporation, redistribution, plant water uptake (transpiration), and drainage. These processes all interact to

FIGURE 1. Water Flow Processes Controlling Unsaturated Zone Transport at an SLB Site

determine how much water comes in contact with the buried waste, as well as how fast and in what direction dissolved radionuclides will be transported away from the waste trench.

When precipitation occurs at a waste site, it is generally absorbed into the soil through infiltration. However, if the precipitation rate exceeds the infiltration rate of the soil (i.e., the maximum rate at which water is absorbed by the soil), then water will pond on the soil surface. If the surface is sloped, the ponded water will flow along the soil surface and could be lost as runoff. Water that is absorbed into the soil is referred to as stored water.

Water stored in the soil profile is subject to three processes that tend to remove water from the soil: evaporation, drainage, and plant water uptake (transpiration). Evaporation is the process where water vaporizes near the soil surface and diffuses into the atmosphere. Drainage occurs when water flows downward toward the ground-water table. Drainage can refer to any downward movement, but in regard to SLB operations, we generally mean water flowing below the depth where the waste is buried. Plant water uptake refers to water taken up by plant roots and lost to the atmosphere through transpiration.

As water infiltrates in the soil from a rain event, the soil surface usually becomes wetter than the rest of the profile. As water is lost through evaporation, transpiration, and drainage, the surface becomes drier than other parts of the profile. As water is removed by evaporation at the surface, water moves up from immediately below the evaporating surface. As water is removed by plant roots, water flows to the roots to replace it. Deep drainage is generally a steady-state process that is occurring continually.

These cycles of wetting and drying give the soil profile a dynamic quality that results in water constantly moving from one part of the profile to another. The movement of water within the profile is known as redistribution. It does not directly lead to loss of water from the soil profile, but it is responsible for supplying water to areas where evaporation, transpiration, or drainage are active. The redistribution process is the most important to waste management in the sense that it determines whether water will move into the waste zone before it is used by plants or drains out of the profile, or whether it will be held near the surface and evaporate. As Figure 1 indicates, redistribution is driven by evaporation, drainage, and transpiration; therefore, a flow model cannot describe one without the other.

An analysis of water flow at an SLB site must account for flow by each of the processes shown in Figure 1. However, a site-specific model need only explicitly describe those processes active at that particular site. For example, in many areas where the soil is sandy, runoff is nonexistent and therefore need not be included in the model. The same is true for transpiration if no plants are present.

MODELING WATER FLOW PROCESSES

A complete water flow model can be thought of as being composed of several component models each of which describe one of the relevant flow processes, such as evaporation or drainage. The complete model predicts water flow by coupling the individual flow processes (i.e., models) together and accounting for the interactions between processes. It is often helpful to conceptualize a complex model as a collection of smaller, component models as long as it is clear that these individual models rarely act completely independent of each

other. For example, redistribution can be thought of conceptually as a discrete process, however, it would be difficult to separate a model into separate components that describe redistribution and evaporation completely independent of each other. Therefore, a functional model cannot be constructed out of an arbitrary set of component models, nor can any particular component model be arbitrarily exchanged for a new one. Often, changing one component model may require modifications throughout the entire model.

Keeping the limitations of the concept of a component model in mind, Figure 2 shows our list of water flow processes together with several examples of models used to describe each of the processes. Infiltration, redistribution and drainage are described by the same basic model. It is based on the assumption that water flow in soils follows the relationship known as Darcy's law. Darcy's law is a mathematical relationship between water flow and water potential (see Taylor and Ashcroft (1972) or Jones (1978) for an explanation of water potential). To be useful in a transport model, Darcy's law is combined

FIGURE 2. Models Available for Describing Processes Controlling Water Flow

with the equation of continuity (i.e., conservation of mass), which produces a transient flow equation requiring two transport parameters. These are shown in Figure 2 as the hydraulic conductivity and water capacity.

The remaining two processes of transpiration and evaporation are generally included in a model as two separate models. Models used to describe both of these processes can be classified as either empirical or mechanistic. Empirical models differ from mechanistic models in that their description of flow is derived purely from experimental observations rather than the identification of any controlling physical process, such as diffusion or convection. Empirical models are justified on the basis of observed correlations between variables, rather than on proven causality, as is the case with a mechanistic approach.

For example, Figure 2 lists the crop coefficient model as an empirical model of transpiration. In this model, the transpiration rate is empirically related to the potential evapotranspiration rate (PET). The PET is the maximum rate at which water can enter the atmosphere, based on the energy supplied to the soil/plant surface through solar radiation, and the vapor density of the air. The crop coefficient model assumes that by knowing the PET, the transpiration rate can be estimated without taking into account the complexities that are involved with water flowing to the roots, through the plant to the leaf, and diffusing from the leaf to the atmosphere.

The assumption that transpiration is related to PET is valid; however, no physical or mechanistic line of reasoning implies that PET is all that is needed to predict transpiration. Therefore, the proportionality between PET and transpiration (i.e., crop coefficient) can only be derived through repeated observations of PET and transpiration during one or more growing seasons. If the crop coefficient is observed to be relatively constant, then the model becomes useful even though the transport mechanisms controlling transpiration are obscured.

Mechanistic models in contrast to empirical models attempt to rely on basic fundamental principles of physics to describe flow. Figure 2 lists root and leaf models as alternatives to empirical models for describing transpiration. In these models, transpiration is predicted by explicitly describing the

flow of water through the soil and into the root, through the root to the stem and into the leaf, and finally from the leaf to the atmosphere through the stomates. This approach obviously increases the complexity of the model, but it has the advantage of being much more versatile, and if well done, instills more confidence in the user that model predictions are accurate.

In most practical situations the model used will include a combination of empirical and mechanistic approaches. Mechanistic approaches are valuable because they demonstrate the processes being described more clearly. However, in some cases empirical models can provide more accurate results because the actual mechanisms controlling flow are poorly understood and an effective mechanistic model cannot be developed.

The evaporation models listed in Figure 2 can also be classified as empirical or mechanistic. Empirical models have been used extensively to predict evaporation and have been successful in short-term simulations, or other situations where evaporation has not been a major component of the water balance. Most empirical models relate evaporation to potential evaporation (PE)^(a) in much the same manner as the crop coefficient transpiration models relate transpiration to PET. One empirical model, known as the square-root-of-time model, empirically describes the evaporation rate as proportional to the time since a rain event (Ritchie 1972). Other empirical models relate the evaporation rate to the water content or water potential of the soil surface (e.g., Beese, van der Ploeg and Ritchter 1977)

(a) Potential evapotranspiration (PET) is a measure of the maximum amount of water that can be absorbed into the atmosphere given the atmospheric vapor density and radiant energy condition. It is normally estimated through the Penman equation (Campbell 1977). PET is sometimes written as the sum of a transpiration term (PT), and an evaporation term (PE). PT refers to the amount of water that could be supplied by plants and PE measures the water that could be supplied by bare soil surfaces. The ratio of PT/PE is usually estimated by measuring the relative surface area of the plant canopy to the exposed soil surface. In the case of full plant cover PT = PET and in the case of bare soil PE = PET. In this report PET will be used when referring to bare soils although in this context they are both the same number (i.e., they are both calculated by the Penman equation). The reason for using PE in place of PET is to emphasize that for bare soils, evaporation is the sole process responsible for water loss to the atmosphere.

Recently, attempts have been made to predict evaporation from a more fundamental description of the process. Because evaporation is by definition a vapor diffusion process, mechanistic evaporation models are fundamentally diffusion models that explicitly describe the movement of water vapor. As indicated in Figure 2, the available diffusion type evaporation models usually are classified as either isothermal or nonisothermal models. Nonisothermal models account for soil temperature and the effect it has on water vapor transport in addition to the effect of water content. Temperature affects the water vapor density at the soil surface, but also affects the diffusion coefficient for soil water vapor. The effect on the diffusion coefficient is described by a parameter, listed in Figure 2, known as the thermal enhancement factor. Isothermal diffusion models ignore thermal affects and describe water vapor flow strictly in terms of isothermal vapor density gradients. Both types of diffusion models require diffusion coefficients for water vapor in soil and a set of atmospheric boundary layer parameters that describe the transfer of water vapor from the soil to the bulk atmosphere.

The modeling exercises described in this report required the simulation of water flow processes in deep soil lysimeters (7.6 m). The soil in these lysimeters was a coarse sand (Gee et al. 1981; Cass, Campbell and Jones 1981), that was kept free of vegetation. For this reason the processes of runoff and transpiration are not included in any of the models used. This restricts the processes relevant to the model validation study to infiltration, redistribution, drainage, and evaporation. Based on Figure 2, this implies that the water flow models used were a combination of models based on Darcy's law and an empirical or mechanistic model of evaporation. We consider Darcy's law to be the only acceptable method of describing infiltration, drainage, and redistribution in soil. Therefore, our evaluation of different water flow models conducted in this study was essentially an evaluation of different evaporation models.

In the absence of transpiration, and in the presence of low drainage rates in arid soils, evaporation becomes the dominant process controlling the site water balance. Four evaporation models were evaluated including two empirical

models, as well as an isothermal and a nonisothermal diffusion model. The process of evaporation from bare soils and the specific models used in our study are described below.

EVAPORATION AND EVAPORATION MODELS

A conceptual model of evaporation from soil following a rain event is shown in Figure 3. The figure shows the changes in evaporation rate under idealized conditions of constant boundary conditions. This could be envisioned as a laboratory experiment where water was applied to a column of soil that was allowed to dry for a long period of time. After a rain while the soil surface is wet, the evaporation rate is at or near PET. The PET rate is determined entirely by atmospheric conditions and is a reflection of the atmospheric demand. This period of maximum evaporation immediately after a rain, when evaporation rates are entirely controlled by atmospheric conditions, is referred to as the first stage of drying. As water is lost by evaporation, the soil surface begins to dry out because the underlying soil cannot deliver water to the evaporating surface fast enough, through the redistribution process, to keep up with the atmospheric demand. As a result of this drying, a layer of dry soil forms at the soil surface and the evaporating surface recedes to a depth of several millimeters to centimeters. The dry layer restricts evaporation in two ways: first, it offers resistance to the diffusion of water vapor from the evaporating surface to the atmosphere; and

FIGURE 3. Conceptual Model of Evaporation Process

In terms of modeling vocabulary, the N&H model imposes a flux boundary condition at the surface during the first stage of drying, equal to PET. As soon as the model predicts that the soil surface has dried out, the boundary condition is changed to a fixed-head or fixed water-potential boundary. This fixed-head boundary restricts the evaporation rate to levels that prevent the soil surface from becoming drier than air dry. During the time when the soil at the surface is air dry, the model sets the evaporation rate equal to the rate of water movement up to the soil surface from below. This causes the evaporation rate to decrease as the depth of drying increases. In this way, stage two drying is simulated. This evaporation model requires no input parameters other than those required for estimating PET and estimates of soil hydraulic conductivity.

The second empirical model of evaporation evaluated in this study was proposed by Beese, van der Ploeg and Richter (1977), hereafter referred to as the Beese model. In this model the evaporation rate is correlated to the water potential at the soil surface. Beese, van der Ploeg and Richter (1977) experimentally determined the curve shown in Figure 4, using laboratory soil samples. Their model sets the evaporation rate equal to PE until the soil surface dries out to -5 J/kg (50-cm suction). During this time the soil is in first stage drying. Second-stage drying after the soil is drier than -5 J/kg , is approximated by the relationship between surface water potential and evaporation rate shown in Figure 5. The model still requires the change to a fixed-head boundary condition when the soil surface reaches air dry.

Isothermal and nonisothermal diffusion models of evaporation were used in this study to represent the class of mechanistic evaporation models. They do not rely on a predetermined evaporation rate imposed as a boundary condition on the model. Instead, these evaporation models explicitly simulate the diffusion, conduction, and convection processes that control evaporation. Figure 5 shows the conceptual model behind the diffusion approach.

The soil-atmosphere interface at the surface of a trench cap is shown in Figure 5. As wind blows across the soil surface, a thin layer of essentially stagnant air forms, known as the atmospheric boundary layer. Immediately below the boundary layer, the dry soil layer that forms during evaporation is

second, it insulates the wet soil below restricts the flow of heat to the evaporative surface, which is necessary to drive the evaporation process. Therefore, as the dry layer thickens, the evaporation rate decreases. This period of decreasing evaporation rate is called the second or falling-rate stage.

The evaporation rate continues to decrease until an equilibrium is established between the rate of water flow to the evaporating surface and the evaporation rate (i.e., vapor diffusion rate away from the evaporating surface). At this point the thickness of the dry layer stabilizes and evaporation enters a steady-state stage that is called the third stage of drying. In this conceptual model the evaporation rate during the first stage of drying is controlled by the atmospheric demand and is independent of the soil properties. In contrast, evaporation during the third stage of drying is controlled by the rate at which the deeper, moist soil delivers water to the evaporating surface. Therefore, the third-stage evaporation rate is controlled by the soil properties and is essentially independent of the atmospheric demand. For third-stage drying to occur, even in our idealized system, we need some steady source of water deep in the soil column such as a water table.

The idealized curve shown in Figure 3 is useful in guiding the development of evaporation models even though the process can be much more complicated in field situations. The changing atmospheric conditions and frequent rains during the wet seasons make it difficult to clearly distinguish between the three stages of evaporation.

Empirical evaporation models define an evaporation rate that is intended to account for both atmospheric (first stage) and soil controlled (second stage) evaporation by using a minimum of parameters. These evaporation rates are then linked to the Darcian model as surface boundary conditions. One of the empirical evaporation models evaluated in this study will be referred to as the Nimah and Hanks (N&H) model (Nimah and Hanks 1973). The evaporation rate defined by the N&H model is equal to PE until the moist soil below the surface dry layer is unable to deliver water at that high rate. During these periods the evaporation rate is set equal to the maximum rate at which water can be delivered to the soil surface.

FIGURE 4. Empirical Relationship Between Soil Water Potential and Evaporation Rate Proposed by Beese, van der Ploeg and Richter (1977)

FIGURE 5. Conceptual Model for Mechanistic Diffusion Models Used to Describe Evaporation

shown. The detailed description of the formation of this dry layer of soil, and the effect it has on evaporation rate is the key feature of the diffusion model, and makes it a mechanistic versus an empirical approach. As explained in the conceptual model presented above, evaporation is controlled by the flow of liquid water from a deep soil to the evaporative surface, the diffusion of water vapor through the dry layer, and the transport of water vapor through the atmospheric boundary layer to the bulk atmosphere.

Beneath the dry soil layer the driving force for liquid flow is the difference or gradient in water potential. Figure 5 shows the driving forces, flow mechanisms, and the transport parameters involved in these three processes. Water transport in this region is the process of redistribution and is described by the Darcian model mentioned above. Extending from the bottom of the dry layer to the atmosphere, the primary driving force is the gradient of water vapor density. If a nonisothermal model is being used, the temperature gradient in the dry soil layer is also accounted for as a driving force. The diffusion model of evaporation interfaces with the Darcian model at the bottom of the dry soil layer rather than as a soil surface boundary condition.

The flow mechanism below the dry layer is conduction. Liquid water flows upward to the dry layer to supply water for the evaporation process. Water is transported from the bottom of the dry soil layer into the atmosphere through vapor diffusion. Water vapor diffuses from the region of high vapor density found at the evaporating surface to the low vapor density of the atmospheric boundary layer. As the water vapor diffuses out of the boundary layer, it is mixed into the bulk atmosphere by convection due to wind circulation. Constant mixing of water vapor at the top of the boundary layer by wind maintains a gradient of water vapor density across the boundary layer.

Transport parameters needed for the diffusion-type evaporation models include hydraulic conductivity and water capacity for the Darcian model describing the redistribution of water upward to the evaporating surface. In addition, the diffusion coefficient for water vapor in soil is necessary to describe diffusion through the dry soil layer. If a nonisothermal model is used, an extra parameter known as the thermal enhancement factor is also needed. This parameter describes the effect of the temperature gradient found

in the layer of dry soil on the diffusion of water vapor. A set of parameters necessary to describe diffusion of water vapor through the boundary layer into the atmosphere, are referred to in Figure 5 as boundary layer parameters. They include the boundary layer resistance, the atmospheric stability coefficient, and surface roughness factor.

MODEL VALIDATION PROCEDURE

Model validation may be defined as evaluating the accuracy of the predictions made by a model. This may seem to be a fairly straightforward process, however, arguments often arise over what aspects of the model or what step in the development process has actually been evaluated by a specific validation procedure. There are many methods of assessing the accuracy of each step in the modeling process (Jones and Gee 1984).

A transport model has a rather complex structure that can be broken into three levels of development. The first step in developing a transport model is to conceptualize the processes that govern transport under the conditions of the simulation. An example of these would be the processes contained in Figure 1.

The next step in the development of the model is the derivation of a set of mathematical equations that quantify the processes of the conceptual model. Examples of these types of equations would include Darcy's law, the equation of continuity, and Fick's law of diffusion, among others. After the mathematical equations are derived they must be translated into a form that can be solved by a computer, often called the discretization of the mathematical model. An example of this step would be the finite difference or finite element techniques used to solve differential equations.

After the equations have been discretized, they must be solved. To do this, numerical algorithms are developed that solve the individual equation, and also link the results of the evaporation submodel with the redistribution submodel, with the infiltration submodel, etc. Finally, all of the algorithms must be transformed into a computer code that can be executed by the computer.

The accuracy of the model predictions depends on the accuracy of each of the several steps outlined above. Therefore, model accuracy or model validity depends on all aspects of the model from conceptualization to typing the code into the computer. Some groups have made rather arbitrary distinctions between model validation and model verification. They claim that validation is related to evaluating the conceptual approach of the model, while verification refers to checking the accuracy of the solution algorithms and coding procedure.

Models in this study were evaluated by using the models to simulate field experiments conducted previously and then comparing model predictions with field measurements. These experiments, together with the set of measured results, form an experimental test case. Our intent is to use test cases to evaluate the conceptual and mathematical assumptions of the models rather than just the numerical accuracy or stability of the algorithms. For this reason, we use the term validation; however, we do so without strong conviction that the exact choice of terminology is worthy of much concern.

DESCRIPTION OF EXPERIMENTAL TEST CASE

Field water-balance experiments were conducted in the Transport Assessment--Arid Task from mid-1978 through 1982. These experiments were conducted at the Buried Waste Test Facility (BWTF) operated by PNL for the NLLWMP (Phillips et al. 1979). The BWTF is an installation of seven soil lysimeters layed out according to the schematic shown in Figure 6. The seven round caissons are 7.6 m deep. Three of these deep caissons are 2.7 m in diameter, and four are 0.6 m in diameter. The two square lysimeters in front of the seven caisson array are 1.5 m x 1.5 m x 1.5 m. A detailed characterization of the soil materials used in the lysimeter can be found in Gee et al. (1981) and Cass, Campbell and Jones (1981). Soil properties needed for model inputs were taken from these two reports.

The water-balance experiments consisted of monitoring soil water content, soil water potential, soil temperature, and climatic conditions at the facility from June 1978 through December 1982. Drainage data were also collected by removing accumulated water from the bottom of the lysimeters. This provided estimates of drainage rates or fluxes at 1.5 and 7.6 m. Half of the lysimeters were irrigated for approximately 1.5 years; however, these data were not included as part of this modeling study.

The simulations presented here are of the water-balance processes of the BWTF from April 6, 1979 to April 30, 1980. The models were set up to simulate water flow through one of the nonirrigated 7.6-m caissons. The field data used to evaluate the results of the model were the change in stored water data

FIGURE 6. Schematic Representation of BWTF

- 1 WATER MOVEMENT CAISSON (TYP. 2 PL.)
- 2 INSTRUMENT CAISSON
- 3 WEIGHING LYSIMETERS
- 4 WIND DIRECTION
- 5 SHORT WAVE RADIOMETER
- 6 NET RADIOMETER
- 7 WIND SPEED
- 8 HUMIDITY SENSOR
- 9 RADIONUCLIDE TEST CAISSON (TYP. 4 PL.)
- 10 NEUTRON ACCESS TUBE (TYP.)
- 11 RAIN GAGE
- 12 TEMPERATURE SHELTER

in the nonirrigated 7.6-m caisson. Total water stored in a soil column is calculated by integrating the soil water content profile. Also, drainage data collected from the nonirrigated 1.5-m lysimeter was used as an estimate of flux at the 1.5-m depth of the modeled caisson. Drainage data collected from the bottom of the field caisson were also available for comparison of deep drainage rates.

Figures 7 and 8 show the field data used for comparison. For reasons to be explained below, the models were not given the exact water contents that were measured in the field as initial conditions. Therefore, comparisons of absolute water storage would not be appropriate. Figure 7 shows the change in storage throughout the year's simulation. Negative numbers show a net loss of water from the profile; positive numbers indicate that cumulative precipitation was greater than cumulative evaporation. These are the data that were compared against model predictions.

FIGURE 7. Change in Profile Water Storage as Measured by Neutron Probe at the BWTF, April 6, 1979, to April 30, 1980

FIGURE 8. Cumulative Drainage at 1.5 m from the South Weighing Lysimeter (SWL) and the South Caisson (SC), 7.6 m.

The simulation started on day 96 of 1979 (April 6, 1979) and ended on day 485 (April 4, 1980). Figure 7 shows that the profile generally lost water from day 96 through day 175, appeared to gain and then lose water until day 300, and then gained water and held it after day 300. This pattern is typical of the seasonal storage changes observed at the BWTF. Most of the water gains are during winter months with the majority of water not being lost until late spring or summer.

These data also illustrate some of the problems that are encountered when dealing with field data. During the period of time from day 175 to 300, the neutron probe readings indicated a gain of over 2 cm of water stored followed by rapid loss. During this period of time only about 1.5 cm of rain were recorded. Obviously the change in profile storage could not be greater than the total rain received. Errors equivalent to as much as ± 0.5 cm water storage are associated with the neutron probe readings due to counting statistics and calibration errors. The moisture changes observed for days 175 to 300 cannot be entirely explained by counting errors, hence, their origin remains unresolved. Although we have no direct proof, we suggest that there was an operator error in reading and recording data during this time period and that actual storage changes exhibited a nearly linear decrease from -2 cm at day 150 to -3 cm at day 300. Further examination of the data shown in Figure 7 did not reveal other obvious problems.

Figure 8 shows the drainage data measured at the 1.5-m and 7.6-m depth. The figure shows the data collected through 1982. No drainage was measured at the 7.6-m depth during the period we simulated; however, since approximately 3 cm of water had drained by the end of 1981, it is likely that some accumulation was undetected during the simulation period. The lack of drainage in the deep (7.6-m) lysimeters for the initial years (1978 to 1980) is attributed to the initial wetting of the relatively dry soil profiles in the lysimeters.

The drainage system in the 1.5-m lysimeter was not 100% efficient, and some water was lost through leakage after drainage began in late 1979. Actual measured drainage is shown in Figure 8. Therefore, the data shown should be regarded as minimum drainage. Figure 8 indicates a cumulative drainage from the 1.5-m lysimeter (SWL) of about 4 cm by the end of 1979. Measurements were

infrequent during much of 1980. Based on the accumulation of 4 cm through 1979 and the measured rate of 4 to 5 cm/year in 1981 and 1982, we estimate actual drainage during the simulation period was probably closer to 3 or 4 cm. The drainage data will be more useful for comparison when we simulate drainage through 1982. However, these data shown in Figure 8 should provide qualitative drainage predictions during the time period of 1979 to 1980.

COMPUTER CODES USED FOR ANALYSIS

It is the goal of this work to evaluate water flow models, and in particular evaporation models from a conceptual and mathematical point of view. The work is not intended to focus on specific numerical techniques or on specific computer codes. However, for obvious reasons specific codes had to be used. Two previously developed water flow models were used in this study. In this section we would like to identify the models used, and summarize their relevant characteristics.

One of the models used is called UNSAT1D. It was originally developed at the University of California, Davis, and was first documented by Gupta et al. (1978). It has been used at PNL and modified to a certain extent. Recent application of UNSAT1D is found in Bond, Freshley and Gee (1982). UNSAT1D is designed to allow the user to choose between the two empirical evaporation schemes mentioned above, the N&H method (Nimah and Hanks 1973), and that proposed by Beese, van der Ploeg and Richter (1977). Therefore, all comparisons of these two evaporation submodels were done with UNSAT1D.

The diffusion-type evaporation submodels were evaluated using a model developed by G. S. Campbell at Washington State University. This model will be referred to here as EVAP. EVAP has not been documented in detail at the present time, however, it is a modified version of the evaporation model presented by Hammel, Papendick and Campbell (1981).

Ideally, we would have used one overall computer model and only modified the specific part of the model (i.e., submodel) that dealt directly with evaporation. This would have required developing a new model or extensively modifying an existing code so that it contained all four evaporation schemes as options. We chose not to do this, but rather to pick two existing codes, which

already incorporated the four methods for predicting evaporation that we wanted to evaluate. Using the two models, UNSAT1D and EVAP, we were able to evaluate the two empirical evaporation submodels with no modifications to UNSAT1D, and the two diffusion evaporation submodels with only minor modification to EVAP.

The major disadvantage to this approach was that the UNSAT1D and EVAP models differ in areas other than the prediction of evaporation. For example, there are differences in node spacing, size of time step, the numerical techniques used to solve the transport equations, and in the use of climatological input data. Therefore, we potentially could misinterpret differences found between predictions from the two models. For example, differences might be attributed to the evaporation submodel used, when they actually resulted from some other aspect of the model unrelated to predicting evaporation. This possibility has been kept in mind throughout our analysis of simulation results. We feel that we have properly identified the results that illustrate the effect of altering the evaporation submodel and the results that reflect other aspects of the model. However, in order that the reader can have a clear understanding of this problem, we will describe in detail how UNSAT1D and EVAP differ and how they are similar.

The major similarities and differences between UNSAT1D and EVAP are summarized in Table 1. Beginning with the similarities, note that both models are one-dimensional, accounting for vertical flow in our simulations. Also they both use a Crank-Nicholson finite difference formulation of the transport equations as the basis of the discretization process. Both models have the same lower boundary condition, assuming unit gradient drainage at the deepest depth simulated. And finally both models used the same climatological input data with the exception of the water vapor density of the air. Other input data such as initial water contents, soil desorption curves $[\psi(\theta)]$, and hydraulic conductivity curves $[k(\theta)]$ were slightly different. These differences will be explained below.

There are eight differences between UNSAT1D and EVAP listed in Table 1. Some of these are responsible for slight differences in model output, while others have no significant effect on model results. The first difference listed in Table 1 is the numerical algorithm used to solve the finite

TABLE 1. Similarities and Differences Between UNSAT1D and EVAP Models

Similarities

1. One-dimensional finite difference scheme
2. Implementation of Darcy's Law based on water potential
3. Unit-gradient lower-boundary condition
4. Used same climatological input data with the exception of atmospheric water vapor density

Differences

EVAP	UNSAT1D
1. Time-centered, Crank-Nicholson finite difference with Newton-Raphson iterative solution scheme	1. Time-centered, Crank-Nicholson finite difference within non-iterative solution scheme
2. Eleven nodes, 1-hr time steps	2. 39 nodes, variable time steps (1 hr $\rightarrow$ 10^{-6} hr)
3. Slightly different initial water contents used due to different nodes spacing, initial profile storage was 55.9 cm of water	3. Initial profile water storage was 52.6 cm of water
4. Accounts for vapor flow throughout soil profile	4. No explicit accounting of vapor flow
5. Predicts soil temperature and coupled heat and water flow	5. No nonisothermal capability
6. Atmospheric vapor density entered explicitly	6. Vapor density estimated by T_{min}
7. Solar radiation and air temperature varied throughout the day	7. Solar radiation and air temperatures assumed constant throughout the day
8. Slightly different formulation of $\psi(\theta)$, $k(\theta)$ curves	8. Haverkamp et al. (1977) type $\psi(\theta)$ curve and power function (Campbell 1974) $k(\theta)$ curve

difference equations describing transport. EVAP uses the Newton-Raphson technique, which is an iterative solution technique specifically designed for non-linear equations. UNSAT1D uses a non-iterative technique that assumes the equations are linear. The assumption of linearity is only valid when small

time steps are taken and, therefore, UNSAT1D varies the time step between 1 hr and 10^{-6} hr in order to obtain accurate solutions. Small time steps are used primarily during infiltration. EVAP uses a constant time step of 1 hr, but the Newton-Raphson technique iterates during each time step with the number of iterations increasing during infiltration. Essentially, UNSAT1D achieves mass balance by reducing the size of the time step, while EVAP iterates during each time step until mass balance is achieved. The differences in solution technique and time steps are not thought to affect the accuracy of the predictions presented here. Both models have internal checks on the mass balance of the system and produce error messages when mass balance errors exceed user-defined limits.

Another difference listed in Table 1 is the number of spatial nodes. EVAP used 11 nodes while UNSAT1D was run with 39. The number of nodes is set by the user. Both models used variable spacing between nodes with nodes being 1 cm apart at the soil surface and on the order of 1 m apart at the 8-m depth. Problems can occur when too few nodes are used. The 39 nodes used with UNSAT1D was assumed to be more than adequate. One run was made with EVAP using three additional nodes at the surface with no significant change in results. Therefore, we feel that the different node spacings used in the two models did not affect the results.

An indirect consequence of the different node spacing were the differences in the initial water content used. To start a model simulation, the water content at each node, known as the initial condition, must be entered into the computer. Initial conditions used in our simulations were obtained from neutron probe records of the BWTF. The location (depths) of the nodes used in the models did not exactly match the location of neutron probe readings taken at the BWTF caissons. Therefore, the initial water contents used for each model simulation had to be interpolated from the actual neutron probe data for each model. Because UNSAT1D used more nodes, we were able to match the neutron probe reading more closely than with EVAP.

A measure of how closely the actual initial conditions were met is obtained by comparing the difference between the total water in the profile as measured by neutron probe data, and the water contents entered into the model

as initial conditions. The neutron probe readings give an estimated profile storage of 52.6 cm. Initial conditions used in UNSAT1D provided a profile storage of 52.6 cm, with EVAP at 55.9 cm. Using different initial water contents obviously affects the results, particularly the prediction of new water contents and initial evaporation rates. However, these effects are limited to times near the start of the model run and should not be significant for the year-long simulation reported here. As mentioned above, this was the reason that change in profile storage was used to evaluate the models rather than absolute storage.

The next difference between the two models listed in Table 1 is that EVAP includes vapor flow and UNSAT1D does not. This is the most fundamental difference between the two models. EVAP was designed to model water vapor flow as a means of explicitly predicting evaporation, which of course is a vapor diffusion process. In addition to the role of vapor flow in evaporation, EVAP also includes water vapor flow throughout the soil profile. The presence of water vapor flow other than in the process of evaporation is not likely to impact the results of the model in any significant way; therefore, the inclusion of vapor flow in EVAP should not be a significant difference except in the description of evaporation which was the purpose of the simulation.

The next difference listed in Table 1 is in predicting temperature. As in the case of water vapor flow, EVAP was designed to predict soil temperature to allow for the evaporation process to be predicted more realistically. The model uses soil temperature as part of the nonisothermal diffusion model. Thermally induced vapor flow is most relevant to evaporation although it is present throughout the profile. In general, it is not expected to be a significant component of the water balance outside of the evaporation process. Therefore, the presence of thermally induced flow in EVAP should not enter into the results except as it affects the prediction of evaporation.

The next two differences shown in Table 1 deal with input and utilization of climatological data. EVAP needs accurate input of the density of water vapor in the atmosphere so these data were input into EVAP. This is because differences in water vapor density between the soil surface and air drive the evaporation and the diffusion models. UNSAT1D, on the other hand, used water

vapor density only in Penman type calculations of PET. Therefore, it was sufficient to estimate atmospheric water vapor density from daily minimum air temperature. This is a reasonable approach considering how the data were used and should not affect the results to any degree.

The second difference related to climatological data was in how the daily average input values were processed. EVAP used empirical formulas to vary solar radiation and air temperature throughout the day to more closely simulate diurnal changes in soil temperature. UNSATID used these data only for computing daily PET values so only daily averages were needed. As with vapor density, the difference in how solar radiation and air temperature input data are used is not significant in determining output results.

The final difference in the two models listed in Table 1 is in the desorption curves and hydraulic conductivity curves. Cass, Campbell and Jones (1981) showed that describing the desorption characteristics of the soil material at the BWTF requires a rather complicated equation. UNSATID did not have the capability to use such a complicated representation, so a simpler equation was used. The equation used was of the form suggested by Haverkamp et al. (1977). The equation used in EVAP was that shown by Cass, Campbell and Jones (1981).

The hydraulic conductivity curve used by UNSATID is a power function of the relative water content (Gee et al. 1981). This was shown to match available experimental data well. The hydraulic conductivity curve used by EVAP was expressed as a function of water potential rather than water content. Because the models had different relationships between water potential and water content (i.e., different desorption curves), the two conductivity curves could not be matched exactly. The equation used in EVAP was adjusted to match the equation used by UNSATID as closely as possible; however, some differences did remain. These differences are minor, but they do show up in the prediction of drainage rates. This will be explained in more detail in the results section.

SENSITIVITY ANALYSES PERFORMED

In addition to the effects of using different evaporation submodels, we also examined two other factors influencing model predictions. One was the rainfall distribution. Rainfall measurements were taken at the BWTF and also

at the Hanford Meteorological Station (MET) operated by PNL. This station is located 30 miles north of the BWTF. Figure 9 shows a comparison of the rainfall measurements made at each location.

The different measurements are reflecting a certain amount of uncertainty and error presented in rainfall measurements, but also the real observation that rainfall patterns do vary over relatively short distances. The major difference between the two data sets is not the total rain measured (19.7 cm at BWTF versus 20.2 cm at MET), but the yearly distribution. The distribution of rain differs in two ways. The first is shown in Figure 9. The BWTF measurements indicate more rain in the spring and less rain in the winter. The second difference, not shown in Figure 9, is in the total number of rain events. The BWTF data set recorded 63 rain events while the MET data include 92 events. Using these two data sets provides a test of how sensitive models are to the detailed rainfall pattern as opposed to total rainfall.

The second factor evaluated other than the evaporation submodel, was whether the model was allowed to have evaporation on days that it rained. This

FIGURE 9. Rainfall Measurements Recorded at the BWTF and the Hanford Meteorological Station

may seem a rather obscure point, but it turned out to be very important. When a model is developed, one of the questions to be answered is this question of rain-day evaporation. Without hourly rainfall data, which is rarely available, one has no good way of answering this question.

SIMULATION RESULTS

The purpose of this study was to evaluate the accuracy of predictions made by water flow models. Actual field experiments where water flow had been monitored previously were modeled (i.e., simulated), and model predictions were compared to monitoring data. The experimental data set used and the models used have been described previously. In this section we will present the results of the simulations and discuss their accuracy with respect to the available field data.

The simulations together with a summary of results are shown in Table 2. The data shown in Table 2 are one type of result obtained from the simulation. These data are cumulative totals for each of the processes reported at the end of the year-long simulation period. Another way of examining the data is to look in detail at the cumulative values throughout the year. This second type of result (i.e., yearly distribution) will be necessary to properly interpret the results and will be included as we discuss each process individually.

The simulations that were run are listed in the far left column of Table 2. Simulations were run using four different evaporation submodels as explained earlier. These were the 'NONISOTHERMAL' diffusion model and the 'ISOTHERMAL' diffusion model that were a part of the model EVAP, and the one-step evaporation method identified as 'UNSAT(N&H)', and the Beese method identified as 'UNSAT(BEESE)' that are part of the model UNSAT1D.

Table 2 also shows the two factors that were examined in addition to evaporation submodel. They are 1) rainfall distribution, and 2) whether evaporation occurred on the days it rained. Two rainfall distributions were used (see Figure 9). The first was that measured at the BWTF facility, and the second that measured at the PNL meteorological station, identified as 'MET', located 30 miles north of the BWTF. The presence or absence of rain-day evaporation is indicated by 'RDE', and 'NRDE' respectively.

The data values reported in Table 2 obtained from each simulation include net change in total water stored in the 7.6 m profile (Del. Stor.), the total drainage past 150 cm (D-5), total drainage past 7.6 m (D-25), and cumulative

TABLE 2. Summary of Model Results--Comparisons of Yearly Water Balance Totals. All results reported in cm.

	<u>Del. Stor.</u>	<u>D-5</u>	<u>D-25</u>	<u>Evap.</u>
<u>NONISOTHERMAL</u>				
BWTF				
RDE	1.3	3.6	1.4	16.9
NRDE	3.2	4.3	1.4	15
MET				
RDE	2.3	4.0	1.4	15.3
NRDE	--	--	--	--
<u>ISOTHERMAL</u>				
BWTF				
RDE	2.5	3.8	1.4	15.9
NRDE	3.9	4.4	1.4	14.4
MET				
RDE	3.8	4.5	1.4	15.0
NRDE	5.6	--	1.4	13.2
<u>UNSAT. (N&H)</u>				
BWTF				
RDE	4.3	7.0	1.0	14.4
NRDE	9.0	10.0	1.0	9.7
MET				
RDE	3.3	4.6	1.0	15.8
NRDE	8.1	6.6	1.0	11.1
<u>UNSAT. (BEESE)</u>				
BWTF				
RDE	5.8	6.7	1.0	12.9
NRDE	--	--	--	--
MET				
RDE	5.3	5.3	1.0	13.9
NRDE	--	--	--	--
<u>BWTF Field Data</u>				
(South Caïsson)	4.98	~5	<3	~13.5

KEY

BWTF - Precipitation data from test site (19.7 cm/63 events)

MET - Precipitation data from Hanford Meterological Station
(20.2 cm/92 events)

RDE - Evaporation model simulated evaporation on rain days

NRDE - Evaporation model simulated no evaporation on rain days

Del. Stor. = annual storage change

D-5 = drainage from 1.5 M lysimeter

D-25 = drainage from 7.6 m lysimeter

Evap. = annual evaporation

-- = no data available

evaporation (Evap). A positive value for Del. Stor. indicates a net increase in profile storage, a positive number for D-5 and D-25 indicate a net downward flux of water, and a positive number for cumulative evaporation indicates water lost by evaporation.

Below the simulation results are the field data that represent the data compiled from records of the BWTF. The change in storage is taken from Figure 7, while the drainage data is from Figure 8. The evaporation data are not from direct measurement, but calculated from the difference between precipitation and the sum of net storage and drainage. Because some uncertainty exists as to which rainfall total to use, cumulative evaporation is reported as an approximate number. Also included at the bottom of Table 2 is a reminder of the difference between the BWTF and MET rainfall patterns (see Figure 9). At the BWTF a total of 19.7 cm of precipitation was recorded as 63 events over the simulation. Records published by the PNL meteorological station for the same period of time show 20.2 cm of precipitation recorded from 92 events.

STORAGE AND EVAPORATION PREDICTIONS

Examining the predictions of deep drainage reveals the most about the accuracy of our estimates of hydraulic conductivity. Examining the predictions of storage and evaporation reveals the most about the effect of changing the evaporation submodel. Table 2 shows that the prediction of evaporation and change in storage are inversely proportional to each other. As the total evaporation increases, the net storage change decreases. Therefore, only one quantity needs to be examined. Because the profile storage was measured directly and evaporation was not, this report will focus on the values of the profile storage.

Table 2 shows several things regarding changes in total water stored in the profile. The first is that the model EVAP, using the diffusion evaporation submodels, predicted less net change in storage than the model UNSAT1D which used the empirical evaporation submodels. This results in part from higher drainage rates predicted with EVAP, but most significantly because the diffusion models predicted more evaporation.

The net storage change at the end of the simulation period predicted with UNSAT1D, including rain-day evaporation, seems to more closely match those measured in the field. However, this result can be misleading. A comparison of model predictions with measured field data throughout the simulation period implies a different conclusion about the accuracy of the models. Figure 10 shows a comparison of predicted versus measured change in storage for the diffusion models and Figure 11 shows the results for the empirical models. Simulations shown in these two figures were run using the MET rainfall distributions and included rain-day evaporation. Figures 10 and 11 reveal that the diffusion models actually tracked the change in storage throughout the year more closely than the empirical models.

The actual field measurements show a fairly active profile. During the spring (through day 175) and summer, the profile generally lost water. During the summer (day 175 to 300), the profile seemed to gain some water but then lost most of it. The uncertainty with this portion of the data has been discussed above. The actual curve should not show quite so much increase in storage during this time interval. The most dramatic change in storage occurs in the winter months (day 300 to 450) when most of the precipitation occurs.

The empirical models predict a fairly constant storage pattern during the summer with only minor evaporation losses. They also predict a less dramatic storage increase in the winter. The N&H and Beese models predict essentially the same low, net storage throughout the spring and summer. This is because evaporation during this period is mostly controlled by the soils ability to deliver water to the evaporative surface rather than by atmospheric demand. The lack of an explicit description of vapor flow apparently caused these models to describe this process poorly.

During the winter months the air is cool and moist, and the soil is wet. Evaporation during this period is controlled by atmospheric conditions and the empirical models performed better. The simulation using the Beese evaporation scheme ended up with the net storage that best approximated the field data, however, it may have been rather fortuitous. A multi-year simulation is needed to show whether the underestimation of spring and summer evaporation would cause a drastic overprediction of storage during subsequent winters.

FIGURE 10. Comparison of Net Profile Storage as Measured and Predicted by the Diffusion Evaporation Models with Rain-Day Evaporation.

FIGURE 11. Comparison of Net Profile Storage as Measured and Predicted by the Empirical Evaporation Models With Rain-Day Evaporation

The predictions from the diffusion models more closely predict the field data, particularly when the uncertainty in field data between day 175 and 300 is taken into consideration. The diffusion models generally underpredicted evaporation in the spring and summer and overpredicted evaporation during the fall and winter. However, the discrepancies were much less than with the empirical models and, therefore, the diffusion models more accurately predicted storage. The most surprising result of the simulations is that the non-isothermal model did not do as well as the isothermal diffusion model. We did not expect this because the nonisothermal model contains a more rigorous description of evaporation based on the accepted conceptual model presented earlier in this paper. This needs to be examined in more detail as does our understanding of the evaporation process.

DRAINAGE PREDICTIONS

The next set of results to be discussed are the predictions of drainage. The drainage or flux prediction at 1.5 m (D-5) are relevant to the flux of water into a burial zone within a burial trench. The deep drainage (D-25) is relevant to deep drainage below a burial trench. One of the most noticeable results shown in Table 2 is that the deep drainage predictions are only dependent on whether the EVAP (1.4 cm) or UNSAT1D (1.0 cm) model was used. They are not dependent on the evaporation model, the rainfall pattern, or the presence or absence of rain-day evaporation. This is because for the simulation period, predictions of deep drainage rates were only dependent on the hydraulic conductivity curves used by the two models. Because that value is different for each model (for reasons explained earlier), the drainage rates are slightly different.

We must be careful not to misinterpret this result. Because the simulation covered a short length of time, the drainage rates were not sensitive to the specific evaporation model. Deep drainage rates are not usually sensitive to surface processes such as evaporation and rainfall on a yearly basis, but they do respond to long-term effects. It is reasonable to assume that the water stored by the profile during 1979 and 1980 will eventually drain out. A multiyear simulation will likely show that drainage rates are sensitive to

evaporation rates when averages over several years are considered. Those models consistently predicting lower total evaporation will likely show higher drainage rates after two or three years.

The future behavior of deep drainage rates can also be inferred by examining the shallow, 1.5-m lysimeter drainage rates (D-5). These drainage rates were more sensitive to the evaporation model than to estimates of hydraulic conductivity. It is interesting that the sum of total evaporation (Evap.) and total 1.5-m drainage (D-5) is almost constant (19.3 ± 0.9) for all simulations. This is equal to the rainfall minus deep drainage, which indicates that essentially all of the water that wasn't evaporated, drained below the 1.5-m depth. In other words, the water stored in the profile is not being stored near the surface, but is being transported downward through the profile and eventually would reach the 7.6-m depth. This result is generally true for bare soils. It illustrates the fact that evaporation is a near-surface process. Water infiltrating to depths below 1.0 m is rarely redistributed upward for evaporation.

The accuracy of these drainage predictions can only be judged qualitatively. The drainage water withdrawn from the shallow 1.5 m lysimeter during the simulation period was less than the actual drainage (see Figure 8). We know this because there was standing water in the lysimeter until the end of 1981. Based on the entire data set contained in Figure 8, we can say that the 1.5-m drainage rate during the simulation period was near 5 cm. Also, no drainage water was removed from the 7.6-m depth until 1981, however, standing water was detected during 1981. Also, based on Figure 8 the 7.6-m drainage rates are estimated at less than 3 cm/year. In view of these data, the 1.5-m drainage data (4 cm) from the diffusion models using rain-day evaporation look reasonable. The drainage numbers from the empirical evaporation models are high, especially those without rain-day evaporation.

The deep drainage data from all models (1.0 to 1.5 cm) are not contradictory with the measured data. The most significant implication of this is that our estimates of liquid-phase, unsaturated hydraulic conductivity were quite reasonable. As stated in Jones and Gee (1984), our evaluation of measurement techniques was in two phases. The first was to compare and evaluate techniques based on consistency and ease of measurement. The results

of this work were published (Jones, Jordan and Gee 1979; Jones and Gee 1984) and recommended the power function approach of Brooks and Corey (1964), and Campbell (1974). We now see that these techniques also produce conductivity estimates that are consistent with field data and useful in Darcian-type models.

MODEL SENSITIVITY TO RAINFALL DISTRIBUTION

The sensitivity of model predictions to the two rainfall distributions is shown in Table 2. As mentioned before, the deep drainage prediction (D-25) did not react at all to the different rainfall distributions. The other three variables did react and reacted consistently. By consistently, we mean that if storage increased, then D-5 increased and cumulative evaporation decreased.

The interesting result is that the diffusion models reacted differently than the empirical models. As shown in Table 2, the diffusion models predicted more evaporation when using the rainfall distribution measured at the BWTF than that from the MET. The empirical models showed less evaporation using the BWTF rain data than with the MET data. The behavior of the diffusion models goes against intuition, which says that higher evaporation rates should be recorded under rainfall distributions showing lower intensity (less rain per event) and higher frequency (more rain events).

A partial explanation for these results is seen by examining the cumulative evaporation predicted by the models throughout the simulation period. Figures 12 and 13 show the cumulative evaporation for the Beese evaporation model and the nonisothermal model respectively. In each figure the different curves obtained using the MET and BWTF rainfall patterns are shown. Figure 9 showed that the major difference between the two patterns was a large rain (2.19 cm) recorded at the BWTF on day 115, which was not recorded at the meteorological station. This caused the cumulative rainfall, as measured at the BWTF, to be higher throughout most of the year. Not until winter did the total rain measured at the meteorological station surpass the BWTF total.

Figures 12 and 13 show that the Beese model and the nonisothermal model reacted differently to the initial large rain recorded at the BWTF. The Beese model predicted that most of the large rain was stored, resulting in nearly

FIGURE 12. Sensitivity of the Beese Evaporation Model to Rainfall Distribution

equal evaporation rates under both the MET and BWTF rain pattern until winter. Then the evaporation rate increased for the MET distribution. The nonisothermal model predicts that most of the large rain evaporated, which resulted in a higher evaporation rate for the BWTF pattern. The difference between the two evaporation totals stayed essentially constant until winter when the model evaporated more under the MET rainfall data than the BWTF data. The increased evaporation in the winter was not enough to make up the difference created by the large rain of day 115. Therefore, the difference in how the models reacted to different rainfall distributions was largely due to how they reacted to the large rain on day 115.

SENSITIVITY TO RAIN-DAY EVAPORATION

The sensitivity to the presence of rain-day evaporation is surprisingly strong. The question of whether to allow the model to evaporate on rain days is not easily answered. The question cannot be answered without detailed

FIGURE 13. Sensitivity of Nonisothermal Diffusion Model to Rainfall Pattern

meteorological data for the day it rains, such as percent cloud cover and hourly rainfall intensity. For example, an early morning rainfall on a clear sunny day would surely be followed by significant rain-day evaporation. A rain day that was cloudy and drizzly would not see any significant rain-day evaporation. Unfortunately our simulations show that this question can be as important as determining which evaporation submodel to choose.

Table 2 summarizes the results of the presence or absence of rain-day evaporation. It shows that most dramatic effect of rain-day evaporation was with the one-step or N&H evaporation model. The change in storage for this model with and without rain-day evaporation is shown in Figure 14. The storage increase is more than doubled when rain-day evaporation is eliminated. Figure 15 shows the sensitivity of the isothermal evaporation model to rain-day evaporation. It is not nearly as pronounced. Both models perform better when rain-day evaporation is included.

FIGURE 14. Sensitivity of Model Results to Rain-Day Evaporation When Using N&H Evaporation Submodel

FIGURE 15. Sensitivity of Model Results to Rain-Day Evaporation When Using Isothermal Diffusion Evaporation Model

CONCLUSIONS

The conclusions that can be drawn from these simulations are most directly applicable to the simulation of soil water balances at the Hanford site near Richland, Washington where the experiments took place. However, if they are going to be of value to the NLLWMP, the results must be generalized. The best way of doing this is to relate the performance of the models to the conceptual model of evaporation shown in Figure 3.

It seems clear that the models that included the diffusion-type evaporation submodels performed best. This was primarily because they tracked the loss of water during the spring and summer better than the empirical models. Evaporation during this time of year is dominated by soil-limited rates where it is important to describe water flow to the evaporating surface from below and the diffusion of water vapor through the dry soil to the atmosphere. Therefore, we conclude that models need to include a description of water vapor flow to describe this type of evaporation adequately.

In the winter months when the evaporation is primarily controlled by atmospheric conditions, all models performed fairly well. The diffusion model tended to overpredict evaporation as did the N&H model. The Beese model performed best. We might conclude then that under wet conditions, or periods of time when evaporation is in the first stage, the empirical models might perform adequately. This suggests that application of the Beese model may be acceptable in the 'humid east', but this should not be taken for granted without testing. Multiyear simulations are needed to determine whether the errors introduced by poor simulation of summer evaporation are propagated from one year to the next.

Regarding sensitivity to rainfall distribution, the case is still open. The results were somewhat confused by the peculiar distribution tested. Generally speaking, the models are not overly sensitive to distribution differences, and they generally predict more evaporation under rainfall patterns showing higher frequency and lower intensity. However, as we have shown, this is not a steadfast rule. More work needs to be done on this issue.

The sensitivity to rain-day evaporation is much greater than we anticipated. The N&H model showed the greatest response to this variable. The inclusion or exclusion of rain-day evaporation should affect all models which rely on first-stage evaporation. Thus, the N&H model was very sensitive. However, this effect may have been exaggerated because in arid climates most of the evaporation that takes place happens within one or two days after a rain. The rain water can infiltrate deep enough into the soil within a day or two to escape any subsequent evaporation. Therefore, in climates such as the humid east where the soils are finer textured and first-stage drying may extend several days, the effect of rain-day evaporation may not be as drastic. However, it is a question that cannot be ignored.

Considering the overall accuracy of the model predictions, and the sensitivity to various factors, we can conclude that using mechanistic diffusion models of evaporation provides a significant advantage over the use of empirical models. The role of thermally induced flow is still uncertain and needs more study. Currently, it appears that the isothermal models perform the best. One final conclusion that is very significant but may have underemphasized been in this report is that procedures previously recommended for estimating hydraulic conductivity have provided measurements that performed well in our models. Our analysis suggests that the Darcian model coupled with a diffusion-type evaporation model that explicitly describes water vapor flow will be the best model to use to describe water balance processes at SLB sites.

REFERENCES

- Beese, F., R. R. van der Ploeg and W. Richter. 1977. "Test of a Soil-Water Model under Field Conditions." Soil Sci. Soc. Am. J. 41:979-984.
- Brooks, R. H., and A. T. Corey. 1964. Hydraulic Properties of Porous Media. Hydrology Paper No. 3. Colorado State University, Fort Collins, Colorado.
- Bond, F. W., M. D. Freshley and G. W. Gee. 1982. Unsaturated Flow Modeling of a Retorted Oil Shale Pile. PNL-4284, Pacific Northwest Laboratory.
- Campbell, G. S. 1974. "A Simple Method for Determining Unsaturated Conductivity from Moisture Retention Data." Soil Sci. 117:311-314.
- Campbell, G. S. 1977. An Introduction to Environmental Biophysics. Springer-Verlag, New York.
- Cass, A., G. S. Campbell and T. L. Jones. 1981. Hydraulic and Thermal Properties of Soil Samples from the Buried Waste Test Facility. PNL-4015, Pacific Northwest Laboratory, Richland, Washington.
- Gee, G. W., A. C. Campbell, P. J. Wierenga, and T. L. Jones. 1981. Unsaturated Moisture and Radionuclide Transport: Laboratory Analysis and Modeling. PNL-3616, Pacific Northwest Laboratory, Richland, Washington.
- Gupta, S. K., K. K. Tanji, D. R. Nielson, J. W. Biggar, C. S. Simmons and J. McIntyre. 1978. "Field Simulation of Soil-Water Movement with Crop Water Extraction." Water Science and Engr. Paper #4013, University of California-Davis, Davis, California.
- Hammel, J. E., R. I. Papendick and G. S. Campbell. 1981. "Fallow Tillage Effects on Evaporation and Seedzone Water Content in a Dry Summer Climate." Soil Sci. Soc. Am. J. 45:1016-1022.
- Haverkamp, R., M. Vauclin, J. Touma, P. J. Wierenga and G. Vachand. 1977. "A Comparison of Numerical Simulation Models for One-Dimensional Infiltration." Soil Sci. Soc. Am. J. 41:285-294.
- Jones, T. L. 1978. Sediment Moisture Relations: Lysimeter Project 1976-1977 Water Year. RHO-ST-15, Rockwell Hanford Operations, Richland, Washington.
- Jones, T. L., W. A. Jordan, and G. W. Gee. 1979. A Test of the Bresler-Russo-Miller Method for Unsaturated Conductivities. RHO-SA-125, Rockwell Hanford Operations, Richland, Washington.
- Jones, T. L., and G. W. Gee. 1984. Assessment of Unsaturated Zone Transport for Shallow Land Burial of Radioactive Waste: Summary Report of Technology Needs, Model Verification and Measurement Efforts: FY 78-83. PNL-4747, Pacific Northwest Laboratory, Richland, Washington.

Nimah, M. N., and R. J. Hanks. 1973. "Model for Estimating Soil Water, Plant and Atmospheric Interrelations. I. Description and Sensitivity." Soil Sci. Soc. Am. Proc. 37:522-527.

NRC. 1982. "U.S. Nuclear Regulatory Commission, 10 CFR 61, Licensing Requirements for Land Disposal of Radioactive Waste." Final Rule. Federal Register 47(248) 57446-57482. Div. of Tech. Information and Document Control, Washington, D.C.

Phillips, S. J., A. C. Campbell, M. D. Campbell, G. W. Gee, H. H. Hooper and K. O. Schwarzmiller. 1979. A Field Test Facility for Monitoring Water/Radionuclide Transport Through Partially Saturated Geologic Media: Design, Construction, and Preliminary Description. PNL-3226, Pacific Northwest Laboratory, Richland, Washington.

Ritchie, J. T. 1972. "Model for Predicting Evaporation From a Row Crop with Incomplete Cover." Water Res. Research 8:1204-1212.

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