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THE ROLE OF MATHEMATICAL MODELING IN LOW-LEVEL RADIOACTIVE WASTE MANAGEMENT

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ABSTRACT

With increased experience in shallow land burial of radioactive wastes, there is general recognition of the need for improved practices to reduce the release of radioactivity to the biosphere. One approach is to use mathematical models to gain insights into the impact of possible preventive and corrective engineering measures. Two deterministic models of hydrologic processes have been examined. On a watershed scale, a unified hydrologic model has been applied to the White Oak Creek Watershed in Oak Ridge, Tennessee. Comparison of predicted and observed streamflow at the basin outlet are favorable. The model has been applied to evaluate the consequences of a disposal area development, operation, and management; including clear-cutting of forested areas, installing near-surface infiltration-reduction seals, and surface water diversion channels. On a localized scale, a near-surface infiltration-reduction seal has been studied using a finite-element model for subsurface flow. The model has been used to calculate spatial moisture content and velocity distributions near the seal. Model results show how the path of infiltrating rainwater is altered.

INTRODUCTION

With increased experience in shallow land burial of radioactive wastes, there is general recognition of the need for improved practices to reduce the release of radioactivity to the biosphere. In order to satisfactorily dispose of wastes in this manner, it is imperative that radionuclides be immobilized or contained to the extent that release to the biosphere remains below acceptable limits.

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In the humid regions of the United States, the dominant mode of radionuclide transport to the biosphere is through the unsaturated and saturated ground-water zones and eventually emanating in surface water streams and lakes. Precipitation that infiltrates through waste trenches provides the carrier mechanism for leaching the radionuclides. Traveling downward to the water table, carrier fluid contaminates the ambient ground water, which typically moves laterally to a surface water discharge zone. These hydrologic processes are amenable to several types of mathematical modeling.

Improved containment and immobilization of radionuclides is possible through the implementation of various preventive and corrective engineering measures at the disposal areas. Such measures could include: the installation of near-surface infiltration-reduction hydrologic seals, deforestation of sub-basin units, surface water diversion channels, ground water cut-off walls, dewatering by well points, and rerouting of stream channels. The present work evaluates two selected scenarios of deforestation, surface seals, and diversion channels through the use of two models. The intent is to examine practical questions concerning the consequences of implementing engineering measures through the use of modeling.

UNIFIED WATERSHED MODEL

On a watershed scale, a physically-based hydrologic model, TEHM, (Huff et al. 1977) has been applied to the White Oak Creek Watershed in Oak Ridge, Tennessee. This model combines the processes of rainfall interception and through fall infiltration, root-zone evaporation, transpiration, saturated and unsaturated subsurface flow, surface runoff, and open channel flow. Previous work has shown the importance of such an approach in studying the hydrology and trace material transport within a watershed (e.g. Munro, et al. 1976). The model uses mechanistic representations of hydrologic processes, but simplifying approximations are introduced for many processes. This trade off maintains a code that is efficient and inexpensive so it can be used in evaluating alternative management scenarios.

TEHM has a history of applications that span several years. In a study at the Walker Branch Watershed (Huff et al. 1977) which is on the ORNL reservation, considerable information was learned concerning model parameters for soil properties, topography, and vegetation. The evapotranspiration component of the model has been applied to study the consequences of forest practices (Swift et al. 1975) and recently used in the development of a handbook for evaluating silviculture practices. More comprehensive studies may be found in Troendle, 1979 and Huff et al. 1978. It is sufficient to say that an extensive base of experience underlies the estimation of several model parameters. For the White Oak Creek basin study estimation of model parameters was based upon available data for the site and past experience.

To verify the models predictive capabilities, a comparison was performed between the observed daily flows at the basin outlet, White Oak Dam, and computer simulated flows for the 1975 water year. With the exception of low flow periods the comparison is favorable (Fig. 1). It is important to note that the preliminary simulation did not include water released by ORNL from municipal supplies; the discrepancy being most obvious during periods of low flow. Additionally, a comparison was performed between the frequency of flows greater or equal to a given rate for both the observations and the simulation (Fig. 2). In the observations of inflow to and outlet from the lake, the discrepancy relates to problems with the gaging stations.

In the simulation, flow at the dam will exceed 4.5 cfs for 60 percent of the time. The 1.5 to 2.5 cfs discrepancy between the simulated and observed flows is explained by the release of imported municipal water supply. It should be noted that at flows greater than 8.0 cfs, there is no distinguishable difference between the flows. The interpretation is that the model adequately simulates storm event flows.

To examine the consequences of a disposal area development, operation and management, the following three sequences of events were imposed: clear-cutting (deforestation) of 70 percent of a small (96 ha) forested area, installation of a near-surface bentonite seal for infiltration-reduction, and finally the installation of surface water drainage and diversion channel network. The objective is to develop a semi-quantitative description of the magnitude of consequences associated with each step in the progression.

In terms of a flow frequency analysis the results of the step-wise implementation are presented in Figure 3. For the sub-basin unit, the median baseline flow (solid line), which is exceeded 50 percent of the time, is 0.5 cfs. When a 70 percent clear-cut is imposed on the system, the median flow increases to 0.8 cfs as result of decreased evapotranspiration during the summer months. This available water, not used by vegetation, increases base flows. At higher flows, there is virtually no change in frequency occurrence. This is attributable to the fact that winter storm runoff is governed more by soil properties than by differences between soil moisture content at the beginning of the event for forested and clear-cut conditions.

The most dramatic changes in flow frequency occur with the installation of a bentonite seal at a depth of 60 cm below ground surface. The median flow drops to 0.3 cfs for the first year following the treatment. The change occurs because the hydrologically-active soil mass has been drastically reduced. With only 60 cm of soil for moisture storage, there is a limit to the amount of water that can be absorbed during wet periods and slowly released during dry periods. Thus, the area loses the ability to generate sustained dry-weather flow. Instead, more runoff is generated during storms, and the frequency of flows of higher

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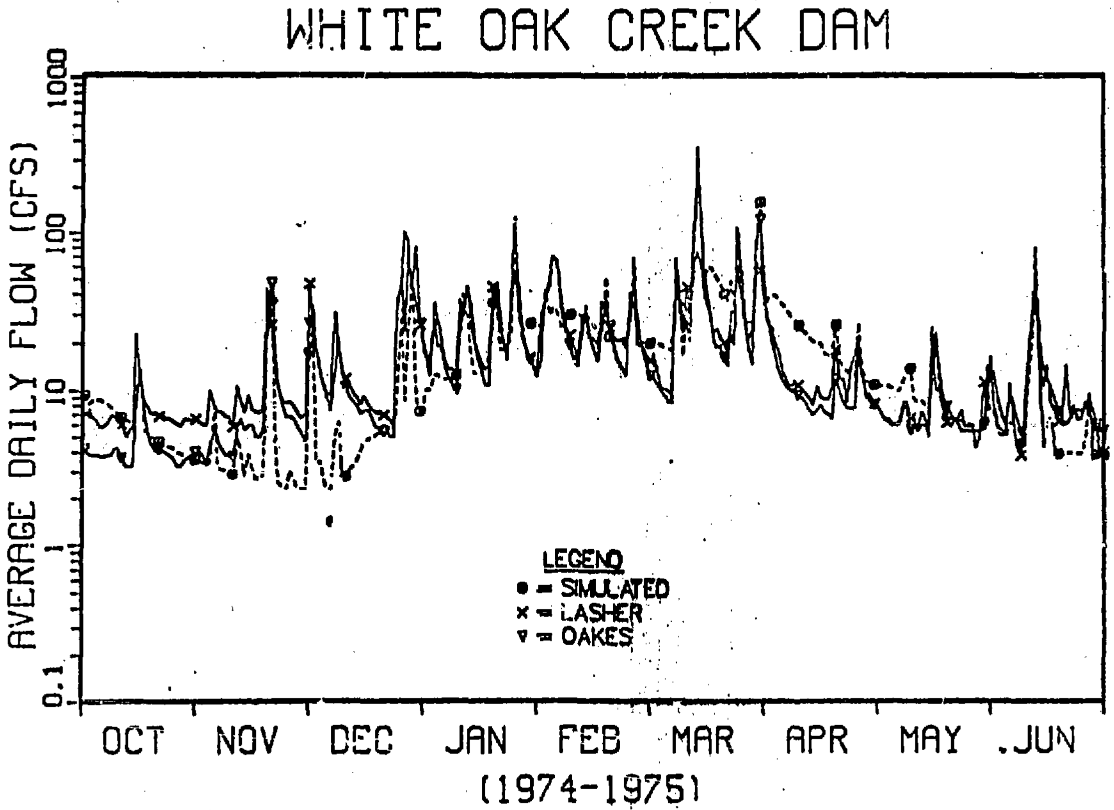

Figure 1. Observed and simulated daily flow hydrographs at White Oak Lake (1974-1975).

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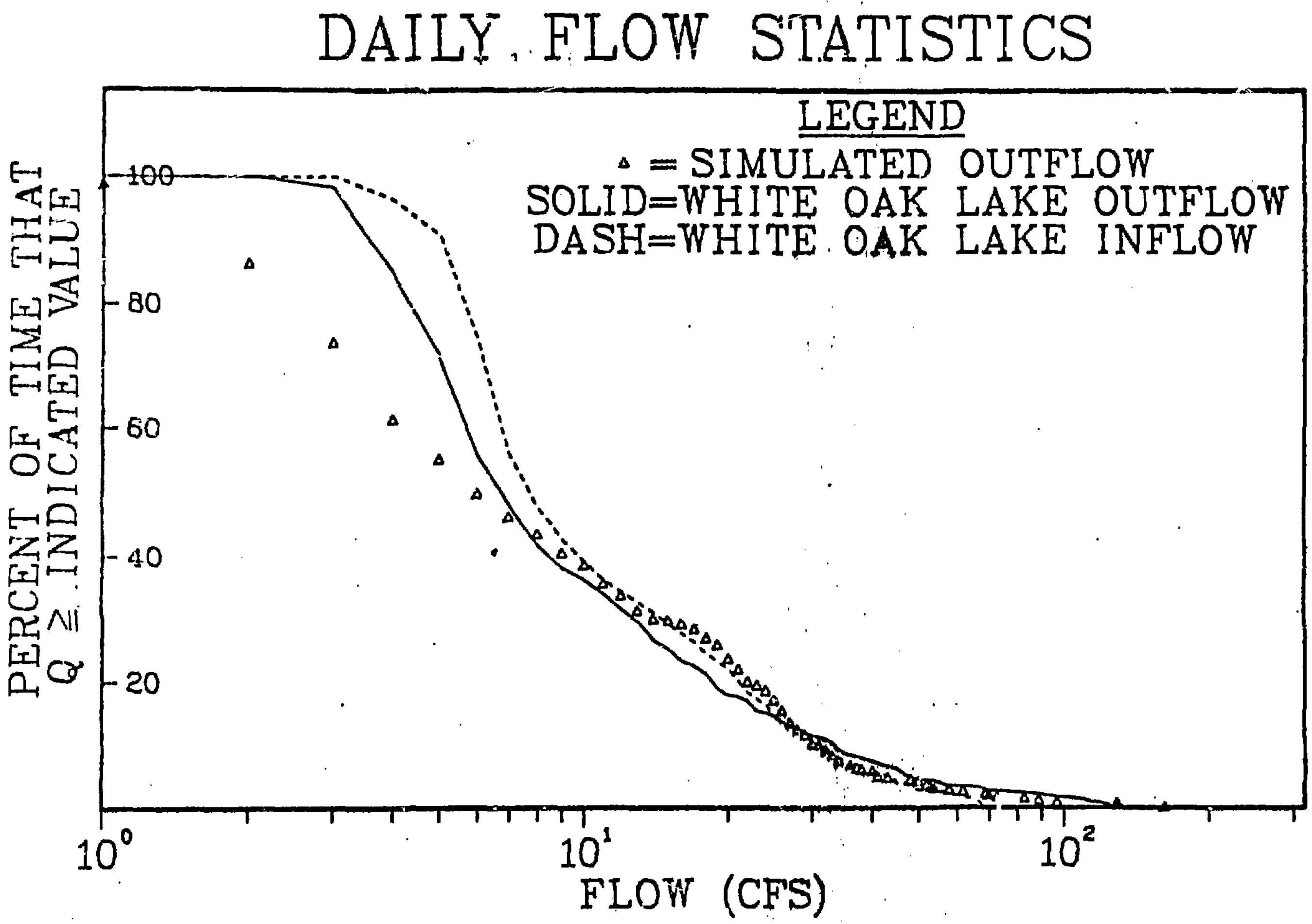

Figure 2. A comparison of the frequency analysis between observed daily flows (1974-1975) and simulated daily flow of White Oak Lake.

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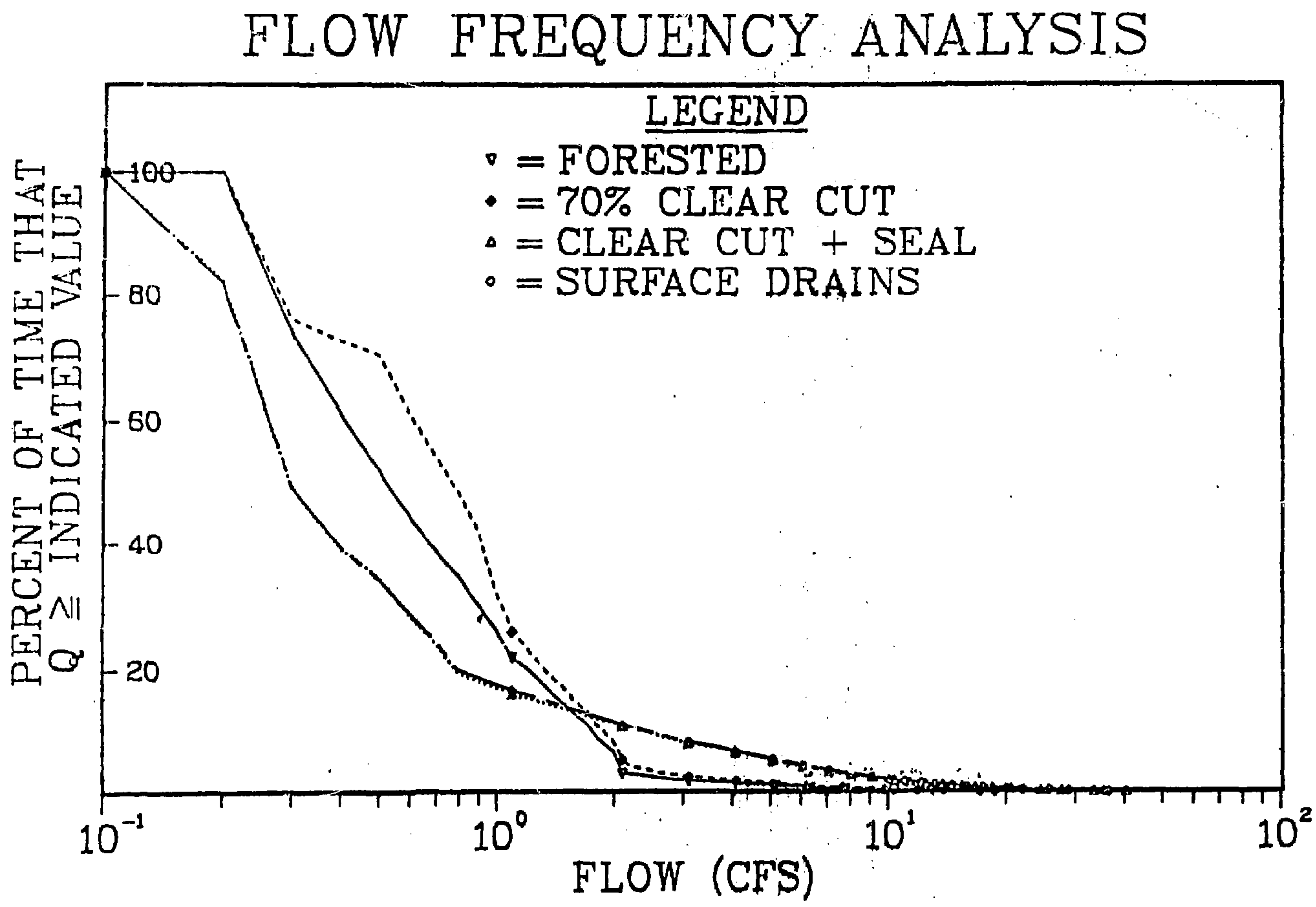

Figure 3. Frequency analysis results for waste disposal management alternatives (solid = forested; dash = 70% clear-cut; chain dask = clear-cut and bentonite seal; dotted = clear-cut, seal and drains).

magnitude increases. In other words, the basin becomes "flashy", and is characterized by a wider range of flow conditions. The minimum flow rate drops and the peak storm flow rate actually more than doubles. for the example situation. An important outcome is the indication that high flow rates were generated by the bentonite seal at 60 cm, and the volume of annual runoff increased from 83 to 96 to 111 cm for the three treatments. The amount of ground-water outflow is drastically reduced after the bentonite seal has been installed. This has important implications for disposal areas where the dominant pathway for radionuclide transport from trenches is through the ground-water zone.

The final treatment simulated was the installation of surface drainage and diversion channels to carry surface runoff away from the disposal area as quickly as possible. The treatment was simulated for an area that already had a bentonite seal in place. There was no detectable effect on flow frequency from this treatment. There was a minor decrease in the peak flow for the major storm of the simulation period after installation of the surface drainage channels. This appears to result from a more rapid runoff rate early in the storm, thus removing some of the flow that contributed to the peak before the drains were installed. However, the inescapable conclusion is that surface drains have virtually no effect on changing flow rates from a disposal area. Their main value would lie in using them to convey runoff generated offsite, thus to prevent an upslope area from adding to the moisture input from precipitation.

MOISTURE TRANSPORT MODEL

On a localized scale, a near-surface infiltration-reduction seal has been studied using a finite-element model [FEM] for moisture transport (Reeves and Duguid, 1975; Yeh and Ward, 1979). In the selection of seal materials for shallow land burial, several aspects must be considered: low hydraulic conductivity, longevity, durability, and costs. Bentonite, a naturally-occurring highly plastic clay, is one such material that has been used for infiltration-reduction (Hawkins and Horton, 1967; Kays, 1977).

The application of the finite-element method to solve saturated-unsaturated water transport has received considerable attention in recent years (Pinder and Gray, 1977; Neuman and Witherspoon, 1971; Neuman, 1973). The model employs quadrilateral elements with bilinear basis functions for the spatial integration, finite-differencing for the time deviative, and Gaussian elimination for the solution of the resulting matrix equation. The reader is referred to the references for further details.

To demonstrate the use of the deterministic model an idealized vertical cross section was delineated for the flow regime of interest (Fig. 4). The section includes: the trench soil cover, a clay admixture seal, and a seal soil cover. The shallow land-burial trench would lie below the

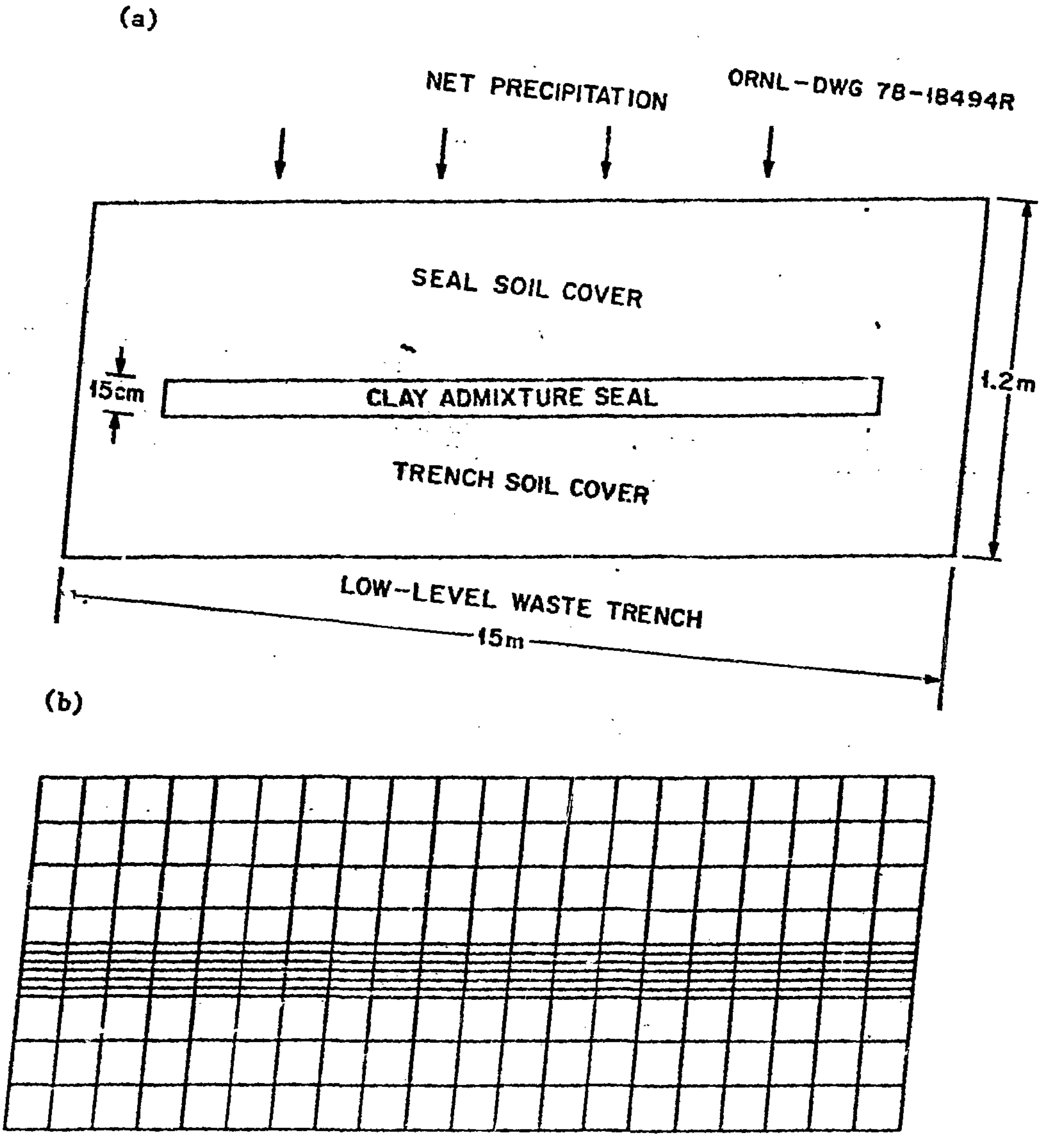

Figure 4. (a) Cross section of a near-surface clay admixture seal.
(b) Finite-element discretization of the flow regime.

section and above the water table (not shown). Incorporation of the trench, as such, was not possible due to the heterogenous nature of the wastes; furthermore, the critical areas of flow include the seal and soil covers in the simulation.

The hypothetical clay seal is 15 cm thick and 12 m long on an inclined slope of 0.02 m/m. The seal cover extends 60 cm to the ground surface. The finite-element discretization of the region used in the simulation is shown in Figure 4b.

To perform a rigorous analysis of this scenario involving the installation of a clay seal in reducing the infiltration of water to the radioactive waste trench, exact boundary conditions must be imposed. Zero flux conditions were imposed on the vertical boundaries, typical of field conditions with a ground-water divide upslope and a series of seals downslope of the seal under investigation. A steady-state Neumann flux condition was imposed on the seal soil cover representing uniform net precipitation, defined as the total precipitation less evaporative losses. Below the trench-soil cover a Dirichlet boundary condition was imposed as the more natural unit-gradient drainage condition yielded a poorly posed problem.

The soil hydraulic properties used for input in both the TEHM and the FEM were identical. The unsaturated moisture release characterization for the local Litz soils were obtained from the literature (Longwell et al. 1963). By an approximation technique (Mualem, 1976) the unsaturated hydraulic conductivity relations were calculated for the soil and clay seal (Fig. 5).

The model provides detailed calculations of the spatial distribution of moisture content and water velocity. Subject to the aforementioned boundary conditions, the flow regime experiences a decrease in moisture content within the clay seal and in the trench soil cover directly beneath the seal. Figure 6 is a perspective plot of the distribution if one were to view the cross section (Fig. 5) from the lower left-hand corner. It should be noted that the distribution is highly dependent upon the chosen boundary conditions. Field measurements, collected to date, of moisture content at eight locations in the ORNL disposal areas neither substantiate nor invalidate the calculated moisture profile.

Of greater significance is the calculated velocity field (Fig. 7). The velocity vectors, exaggerated five-fold vertically, clearly depict the reduction of infiltration to the trench. The high velocity in the seal cover typically exceed those in the clay seal (10^{-13} cm/sec) by eight orders of magnitude. It is clearly evident that installation of the seal dramatically influences the flow paths, diverting water that would otherwise enter the trench.

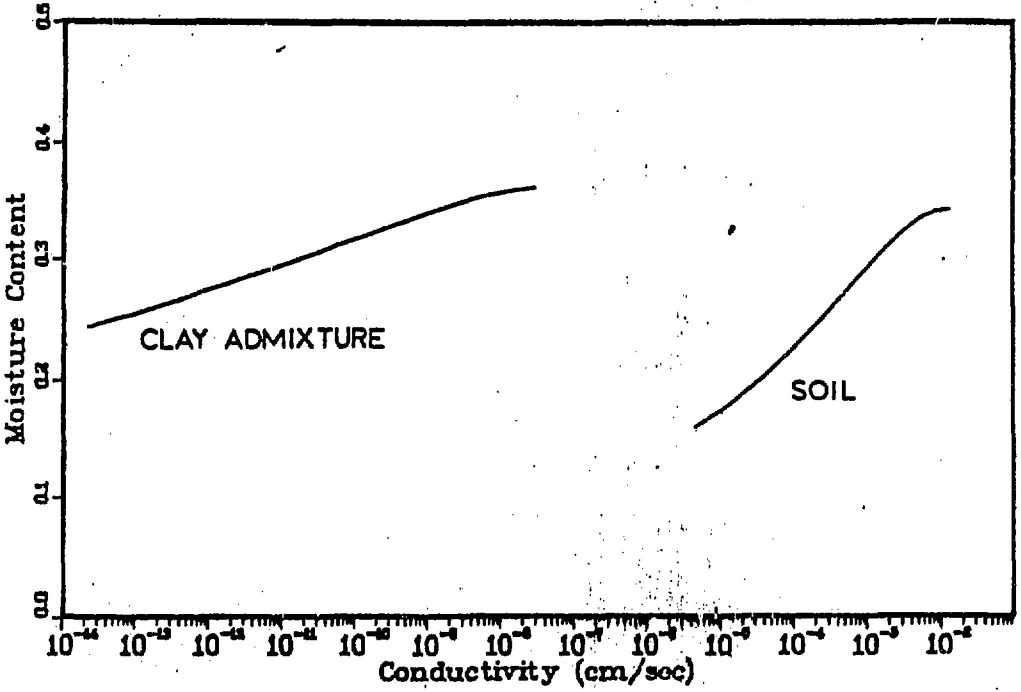

Figure 5. Relationship between hydraulic conductivity and moisture content.

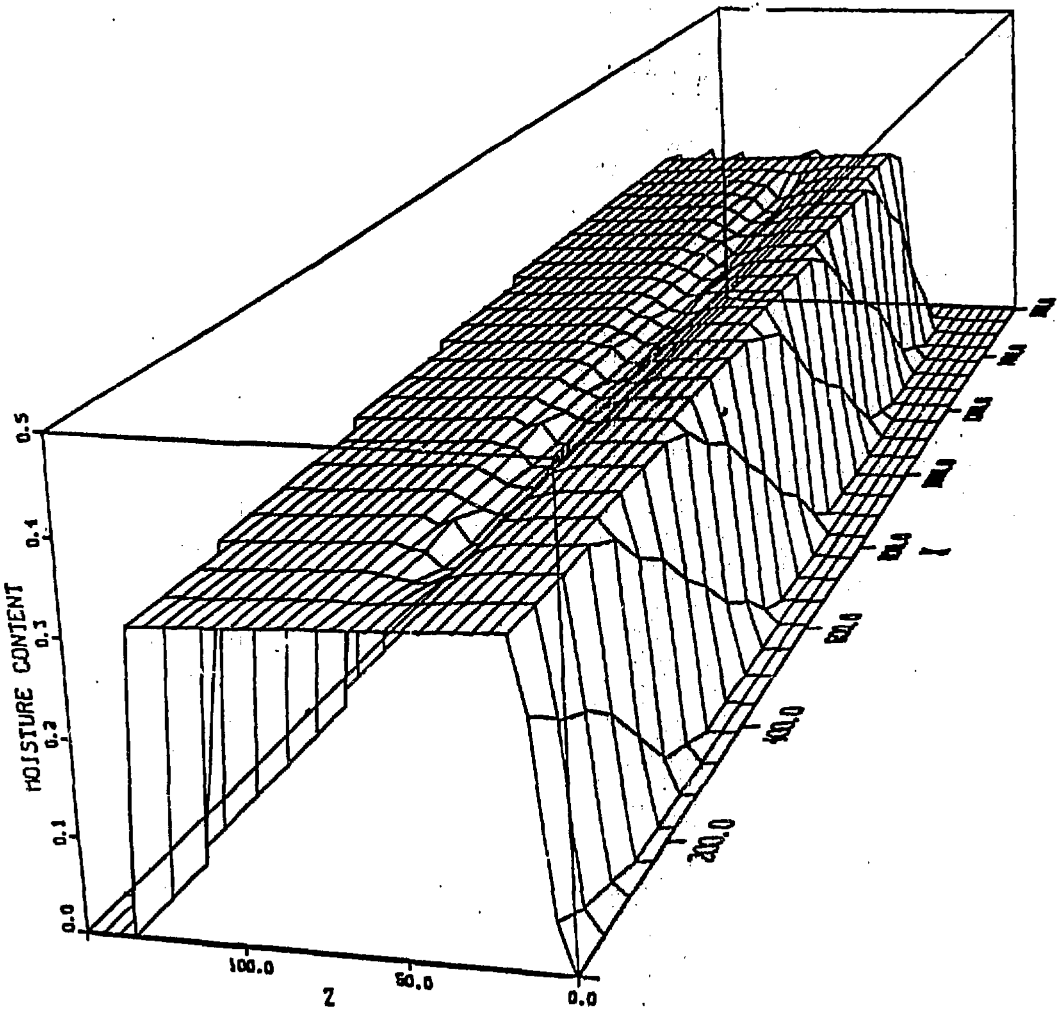

Figure 6. Perspective plot of moisture content distribution. The vantage point is from the lower left hand corner of the cross section.

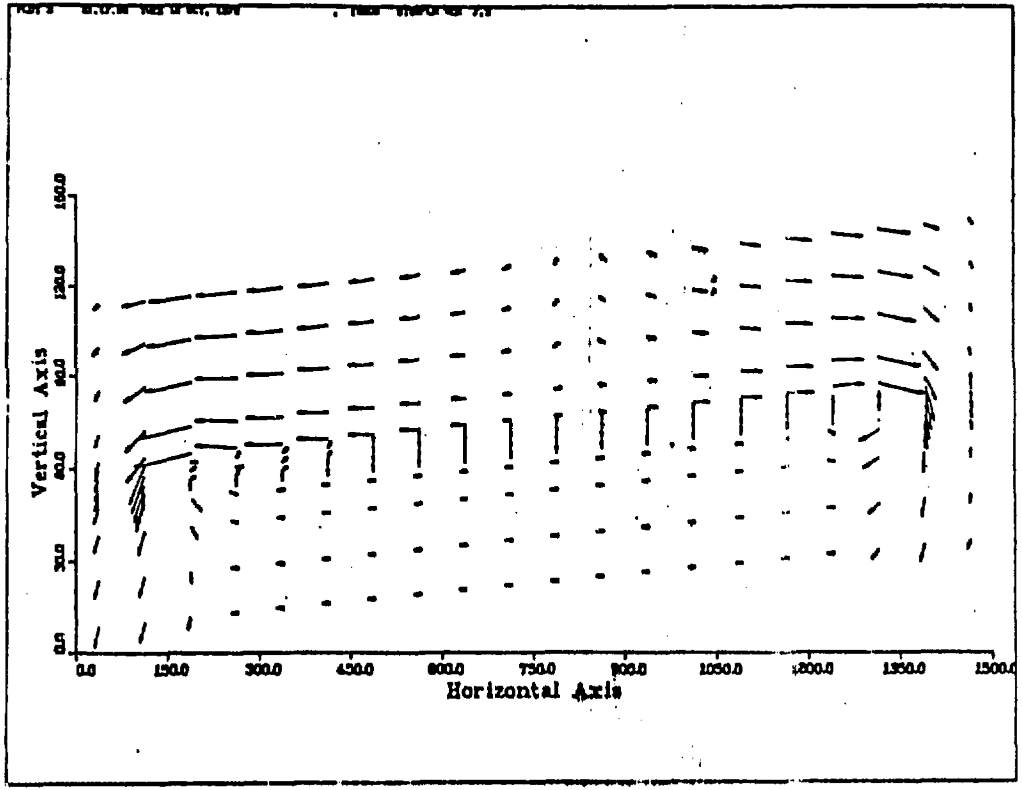

Figure 7. Velocity field plotted at element centroids and average for each element.

SUMMARY

In response to the need for improved practices in the management of shallow land burial of radioactive wastes, two scenarios, one on a watershed and the other on a localized scale have been studied through the use of mathematical models. Semi-quantitative insights have been gained as to the consequences of implementing preventive and corrective measures. Clear-cutting forested areas and installing near-surface infiltration-reduction seals increase peak storm and total annual runoff. Conversely, minimum flows and ground-water outflow are decreased. Surface drains have little impact on the overall hydrologic balance. On a localized scale, a detailed study of a near-surface seal indicated that although the change in the soil moisture distribution was not significant, the alteration of the velocity field substantially reduce the possibility of contact of water and the wastes.

The scenarios developed are not intended to be conclusive; rather, the intent is to present the capabilities of hydrologic models and to provide insight on the management of shallow land burial sites. Through mathematical modeling of hydrologic processes, practical problems concerning the implementation of preventive and corrective measures can be evaluated.

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