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**An Assessment of the
Effect of a Bentonite Seal
on Groundwater Storage
in Underlying Waste
Disposal Trenches at
Oak Ridge National Laboratory**

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ENVIRONMENTAL SCIENCES DIVISION
Publication No. 1560

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AN ASSESSMENT OF THE EFFECT OF A BENTONITE SEAL
ON GROUNDWATER STORAGE IN UNDERLYING WASTE DISPOSAL
TRENCHES AT OAK RIDGE NATIONAL LABORATORY

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ENVIRONMENTAL SCIENCES DIVISION
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ABSTRACT

ARORA, H. S., D. D. HUFF, D. S. WARD, and O. M. SEALAND.
1981. An assessment of the effect of a bentonite seal on
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Near-surface bentonite seals have been installed for drainage control in sections of low-level solid radioactive waste disposal areas at Oak Ridge National Laboratory. For a 49-trench section that was sealed in Solid Waste Disposal Area 6 the water-table elevation was periodically measured to assess the effectiveness of the seal for controlling the intrusion of water. Water was found in a majority of trenches throughout the study period (May 1978 - December 1979). Mean seasonal water-table fluctuations indicated an average rise of 131 ± 56 cm in waste trenches between October 30, 1978 (minimum level) and February 15, 1979 (maximum level). This mean difference corresponds to an estimated gain of $1,000 \text{ m}^3$ of groundwater storage in the trench area. The measured depths to water in the trenches showed a general correspondence with those in monitoring wells (augered during September 1979) outside the trenches in the undisturbed zone in the downslope southern half of the study area. In contrast, the measured depths to water were relatively greater in wells in the undisturbed zone in comparison with those in trenches in the upslope northern half of the study area. This suggests that perched water tables developed within the trenches in the upslope area. The groundwater table (potentiometric surface) contours essentially followed the topographic contours and indicated a predominant gradient

toward the south-southwest, which is in the direction of a backfilled topographic draw with a known seep at its base. The reported hydrologic characteristics of the Oak Ridge area, laboratory studies in the development of bentonite application rates, and simulation studies using a hydrologic computer code suggested that a significant part of the groundwater observed in the study area was associated with groundwater intrusion from the surrounding upslope area. These studies further suggest the need for direct measurement of the infiltration rate for the seal in order to differentiate the vertical and lateral recharge of groundwater in the area.

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1. INTRODUCTION

Burial in shallow trenches in the White Oak Creek drainage basin is the principal mode of disposal at the Oak Ridge National Laboratory (ORNL) of low-level solid radioactive wastes. These operations were initiated in 1944 (Webster 1976). Six separate solid waste disposal areas (SWDAs) have been used during the intervening years, but five of the areas have been closed. Since 1969, only SWDA 6 has been used for waste disposal (Fig. 1). The history of burial operations and general geohydrologic characteristics of the White Oak Creek drainage basin were described by Webster (1976).

Movement of water through the disposed waste has resulted in radionuclide release to the nearby Clinch River via White Oak Creek. Evidence of groundwater transport of buried radionuclides has been found by examination of well waters from most of the earlier disposal operations (Duguid 1976) and subsequent surface transport is indicated by the occurrence of contaminated sediments in several stream tributaries that drain the SWDAs (Cerling and Spalding 1980), as well as several surface seeps (Duguid 1976, Cerling and Spalding 1980). The contamination arising from both surface-water releases and groundwater discharge from waste disposal areas and ORNL plant discharges is monitored at several sampling locations and finally at White Oak Dam (Station 5), located in the lower portion of the drainage basin near the confluence of White Oak Creek and the Clinch River (Fig. 1).

During the four-year period from 1974 through 1977, the average annual concentration of ^{90}Sr , one of the major radionuclides of concern at ORNL, in water discharged over White Oak Dam ranged from

Fig. 1. Location of solid waste disposal areas and selected sampling stations in the White Oak Creek watershed.

80 to 195% of maximum permissible concentration (MPC_w) (Stueber et al. 1978).^a However, the ^{90}Sr concentration in Clinch River water downstream from White Oak Creek is usually less than 1% of MPC_w because of dilution. At the present time, over 50% of the ^{90}Sr entering the Clinch River from the White Oak Creek may be attributed to leachate leaving the six disposal areas (L. C. Lasher, ORNL, personal communication, 1980). Although a variety of other radionuclides are observed in the discharge to the Clinch River and may, in part, be emanating from burial grounds (Webster 1976), their concentrations are well below the established guidelines. In keeping with the objective to maintain releases to "as low as practicable," a concerted research effort has been directed toward studying the transport of radionuclides and in seeking methods for retarding contaminant outflows from waste trenches.

Infiltration of precipitation in Oak Ridge and other burial sites located in humid regions is assumed to be the most significant contributor to leaching of contaminants from the waste, transport in groundwater, and release to the terrestrial and fluvial environments. Near-surface sealing with a bentonite-shale mixture has recently been instituted for soil water drainage control in disposal areas. Five sections of SWDAs 5 and 6 have been sealed to date. Engineering feasibility and cost estimate studies have concluded that \$2.38 million would be required to seal SWDA 4 (Appendix). It is imperative that

^aThe maximum concentration of a particular radionuclide that would result in unacceptable radiation dose to a critical organ over a 50-year period of continuous contaminated water ingestion or exposure is referred to as the maximum permissible concentration in water (MPC_w).

the effectiveness of an existing seal be evaluated before such large sums of money are committed or additional sealing of sections of SWDA 6 is contemplated.

The primary objective of this study was to make an initial evaluation on the groundwater movement in a bentonite-sealed area in SWDA 6. In particular, it was desired to ascertain the effect of the bentonite seal in preventing water from entering the trenches under it in the disposal area. Seasonal water-table fluctuations were used to estimate the changes in groundwater storage in the area, and a computer simulation model (TEHM) developed by Huff et al. (1977) was used, in part, to ascertain the source of groundwater.

2. THE INVESTIGATED AREA

SWDA 6 is located north of the White Oak Lake, bounded by White Oak Dam, in Melton Valley (Fig. 1). This site includes 28 ha of gently to moderately sloping land that is divided into several smaller sections by natural gullies and seasonal streams. The disposal area is underlain by the Conasauga Group, which consists of gray calcareous to silty shales that are interbedded with limestone and siltstones. The Conasauga strikes approximately N 55 E and dips toward the southeast, commonly at angles of 30° to 40°. Weathering persists generally to a depth of about 6 m and is less in areas of low relief. The weathered siltstones and shales have well-developed joints that are open near the surface. Small faults and sharp folds are common throughout the area (Lomenick and Wyrick 1965).

The climate of the Oak Ridge area is typical of the humid southern Appalachian area and is significantly influenced by topography. The mean annual precipitation is 1290 mm, and Elwood and Henderson (1975) estimated that approximately 45% of the annual precipitation was lost by evapotranspiration in a forested watershed on the Oak Ridge Reservation. Although precipitation is fairly well distributed throughout the year, well-defined seasonal variations exist. Monthly maxima normally occur from January to March with a secondary maximum occurring in July. September and October are usually the driest months. The coldest month is normally January (mean 3.6°C), with July being the hottest (mean 24.8°C). Additional climatological data for the Oak Ridge area can be found in reports by McMaster (1967) and the Oak Ridge Atmospheric Turbulence and Diffusion Laboratory (1972).

Geohydrological investigations conducted during 1964-65 at the site proposed for SWDA 6 indicated that the depth to water was less than 1.8 m throughout much of the low-lying areas and greater than 6.4 m in three topographically high areas. For a 9-month period during 1964-65, the depth to water decreased during the late winter and early spring months. Lomenick and Wyrick (1965) described the water table configuration of the area as "essentially a subdued replica of the land surface."

Three bentonite-seal sections (19-trench, 49-trench, and 21-trench sections) within SWDA 6 are shown in Fig. 2. The 19- and 49-trench sections were considered initially for this study in April 1978. The area covering 21 trenches was sealed later in August 1978 and thus was not considered for the present study. The 19-trench section sits atop a narrow leveled ridge and is a topographically high area with relatively greater depths (> 4.9 m) to groundwater (Lomenick and Wyrick 1965) than other waste disposal sections in SWDA 6. On the other hand, the 49-trench section is located on a gently sloping hillside that had relatively shallow depth (< 4.9 m) to water prior to the initiation of burial operations. Investigations after installation of the seal indicated the presence of water in a number of waste trenches. Analysis of filtered waters collected from some of these wells (to be discussed later in this report) revealed the presence of several radionuclides of interest. Thus, the 49-trench section was selected for these investigations because of the more representative terrain, the observed shallow depth to water, and the radionuclides present in the trench waters.

Fig. 2. General topography of SWDA 6 and location of three near-surface bentonite sealed sections.

The 49-trench bentonite-seal section covers an area of approximately 5,000 m². The major runoff occurs along a few gullies toward the south-southwest direction. The difference between the topographic features of the study area and its immediate vicinity in 1978 (Fig. 2) and those reported in 1965 prior to use of the site suggest that leveling of small hillocks and general grading operations have considerably modified the elevation contours (Lomenick and Wyrick 1965). Of particular significance is the filling of a natural topographic draw which covered a major portion of the southern-half of the sealed area (described later in this report).

Prior to development for disposal operations, SWDA 6 was typical of the ecological systems which occur in the Appalachian region of the eastern United States. The study area was heavily wooded, and the forest vegetation included conifers and hardwoods.

The study area was used for waste disposal during 1973-74. To prepare for disposal, the site was cleared of vegetation, and some grading of the surface was performed as mentioned earlier. Waste inventory records for some of the trenches in the area indicate that materials buried in these trenches included building rubble and laboratory trash, as well as large contaminated machinery.

Presence of water in trenches prior to installation of the bentonite seal was indicated by measurements in trench 129 (D. A. Webster, personal communication, 1979). Water level fluctuated over a range of 0.3 m from March 18, 1976 to August 4, 1976. The water level dropped below the bottom of the well (water table < 242.1 m above mean sea level) on August 23, 1976 and remained below that level until

November 1976 when the near-surface bentonite seal was installed. Monitoring was discontinued when the well casing was bent and filled with mud during the bentonite seal installation. Additional evidence of water in trenches in the area was provided by the collection of water samples (for radionuclide analysis) from several trenches in June 1976 (Tamura et al. 1980).

3. NEAR-SURFACE SEALING

The application of the near-surface seal to the study area was completed in two general stages. The first stage involved development of design criteria for the seal, based on laboratory analyses and recommendations by the American Colloid Company of Skokie, Illinois. The optimal bentonite-shale composition of the seal material and the optimal moisture content to insure maximum compacted density were studied in the laboratory (Tamura et al. 1980). The result was a design composition of 5% bentonite by weight, compacted at 20% moisture content. This was expected to result in a seal density in the range 1522-1889 kg/m³. The expected average hydraulic conductivity for such a seal is $2.41 \pm 0.33 \times 10^{-8}$ cm/s (n=3).

The second stage of the sealing process was the actual installation. A bentonite-Conasauga shale seal (approximately 7.5 cm thick) was installed and covered to a depth of 60 cm in the 49-trench section in SWDA 6 in October/November 1976. All the trenches except T207 and T156 (Fig. 3) were completely covered by the seal. The initial step in seal installation was to strip and stockpile 0.6 m of topsoil and overburden from the site. Granular grade Volclay Saline Seal 100 (American Colloid Company) was spread over the area at an application rate of 19.5 kg/m² (4 lb/ft²) and was blended into the top 7.5 cm of exposed soil with a disc harrow to attain a 5% bentonite-shale mixture. After discing and adding water to achieve a moisture content of approximately 20% (determined gravimetrically at several locations in the area), the material was compacted. Hand

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Fig. 3. Trench alignment and location of presently existing monitoring wells in the 49-trench bentonite seal section in SWDA 6.

application was employed for sealing around the trench observation wells to ensure a continuous seal. The top soil and overburden were then replaced. The burial ground was covered with grass in order to permit some evapo-transpiration and to reduce soil erosion. The grass is periodically mowed as part of routine maintenance.

4. DESCRIPTION OF MONITORING WELLS, FIELD OBSERVATIONS, AND COMPUTER SIMULATIONS

4.1 Monitoring Wells

Prior to waste disposal, perforated well casings were usually placed in the low end of trenches to facilitate the monitoring of fluids after the trench was filled with waste. These original wells in several of the 49 trenches were filled with mud, destroyed, or damaged and thus were not suitable for monitoring purposes. A new set of 40-PVC pipe-cased wells were augered during August-September 1978, and the older perforated corrugated pipe wells were removed or plugged with concrete in all but three (T156, T177, and T207) of the trenches. Trench monitoring wells in the remaining six trenches located in the southern segment of the study area (T145, T147, T150, T163, T173, and T183) were installed in September 1979. The depth of waste trenches varies from 4.0 to 4.6 m in the area. However, metallic objects were encountered during augering in several trenches and consequently their well depths vary from 3.0 to 5.5 m.

One monitoring well (W317), which was augered prior to the initiation of burial operations (Lomenick and Wyrick 1965), is still intact in the vicinity of these trenches. A limited number of shallow (5.65 to 8.93 m deep) monitoring wells were also augered in undisturbed areas adjacent to waste trenches (Fig. 3).

4.2 Field Description of Augered Material

A brief field description of geologic material was made during the augering of 12 wells in the undisturbed zone adjacent to waste trenches. A continuous zone of highly saturated material of variable thickness

(perhaps 0.3 to 0.7 m) was observed at approximately 236 m above mean sea level (msl) in the area. As expected, folds and fractures which are commonly found in the area could not be delineated in the augered material. Based on extensive spatial variability in the geologic strata, the study area was roughly divided into two halves. The upslope northern half was characterized by partially saturated moist zones (10-50 cm thick) from surface downward followed by relatively thick (50-200 cm), dry, slightly weathered, impermeable strata. In comparison, the downslope southern half exhibited relatively diffuse soil horizons and softer material to greater depths. The residual material was darker in color due to the presence of organic matter and was much easier to auger. Some of the wells (W402, W399) appeared to extend their full length in fill material.

4.3 Pumping Tests

Pumping tests were conducted in two trenches (T135 and T207) to provide information for estimating the average net moisture storage capacity^b of trench materials and to characterize the rate of recovery of groundwater following the tests. Trench 207 is small (approximately 8 m long and 2.5 m wide) compared to other trenches and is at least partially outside the seal area. Trench 135 is more representative of other trenches in size (approximately 17 m long and 3 m wide) and lies under the central region of the sealed area.

The wells were continuously pumped, except for mechanical failures or after-work hours, at a rate of approximately 30 l/min with a

^bThe moisture storage capacity refers to the volume of water that can be stored per unit volume of soil and may refer to either saturated or unsaturated conditions.

centrifugal pump. Fluids were collected in a holding tank, and the total volume withdrawn was estimated visually as a fraction of the total known capacity of the tank.

Figure 4 shows water-table elevations in the trenches over a three-month period that includes the pumping tests. Approximately 3,500 l and 11,000 l of fluids could be pumped from trenches 207 and 135, respectively. The error on both volume estimates is estimated at approximately $\pm 15\%$. The water table fell 76 and 85 cm in trenches 207 and 135, respectively, as measured at the observation wells in the trenches, during pumping. Since no observation wells other than the ones being pumped were present in the two trenches, it was impossible to determine the water-table profile in the trenches during the test. However, a crude estimate of the range of moisture storage capacity within the trench can be derived from assumptions about the water-table configuration at the start and finish of the pump test, and the amount of fluids entering the trench from the surrounding formation.

The simplest assumption concerning water-table configuration during the pumping tests is that it remained essentially horizontal over the length of each trench throughout the tests. This assumption is undoubtedly invalid, but it does provide a lower limit to estimate moisture storage capacity. The area of trench 135 is 51 m^2 . For a uniform drop of 85 cm in the water table (corresponding to 11,000 volume withdrawn), the computed moisture storage capacity (m^3/m^3) or coefficient of storage^c would be about 0.25. If, on the other

^bThe coefficient of storage is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Fig. 4. Hydrographs of two pumped out wells in solid waste trenches in SWDA 6 and their recovery.

hand, one assumes a conical water-table profile, where the maximum measured drawdown occurs at the well casing, it is possible that the volume de-watered would be as little as one half that for uniform and horizontal drawdown. Under the latter assumption, the coefficient of storage would be about 0.50.

In the above estimates, it is assumed that all water withdrawn by pumping comes only from the trench, and none from the surrounding formation. Based upon preliminary data derived from infiltration experiments on Conasuaga shale sub-horizons (R. J. Luxmoore and B. P. Spalding, personal communication, 1980), saturated hydraulic conductivity is approximately 2 cm/day. For a horizontal surface area of about 30 m² and an assumed hydraulic gradient of 0.25, inflow during a two-day period would yield only about 320ℓ. Thus, the inflow of water from the surrounding formation is probably negligible, even if there are considerable errors in the assumed values. Similar computations yield an estimated range in coefficient of storage of 0.23 to 0.46 for trench 207.

The foregoing discussion indicates significant uncertainty in the fractional moisture retention value for trench material. It is inappropriate to depend heavily upon such an estimate, but it would also be senseless to ignore the information in assessments of bentonite-seal behavior. For our purpose, we have selected a value of 0.25 to represent the coefficient of storage, with the recognition that this is a lower-limit value.

4.4 Water-table Monitoring

Regular monitoring of the depth to water in wells both within and outside of trenches was initiated in April 1978. Measurements were made periodically at 2- to 4-week intervals. The data were employed to delineate spatial and temporal variability in water-table elevations. A computer program was used to plot water-table contours in the area. The program was designed to compute isopleth water-level contours at 91 cm (3 ft.) intervals as a function of trench-well elevation and the water-table elevation on a given date. Water samples also were collected from these monitoring wells for radionuclide analysis.

4.5 Hydrologic Simulations

Earlier work (Ward et al. 1979) has shown the value of using simulation models to explore possible hydrologic consequences of development of a shallow land disposal area. In particular, vegetation removal and installation of a near-surface seal led to increased runoff and a dramatic change in the proportions of surface and subsurface runoff compared to a forested site. As a basis for making quantitative estimates concerning runoff and groundwater recharge in and near the seal area, the Terrestrial Ecosystem Hydrology Model, TEHM (Huff et al. 1977), has been used.

The area under consideration was subdivided into non-sealed and sealed areas for simulation studies. Both subareas were considered to have a grass vegetation cover, with a leaf area index ranging between 0.001 and 3.20 from winter to summer. Soil properties were derived from published results for Litz Series soils (Longwell et al. 1963).

The Litz Series soils are common in upland benches in Melton Valley in the White Oak Creek drainage basin (McMaster and Waller 1965). The saturated hydraulic conductivity used for the bentonite seal was 2.4×10^{-8} cm/s. Precipitation data were taken from nearby Walker Branch Watershed, and climatic variables were measured at Oak Ridge, Tennessee. The period including the greatest (October 30, 1978) and the least (February 15, 1979) mean depths to water during monitoring was selected for determining the extent of water entry into the trenches. The simulations covered the period May 1978 through March 1979. This allowed a six-month "warm-up" period for the effects from estimated initial conditions to be minimized.

5. RESULTS AND DISCUSSION

5.1 Water-table Elevation and Seasonal Fluctuations

Water-table elevations in trench wells represent the standing-water depth of free fluid in the waste trench. Hydrographs (apparent water-level elevation with time) of three representative trench observation wells (T156, T177, and T207) located within the study area and that of a monitoring well (W317) located in the vicinity, over a period from April 1978 to June 1979, are presented in Fig. 5. Precipitation events for the corresponding period (D. A. Webster, personal communication, 1979), recorded in the vicinity of the study area, are also shown. The winter rise and summer fall in the water-table elevation appears to follow a consistent pattern for most trenches in the study area.

Actual water-table fluctuations in many waste trenches likely exceeded the observed values for two reasons. First, the depth of several well casings was less than the total depth of waste trenches which made it impossible to measure the depth to water during the dry summer months. Second, water-table fluctuations were only periodically monitored and the contributions of several major precipitation events (> 2 cm per day) recorded during the monitoring period may have been neglected when readings were taken.

A direct comparison of present water-table elevation data with earlier measurements reported by Lomenick and Wyrick (1965) is not strictly valid because of topographic modifications during grading, vegetation changes, and different climatic conditions preceding

Fig. 5. Hydrographs of three solid waste trench wells (T156, T177, and T207) and that of a nearby monitoring well (W317) in SWDA 6 and precipitation events for the corresponding period.

measurements. A maximum groundwater table elevation of approximately 238.5 m was reported on April 22, 1966 in earlier studies for monitoring well 317, while our recorded elevations were 238.7 m and 238.9 m on April 14, 1978 and April 28, 1979, respectfully. However, a maximum water-table elevation of 239.9 m was recorded on December 16, 1978 in our studies. It may be noted that the land surface elevation at well 317 was approximately 241.9 m above msl in 1965 and is presently estimated at 241.4 m (792.0 ft.) above msl which would suggest a lowering of the water table at this time. The data reported by Lomenick and Wyrick (1965) were obtained prior to land perturbation and represented the maximum water-table elevation recorded during the period October 1964 to July 1965. These data for a single well may be indicative of the extent of seasonal variations in depth to water in the area. However, if the observed 1.4-m rise in maximum water-level elevation that occurred between 1966 and 1978 is representative, the data suggest an overall rise in the maximum water table. Additional evidence of generally higher water levels (water-level elevations of 239.7, 239.4, and 239.5 m respectively in January 1975, December 1975, and December 1976) in well 317 (D. A. Webster, personal communication, 1979) also supports the premise. However, these data are insufficient to allow determination of the effect of the seal on water table elevations. The rise may have resulted from waste disposal operations, changes in vegetation, or a long-term change in precipitation and evapotranspiration.

5.2 Groundwater Level Contours and Flow Patterns

Generalized groundwater flow patterns in an area may be inferred from potentiometric contour maps. Smoothed contours based on water-table measurements on December 7, 1979 are shown in Fig. 6. The figure shows the monitoring wells in trenches (open triangles) and outside the trenches in the downslope half of the study area (filled-in triangles) that were used to derive the contours. Existing water levels in portions of the study area may be lower than shown because water-level elevations in some of the trenches were below the bottom of the observation wells. The water-level depth in a trench well with no observed standing water is assumed equivalent to the depth of the observation well.

Water-table contours generated from the data obtained in waste trenches were subsurface expressions of the present land surface except for an area in the Southwest corner. The depths to water observed on December 7, 1979 were > 3.6 m in the northern upslope segment and decreasing lower values gradually to < 2 m in parts of the downslope half. Since a correspondence in depths to water is lacking between wells within and outside of trenches in the upslope half of the study area, these data indicate that perched water-tables have developed in the area and a state of quasi-equilibrium exists in depths to water in waste trenches. This is in contrast to the water-tables in the downslope southern half of the area which reflect a general correspondence between the two measurements.

Groundwater flow patterns inferred from water-table contours (the direction of flow is normal to contour lines) indicate that major

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Fig. 6. Smoothed water-table contours generated in the computational process. Wells located in the undisturbed zone in the northern half of the area were excluded.

drainage is probably in a south-southwesterly direction. The surface contours of the area prior to the initiation of burial operations (dotted contours in Fig. 7) reveal topographic draws covering a significant portion of the downslope southern half. Recent contours (solid lines in Fig. 7) indicate that the natural draw in this area was backfilled. Backfilling of the topographic draws may explain the occurrence of a contaminated seep observed by Cerling and Spalding (1980) in the nearby tributary consistent with the previous contour and present potentiometric contour (Fig. 6). Additional data on the nature of the seep is being collected by augering additional wells for intercepting the groundwater flow contributing to the seep.

5.3 Changes in Groundwater Storage

The change in groundwater storage within a given area is determined by net infiltration (infiltration less evapotranspiration losses), and net migration of groundwater into the area. The magnitude of the storage change for a given time interval can be approximated from a knowledge of water-table fluctuation and soil properties such as porosity and field capacity. During the period from October 30, 1978 to February 15, 1979 (the greatest and the least depths to water observed during monitoring), the water table associated with trenches rose by an average of 131 ± 56 cm over the study area (Table 1). Trenches in the upslope northern segment of the seal area showed a smaller average change of water-table elevation than those located in the downslope southern segment (94 ± 48 vs 178 ± 52 cm, respectively). Based upon the estimated available fractional storage capacity of 25% in the trenches (from pump tests discussed earlier), and a total trench

Fig. 7. Current surface contours (solid lines) of the 49-trench bentonite seal section of SWDA 6 and surface contours (dotted lines) prior to the initiation of burial operations indicating the backfilling of a natural depression in the southwest corner of the study area.

Table 1. Mean water-table fluctuations in waste trenches in four segments (Fig. 3) of the 49-trench bentonite seal section in SWDA 6

Segment	Number of wells	Water-table fluctuation ^a (cm)
Northern	11	94 ± 48
North Central	11	99 ± 49
South Central	13	149 ± 34
Southern	9 ^b	<u>178 ± 52</u>
Overall mean		131 ± 56

^aDepth to water table observed on 2/15/79 minus depth to water table observed on 10/30/78.

^bData for six trench monitoring wells installed in September 1979 not included.

area of about $3,000 \text{ m}^2$, the observed water-table rise in the trenches corresponded to a total change in storage volume of about $1,000 \text{ m}^3$ over the 108-day period (Table 2). This would correspond to a recharge of about 200 mm of water over the entire study area. Total precipitation during this period was 504 mm, thus change in storage is approximately 40% of precipitation.

The net inflow of water in the sealed area is the sum of vertical recharge (from infiltration due to local precipitation and surface runoff from surrounding upslope areas) and lateral recharge (groundwater intrusion) less groundwater outflow. Although the present data are insufficient to delineate the contribution of vertical and lateral recharge toward groundwater storage, a number of subjective observations and simulation studies (described below) indicate that a significant part of additional groundwater storage was associated with groundwater intrusion from the surrounding upslope area.

5.3.1. Vertical recharge: Multiple modes of vertical recharge may be responsible for the entry of water into waste trenches in the sealed area. Rainwater may contact the waste from direct infiltration through an ineffective seal (resulting from inadequate bentonite application rates) or through mechanical imperfections (resulting from poor quality control during installation) in the seal. Even though the seal may be largely effective, the water impounded by the seal may eventually find its way into the trench because of increased retention time caused by subsidence within trenches and/or the failure of the seal design to drain the excess water out of the area.

Table 2. Estimated change in groundwater storage volume in 49-trench bentonite seal section in SWDA 6 for the period October 30, 1978 to February 15, 1979

Approximate land area covered by trenches	3000 m ²
Approximate intertrench undisturbed land area	2000 m ²
Approximate area of the study plot	5000 m ²
Mean water-table fluctuation observed from October 30, 1978 to February 15, 1979	131 cm
Increase in water volume per unit trench area (based on coefficient of storage value of 0.25 as deduced from pump tests, 131 x 0.25)	33 cm
Approximate increased volume of groundwater stored in waste trenches	1000 m ³

Older well casings installed for monitoring fluids in trenches were perforated to their entire length and may have acted as funnels for the impounded water to enter the trench. An unsatisfactory plugging of these older well casings after the installation of new PVC casings has also been observed for some wells. One hole in the seal where an old well-casing was removed was observed to allow direct entry of surface runoff into a trench below the seal. The hole was plugged January 4, 1980; but if one assumes that the opening was present during the study period, it could have allowed an entry of about 100 m^3 of water below the seal. This estimate assumes a contributing area of about 250 m^2 and a surface runoff above the seal of about 35 cm, as derived from TEHM simulations. A number of observations in present studies suggest that the seal was at least partially effective in impeding drainage, although the available monitoring facilities were inadequate to allow direct estimates of the effective rate and amount of drainage (degree of imperviousness) through the seal. This interpretation is based in part on an absence of free water in some of the trenches in the northern segment of the study area (e.g., T30 and T31) throughout the monitoring span. From previous laboratory studies, it is considered unlikely that the bentonite seal should be entirely ineffective in reducing infiltration. The relatively slow recovery from pumping in trench 135 compared with that of trench 207 which is partly outside the sealed area also suggests the effectiveness of the seal. Subjective field observations during augering of wells showed an accumulation of soil moisture above the seal and revealed that surface runoff was higher from the seal area than surrounding areas, also suggesting that the seal was at least partially effective.

Results from TEHM simulation studies (Huff et al. 1977) show that an unsealed area would have an input to groundwater of about 24.8 cm, or 1,240 m³ during the period from October 30, 1978 to February 15, 1979 (Table 3). If the seal operated as designed with a saturated hydraulic conductivity of about 2.4×10^{-8} cm/s, 0.2 cm or 10 m³ of drainage would penetrate through the seal. Thus, net drainage could account for observed changes in groundwater storage in the trenches only if the seal were almost totally ineffective.

Further studies are planned to determine infiltration rates in the area for documenting the effectiveness of the seal.

5.3.2. Lateral recharge: Another possible explanation for net accumulation of groundwater under the seal is lateral migration from a recharge area that is upgradient. An examination of topography in the vicinity of the seal shows that the recharge area is approximately 0.6 ha (Fig. 2; shaded area), assuming that groundwater divides are coincident with topographic divides. Accumulation of soil moisture after removal of native forest woodland or scrub has been shown by observations reported in several countries (Peck 1978). Increased water consumption by forests in comparison with grasslands under the same conditions was primarily attributed to deeper rooting depths. Because the native vegetation has been cleared in areas of higher elevation above the sealed section, the expected increased soil moisture may be accumulating in the shallow weathered zone of the Conasauga shale followed by a lateral flow of groundwater toward the sealed area. Simulated drainage to groundwater (24.8 cm) suggests that about

Table 3. Results of hydrologic simulation studies for grassed areas with and without a near-surface bentonite seal, October 30, 1978 to February 15, 1979, inclusive

Variable	Area	
	With seal mm	Without seal mm
Precipitation	503.9	503.9
Evapotranspiration	29.7	31.9
Storm runoff	472.1	224.4
Groundwater recharge	2.1	247.6

1,490 m³ of water percolated to the groundwater system in the recharge area. Assuming a coefficient of storage by volume of 0.10 (the difference between saturation and field capacity) for the Conasauga shale and a rise in the water-table elevation ranging between 100 and 180 cm in the recharge area, between 890 and 410 m³ of excess water could have migrated laterally into the seal area. As discussed in an earlier section, water appears to collect in the trenches as a perched saturated zone. If we assume that all lateral migration is intercepted and stored by trenches, the net migration into the area could be of the order of 400 to 900 m³. Since this is somewhat less than the estimated change in storage beneath the seal, lateral migration should not be considered as the only source of groundwater flow to the trenches. This analysis strongly suggests that both lateral migration and vertical drainage contribute to groundwater movement beneath the seal.

5.4 Synthesis and Suggested Improvements

The foregoing analysis indicates that the bentonite seal in the study area was not successful in preventing water from entering the trenches under it and that the prime objective of hydrologic isolation of buried waste by the installation of a near-surface bentonite seal was not achieved.

Based on a presumed trench depth of 4 to 4.6 m from the land surface, trench water-level data further establish that a significant volume of groundwater contacts the waste, and radionuclides are transported from the trenches. Radionuclide distribution in water samples obtained from trench observation wells in June 1978 indicates a

random pattern in regard to type and concentration (Table 4). The ratio of the velocity of the radionuclides in the leachate relative to the groundwater velocity (the retardation factor, K_f), in a formation, is determined by the sorptive properties of the soil. The estimated volume of additional groundwater storage (1,000 m³/yr, Table 2) may significantly contribute to the radionuclide load of the nearby tributary for a number of years. However, the relative importance of the area as a source of radionuclide input to the tributary will continue to rise as the sorptive capacity of the soil dwindles with continuous leaching of radionuclides.

Although infiltration of precipitation is considered the major contributor to changes in groundwater storage, multiple modes described earlier may be responsible for the entry of water into waste trenches in a sealed area. Lateral migration of groundwater appears to be the most important factor in explaining the changes in groundwater storage in the trenches in the study area.

The investigations described here were designed as an exploratory study of the effect of a bentonite seal on groundwater movement and storage. These results suggest that the seal though not totally effective was at least partially effective, as evidenced by the absence of water in trenches 30 and 31 in the upslope northern section of the study area. However, effective controls and monitoring are necessary to establish the degree of effectiveness of the seal. The following measures are suggested for a comprehensive evaluation of future near-surface bentonite seals:

Table 4. Radionuclide analyses of filtered water collected from solid waste trenches and two nearby monitoring wells in the 49-trench bentonite seal section of SWDA 6

Trench number	Gross a (cpm/ml)	⁹⁰ Sr		⁶⁰ Co (dpm/ml)	¹³⁷ Cs (dpm/ml)
		1978 (dpm/ml)	1976 (dpm/ml)		
36	≤0.5	1.1 ± 0.1	--	0.10 ± 0.02	0.19 ± 0.04
42	≤0.5	5.4 ± 0.2	8.04	0.047 ± 0.009	0.08 ± 0.02
127	≤0.06	2.5 ± 0.2	2.97	≤ 0.03	0.05 ± 0.01
133	≤0.07	12 ± 1	--	51.8	0.5 ± 0.1
135	≤0.5	27 ± 2	38.6	0.015 ± 0.007	0.23 ± 0.02
137	≤1	(5.35 ± 0.03) × 10 ²	1.7 × 10 ³	0.028 ± 0.009	0.33 ± 0.06
141	≤1	8.1 ± 0.3	--	0.56 ± 0.03	0.041 ± 0.009
145	≤2	60 ± 1	1.14 × 10 ²	0.91 ± 0.03	5.9 ± 0.8
147	≤1	11.6 ± 0.4	--	≤ 0.02	0.9 ± 0.3
150	≤1	(8.57 ± 0.14) × 10 ²	2.95 × 10 ³	0.31 ± 0.02	28 ± 4
156	≤0.3	0.25 ± 0.06	9.76	≤ 0.04	≤ 0.07
160	≤0.5	2.5 ± 0.2	--	≤ 0.03	≤ 0.02
166	≤0.8	(6.23 ± 0.01) × 10 ²	--	≤ 0.05	0.5 ± 0.2
168	≤0.8	5.9 ± 0.2	--	≤ 0.02	≤ 0.2
173	≤0.8	(5.07 ± 0.12) × 10 ³	1.96 × 10 ³	0.06 ± 0.02	2.6 ± 0.4
183	≤0.3	33 ± 2	--	0.022 ± 0.007	≤ 0.05
187	≤0.4	36 ± 2	--	≤ 0.34	0.22 ± 0.09
191	≤0.2	230 ± 9	--	0.08 ± 0.02	19.0 ± 0.3
205	≤2	9.2 ± 0.4	--	0.04 ± 0.01	≤ 0.09
207	≤1	0.19 ± 0.05	--	0.17 ± 0.07	≤ 0.04
W107	≤0.5	0.42 ± 0.07	--	≤ 0.06	≤ 0.06
W107	≤0.5	0.12 ± 0.04	4.30	≤ 0.02	≤ 0.2

(1) Availability or collection of daily groundwater fluctuation data prior to the installation of the seal with more frequent measurement of depth to water-table both within and outside the waste trenches. A representative segment of the study area should be left unsealed to serve as a control.

(2) Establish appropriate steps to eliminate the contribution of groundwater intrusion in the area and water entry from surrounding unsealed areas by appropriate drainage systems or groundwater interception barriers to lateral flow.

(3) An effective quality control during field installation of bentonite seals in order to minimize the possibility of mechanical imperfections. Design modifications are also necessary for draining excess water impounded by the seal.

(4) A sharply focused monitoring program for a comprehensive water budget evaluation of the study area with an accurate estimate of hydrologic parameters, i.e., field capacity of soil and waste, horizontal and vertical permeability, infiltration rate, surface runoff, stream flow measurements, and evapotranspiration.

6. SUMMARY AND CONCLUSIONS

The purpose of this investigation was to make an evaluation of the effect of a near-surface bentonite seal on groundwater storage in a solid waste disposal area (SWDA). These studies reveal that the prime objective of hydrologic isolation of buried waste was not achieved by the installation of the seal in a representative section of SWDA 6.

Periodic water-table measurements in the 49-trench sealed section in SWDA 6 indicated the presence of a water-table in a majority of the trenches throughout the year. Seasonal water-table fluctuations showed 94 ± 48 cm in the northern segment, 99 ± 49 cm in the north-central segment, 149 ± 34 cm in the south-central, and 178 ± 52 cm in the southern segment in waste trenches from the period October 30, 1978 to February 15, 1979. An average rise of 131 ± 56 cm for the whole area was estimated to indicate a gain in groundwater storage of about $1,000 \text{ m}^3$ during this time period.

The depths to water in trenches did not correspond to those in monitoring wells (augered during September 1979) in the undisturbed zone in the upslope half of the study area. This suggests the presence of perched water within the trenches and the possibility of lateral transfer through preferred paths (fracture zones) within the shale. The groundwater table contours essentially follow the topographic surface contours and reveal a major drainage from the area to the south-southwest - the direction of a backfilled topographic draw with a known seep. A significant part of the groundwater observed in the study area could be attributed to groundwater intrusion from the

surrounding upslope area. This conclusion is based on the reported hydrologic characteristics of the Oak Ridge area, laboratory studies in the development of bentonite application rates, and simulation studies using the TEHM computer code.

Since vertical soil water transport (resulting from mechanical imperfections during installation or inadequate bentonite application rates) may be responsible for the entry of water into the trenches below existing seals, a determination of in situ infiltration rates for bentonite seals should be completed before additional areas are sealed in the future. In addition, care should be taken to insure that groundwater recharge to a seal area from upslope is minimal.

7. REFERENCES

- Cerling, T. E., and B. P. Spalding. 1980. Areal distribution of ^{60}Co , ^{137}Cs , and ^{90}Sr in streambed gravels of White Oak Creek watershed, Oak Ridge, TN. ORNL/TM-7318. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Duguid, J. O. 1976. Annual progress report of burial ground studies at Oak Ridge National Laboratory: period ending September 30, 1975. ORNL-5141. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 56 pp.
- Elwood, J. W., and G. S. Henderson. 1975. Hydrologic and chemical budgets at Oak Ridge, Tennessee. pp. 31-51. IN A. D. Hasler (ed.), Coupling of Land and Water Systems. Ecological Series 10. Springer Verlag, New York.
- Huff, D. D., R. J. Luxmoore, J. B. Mankin, and C. L. Begovich. 1977. TEHM: A terrestrial ecosystem hydrology model. ORNL/NSF/EATC-27. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 152 pp.
- Lomenick, T. F., and H. J. Wyrick. 1965. Geohydrological evaluation of solid waste storage area 6. ORNL/TM-1327. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 17 pp.
- Longwell, T. J., W. L. Parks, and M. E. Springer. 1963. Moisture characteristics of representative Tennessee Soils. Bulletin 367, University of Tennessee. 46 pp.
- McMaster, W. M. 1967. Hydrologic data for the Oak Ridge area, Tennessee. U.S. Geological Survey Water-Supply paper 1839-N. 60 pp.

- McMaster, W. M., and H. D. Waller. 1965. Geology and soils of White Oak Creek basin, Tennessee. ORNL/TM-1108. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 35 pp.
- Oak Ridge Atmospheric Turbulence and Diffusion Laboratory. 1972. Daily, monthly, and annual climatological data for Oak Ridge, Tennessee, townsite and area stations, January 1959 through December 1971. NOAA Report ATDL-61.
- Peck, A. J. 1978. Salinization of non-irrigated soils and associated streams: A review. Aust. J. Soil Res. 16:157-168.
- Tamura, T., L. D. Eyman, A. M. Stueber, and D. S. Ward. 1980. Progress report of disposal area studies at Oak Ridge National Laboratory: Period of October 1, 1975 to September 30, 1977. ORNL-5514. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 92 pp.
- Stueber, A. M., D. E. Edgar, A. F. McFadden, and T. G. Scott. 1978. Preliminary investigation of ^{90}Sr in White Oak Creek between monitoring stations 2 and 3. ORNL/TM-6510. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 78 pp.
- Ward, D. S., D. D. Huff, and L. D. Eyman. 1979. The role of mathematical modeling in low-level radioactive waste management. pp. 213-228. IN M. E. Mitchell (Compiler), Compilation of the papers presented at the 1979 UCC-ND Waste Management Seminar, March 6, 1979. Report No. K/C-1347, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee. 404 pp.
- Webster, D. A. 1976. A review of hydrologic and geologic conditions related to the radioactive solid-waste burial grounds at Oak Ridge National Laboratory, Tennessee. U.S. Geological Survey Open-File Report 76-727.

8. APPENDIX

INITIAL COST ESTIMATES FOR PLACEMENT OF A BENTONITE SEAL
IN SOLID WASTE DISPOSAL AREA 4 (9.3 ha) at ORNL^a

Materials

Bentonite - Volclay (1.8 x 10 ⁶ kg)	\$ 391,200
Grass seed (9.3 ha)	13,800
Jute mat to minimize erosion (9.3 ha)	51,750
Covers over monitoring wells (15)	350
Replace asphalt ditches	3,300
Miscellaneous expenses	<u>46,600</u>
	\$ 507,000

Labor and equipment

Bentonite loading and unloading	\$ 88,070
Excavation of 0.6 m cover and backfilling	300,000
Hydroseeding	17,250
Jute matting	6,260
Hand compaction around monitoring wells	200
Soil to replace accidentally contaminated debris	16,000
Cover over monitoring wells	310
Removal and disposal of accidentally contaminated debris	20,810
Removal and replacement of surface drainage ditches	17,430
Miscellaneous overhead	186,570
Health physics monitoring	<u>65,100</u>
	\$ 718,000

Other costs

Indirect cost (35% of materials and labor)	\$ 429,000
Engineering (15% of material, labor, and indirect cost)	248,000
Contingency (25% of material, labor, indirect cost, and engineering)	<u>476,000</u>

Total project cost, FY-78 dollars \$2,378,000^b

^aORNL Engineering Division.

^bEquivalent to \$25.50/m².

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