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A Hydrologic Modeling Study of Water Balance Relationships at the Area P Landfill in Los Alamos, New Mexico

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A HYDROLOGIC MODELING STUDY OF WATER BALANCE RELATIONSHIPS AT THE AREA P LANDFILL IN LOS ALAMOS, NEW MEXICO

by

John W. Nyhan

ABSTRACT

The water balance relationships of the Area P landfill in Los Alamos were studied in a preliminary attempt to hydrologically characterize and successfully close this shallow land burial site. The current Resource Conservation and Recovery Act status of the site is discussed, and plans to reach site closure are presented along with the waste use history and description of the site. The precipitation and temperature at the Area P landfill are evaluated and soil volumetric water content data collected at the site are presented, along with calculations of water inventories in the backfill and underlying tuff. The results of hydrologic modeling studies are then presented for various scenarios at the landfill, for both those with and without a final closure cover. A final set of design recommendations is presented relative to improving the final approved closure plan for this landfill.

I. INTRODUCTION

Although shallow land burial (SLB) of wastes began with early civilizations, recently developed rules and regulations require the ability to model hydrologic processes on SLB systems used for the disposal of wastes, such as Waste Disposal Area P at Los Alamos. An important part of hydrologic models for SLB systems is the surface water balance. This balance is an accounting (or budgeting) of water from the soil through its entire profile to the plant rooting depth, an accounting that includes input, output, and storage terms. Precipitation is the input to the system, whereas outputs are net surface runoff, evaporation and transpiration losses, and net subsurface flow. The subsurface flow can be either lateral or vertical; the vertical downward flow below the root zone is often called deep seepage or percolation. Changes in soil water content account for gains in or losses of water stored in the soil profile (see Fig. 1).

Trench covers that isolate wastes at SLB facilities are subject to the interactive factors of a dynamic system, which includes water dynamics. Failure of the trench cap can cause excessive soil erosion, plant and animal intrusion into the waste, and percolation of infiltrated water into the waste ultimately allowing mobilization and transport of chemical wastes. Such failures emphasize the importance of water management at SLB facilities; these failures have been summarized by Nyhan (1989).

Migration barriers are used in SLB facilities to slow or stop the movement of water and contaminants, and are a single component embedded in a complex environmental system (Lane and Nyhan 1984). Migration barrier (moisture, or capillary, barrier) performance is very much a function of interactive processes operating to control water dynamics at SLB facilities. Traditional engineering solutions, which do not include analyses of these interactive factors, have already led to numerous SLB failures. Future designs that ignore the interactive factors controlling the performance of SLB facilities are likely to reproduce many of the failures of the past, including losing the integrity of migration barriers.

However, strictly speaking, with or without a migration barrier in the SLB profile, the current state of the art is that adequate data do not exist from carefully instrumented, large-scale field experiments on the movement of water and contaminants under unsaturated conditions to enable a site operator to define and

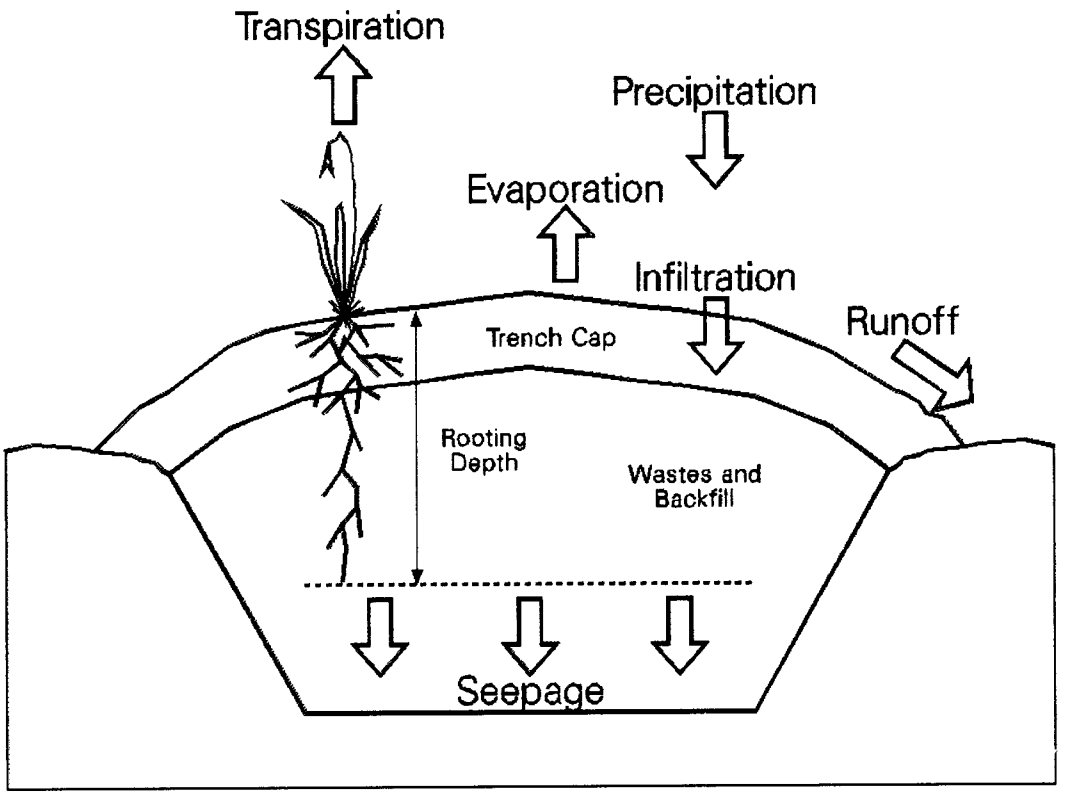

Fig. 1. Hydrology of SLB of waste materials.

engineer suitable barriers to prevent the migration of waste materials out of an SLB facility. Without these data, current modeling capabilities are inadequate for engineers to use to properly design and evaluate the long-term performance of migration barriers.

In spite of the latter observation, our approach has been to gather a limited amount of hydrologic field data and to calibrate a model at small field scale, making the assumption that we can eventually extrapolate to a field scale as large as Waste Disposal Area P. Using these field data, infiltration and percolation through the soil to the plant rooting depth are both the upper boundary and initial conditions for subsurface water flow and contaminant transport calculations. However, because water management can in fact vary the potential subsurface water flux by orders of magnitude, SLB designs should include analysis of surface and near-surface water dynamics to calculate a water balance and the upper boundary conditions for subsequent subsurface flow calculations. Thus, water balance relationships must be taken into account if SLB sites are to be hydrologically characterized and successfully closed out.

A. Performance Requirements for Closure of Burial Sites

Site-closure performance requirements are criteria set before closure of the facility, by which the acceptability of the site for closure is to be judged. Performance requirements may be written either in the form of prescriptive requirements or performance objectives. The prescriptive requirement demands specific technical design features. Use of prescriptive requirements permits more straightforward regulation of a greater number of sites. Performance objectives mandate a level of performance without stipulating how that performance should be attained. Use of performance objectives, such as maximum exposure to radioactivity at levels that are below measurable limits, requires significant technical substantiation by site

operators to show that closure designs will meet intended performance objectives. Performance objectives allow actions to be tailored to site-specific conditions, but do not preclude adoption of prescriptive requirements.

Because the Department of Energy (DOE) Order 5820.2 contains only general requirements for site closure, other pertinent regulations should be reviewed in the development of site-specific performance requirements, such as those published by the Nuclear Regulatory Commission (NRC), the Environmental Protection Agency (EPA), and the New Mexico Environmental Improvement Division (EID). Specific performance requirements found in present regulations 10 Code of Federal Regulations (CFR) 61 (US NRC 1982), 40 CFR 265 (US EPA 1980), and 50 CFR 191 (US EPA 1985) for closure of disposal sites containing low level wastes (LLW), transuranic (TRU) wastes or hazardous wastes are shown in Table I. Regulations for disposal of LLW and TRU are based both on site selection and design requirements stipulated under these requirements, and are based on a site containing only one waste type.

Obviously, it is the intent of the postclosure requirements (Table I) to limit the exposure of the general public to radioactive and hazardous wastes for time periods ranging from 30 to 10,000 yr. However, the hydrologic model used in the current study was developed using the results of about only 40 yr of field research. Clearly, we cannot wait 10,000 yr before using the water balance relationships in this model to evaluate SLB site designs—we need to make our best estimate based on the field data currently available at Los Alamos.

These same types of considerations also apply to the performance of moisture barriers (Pertusa 1980). Based on a study of liner materials used in various SLB configurations, liner service life (as a moisture barrier) and cost have been estimated (Fig. 2). Life expectancies for liners to be used to retain radioactive waste solutions were also estimated for some liner materials. Past experience indicates that synthetic liners, in general, have an expected life of around 25 yr. Although some research is under way in several DOE laboratories to determine the long-term effects of different chemicals and leachates on synthetic liners, these experiments have been in progress for less than 8 yr. This is far too short a time to provide data on long-term stability needed for disposal of wastes. Although synthetic liners may provide a short-term solution to containment of wastes, they do not at present provide a cost-effective containment even for the short run. The conclusion from this study and others is that moisture barriers constructed of clay and clay admixtures (Abeele 1984b, Abeele 1986a and 1986b, Abeele *et al.* 1986) offer the most inexpensive barrier for a given containment time of the waste.

B. Role of the Hydrologic Model Employing Water Balance Considerations

Water balance at an SLB facility, as conceptualized in Fig. 1, is a paradigm for interactive factors, especially surface and near-surface water balance dynamics, that control the performance of SLB facilities. If we restrict our attention to net rates and amounts and consider one-dimensional movement of water in the soil profile, then we have the following simplified water balance equation:

$$\frac{ds}{dt} = P - Q - ET - L \quad , \tag{1}$$

where

$\frac{ds}{dt}$ = time ratio of change in soil moisture,
P = precipitation,
Q = runoff,
ET = evapotranspiration,
L = seepage or percolation, and
t = time.

Applying this equation to the plant rooting depth within the closure cover at Waste Disposal Area P illustrates that the rate of change in soil moisture with time (ds/dt) is equal to the difference between input (P) and output (Q, ET, and L).

The CREAMS model (a Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems) was initially developed and intended for modeling field-scale agricultural systems

TABLE I. Postclosure Requirements for Disposal of LLW, TRU, and Hazardous Waste (US NRC 1982; US EPA 1980; US EPA 1985)

Statute	Sites Governed	Postclosure Performance Objectives
Doe Order 5820.2 Chapter III[a]	DOE low-level waste disposal sites.	– Annual dose limit of 500 mrem to any member of the general public; doses must be maintained at levels as low as reasonably achievable. (Operational limit only. No DOE-wide limits exist for closure.)
10 CFR 61[b]	Commerical sites for shallow-land disposal of low-level waste.	– Annual dose to any member of the general public not to exceed 25 mrem to whole body, 75 mrem to thyroid, 25 mrem to any other organ. – Protection of individuals from inadvertent intrusion. – Long-term stability of site (500 yr). – 100-yr maximum institutional control period. – Buffer zone.
40 CFR 191[c]	Sites developed for management and disposal of spent nuclear fuel, high-level and transuranic radioactive wastes.	– Long-term stability of site (10,000 yr). – Meet release limits for specific radionuclides (191.13). – Annual dose to any member of the general public not to exceed 25 mrems to whole body, 75 mrem to thyroid, 25 mrems to any other organ, for 1000 yrs after (undisturbed) disposal. – Meet specific ground water protection requirements for 1000 yr disposal (undisturbed).
40 CFR 265[d]	Hazardous waste facilities.	– Minimize need for further maintenance of hazardous waste constituents, leachate, contaiminated rainfall, or waste composition products to the ground or surface waters or the atmosphere.

[a]Radioactive waste management, management of low-level waste, currently replaced by DOE Order 5820.2A.
[b]Licensing requirements for land disposal of radioactive waste.
[c]Environmental standards for the management and disposal of spent nuclear fuel and high-level and transuranic radioactive wastes.
[d]Interim status standards for owners and operators of hazardous waste treatment, storage, and disposal facilities.

(Knisel 1980) using the water balance approach. The model has since been used in several areas of waste management research in semiarid climates, including erosion studies (Nyhan and Lane 1982), water balance and primary production of desert shrubs (Lane *et al.* 1984), and landfill cover design (Hakonson *et al.* 1982, Nyhan *et al.* 1984). CREAMS has been tested in a limited way with respect to percolation of water below a surface rooting zone, but not in any detail with respect to the effects of native plant cover on soil water storage.

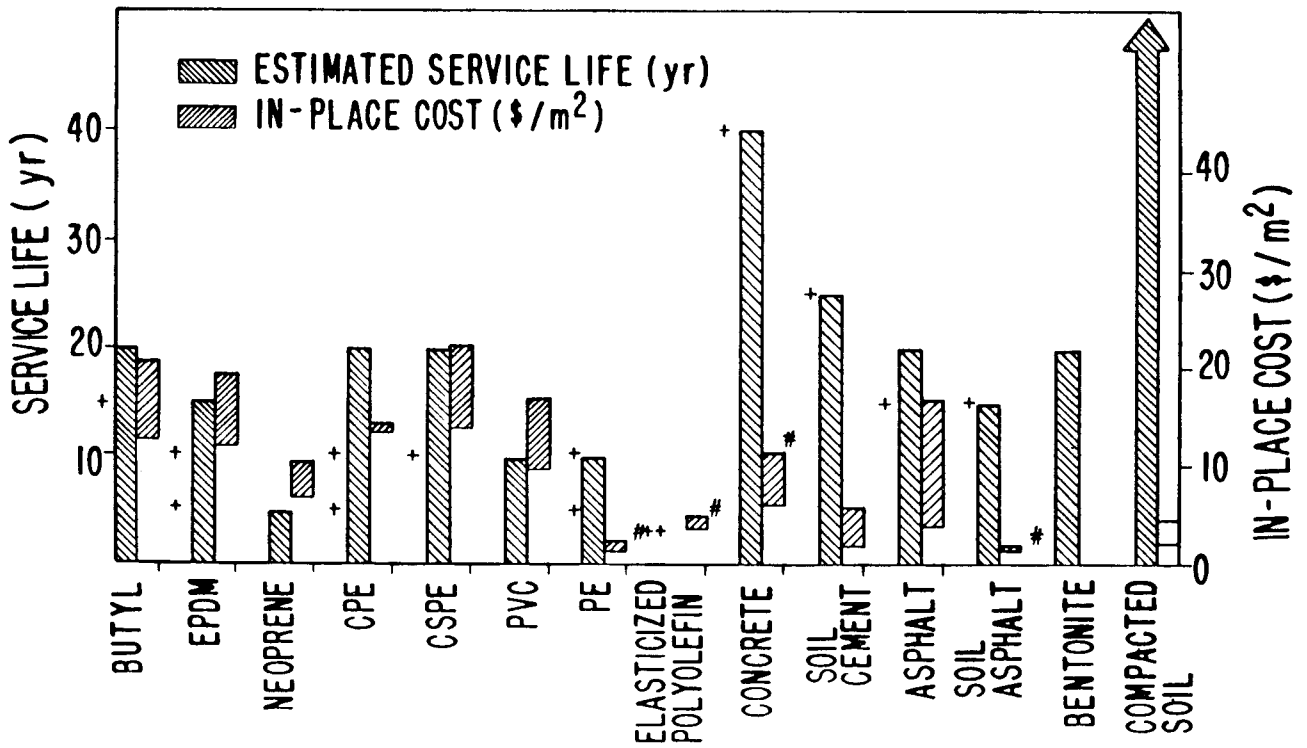

Fig. 2. Comparison of expected service life vs in-place cost (1976). Unless noted, service life estimate is for water-retaining structures. A + is the radwaste estimate; ++ means no estimate is available (because the liner was invented in 1975). Cost estimate includes excavation, installation, backfilling, compaction, and seeding (glacial till). A # means the cost does not include construction of subgrade or earth cover (Pertusa 1980).

In the present study, CREAMS was used in the daily rainfall/runoff mode to obtain a complete water budget (estimates of runoff, evapotranspiration, percolation, and soil water storage or water content in the soil column to the depth of the rooting zone) on each day that there was a precipitation event using the water balance equation. Monthly and annual water budgets are also obtained. The model is one-dimensional, calculating the process of vertical transport of water in the soil column using a seven-layer representation of the profile from the surface extending through the rooting zone of the vegetative cover. Initial responses to precipitation are calculated on a daily time-step using a modification of the Soil Conservation Service (SCS) curve number model (Knisel 1980).

C. Scope and Limitations of the Study

This report deals only with the hydrologic component of the CREAMS model and was applied only to the consideration of the upper, flat portions of Waste Disposal Area P. The erosion component of CREAMS is actually driven by the hydrologic component of CREAMS, and it could be used in the future to evaluate the site for soil erosion losses over time. However, our attention was limited to the daily rainfall/runoff model discussed earlier, which was only applied to a configuration we had field and modeling experience with, and not to the steep slopes at the northern edge of Area P.

The CREAMS model is a widely known and accepted model used in waste management. However, research scientists, users, and program administrators should not regard the CREAMS model as an absolutely accurate and final representation of hydrologic processes in the surface and near-surface areas of SLB facilities. Instead, the CREAMS model is one step in continuing efforts to understand and improve models of the water balance and associated technology for surface-water management.

With these limitations in mind, the Resource Conservation and Recovery Act (RCRA) status of the Area P landfill is first discussed, and two proposed prototype closure plans for the area are described. Several phases of the hydrologic modeling activities at Waste Disposal Area P are then presented, starting with a description of the waste use history of the site. An evaluation of the backfill moisture data previously collected at the site is presented, followed by an evaluation of the precipitation and air temperature input terms to be used in the modeling activities. The results of the hydrologic modeling studies are then presented for various scenarios with the Area P landfill as it exists today, with and without a final approved closure cover. A final set of design recommendations is presented relative to improving the final approved closure of this landfill.

II. CURRENT STATUS OF AREA P LANDFILL

Harold Valencia's (DOE) letter (2/3/88) to Mike Burkhart (EID) best sums up the current RCRA status of Waste Disposal Area P:

> The Department of Energy (DOE) did not choose to continue operation of the Technical Area (TA) 16 Area P landfill at Los Alamos National Laboratory (LANL) after November 8, 1985. Therefore, DOE did not apply for a Resource Conservation and Recovery Act (RCRA) permit at this site Consequently, DOE was required under the loss of interim status provisions (40 CFR 270.10) to submit a Closure and Post-Closure Plan for this landfill. Pursuant to the DOE Closure and Post-Closure Plan dated November 25, 1985, for the Area P landfill reflected interim status standards for such activities. DOE recognizes, however, that upon receiving a RCRA operating permit, Area P post-closure (and possibly closure) activities will be subject to permitting standards (*i.e.*, 40 CFR 264) rather than interim status standards (*i.e.*, 40 CFR 265).
>
> Under separate cover, the amendments are submitted with the intent that the Area P landfill fully comply with both standards. Equally important however, is the collection of a consistent and reliable water quality data base from which critical decisions concerning potential statistically significant changes in individual water quality parameters can be made. Thus, the proposed ground-water quality monitoring program for Area P has been modified to reflect sufficient flexibility so that DOE will comply with both 40 CFR 265 and 264 requirements, even though only a single regulatory standard will be in effect at any given time.

Currently, an approved final site closure plan for the Area P landfill does not exist. However, the water balance modeling presented later in this report was performed in support of a ground water waiver which the Laboratory is demonstrating for this landfill.

The first attempt at a closure plan for Waste Disposal Area P was submitted to the Laboratory in November 1985 (Delta H Engineering, Ltd. 1985). At that time the west (retired) portion and the east (active) portion of the landfill were proposed to be closed separately. Briefly, the only closure activity proposed for the west portion of the landfill was to leave the existing cover of vegetation on the surface, the reasoning being that this land area would pose less of a risk to human health and the environment. The closure proposed for the east portion of the landfill involved its stabilization with a thick concrete blanket installed on a reinforcing steel base set on a layer of gravel.

An approved final site-closure plan still did not exist for the Area P landfill in 1986, but another prototype plan is presented in Fig. 3 just to show an example of another closure plan considered by Laboratory personnel for this site. The cover consists of a 3-ft-thick soil layer underlain by subsequent layers of a geotextile, a high density polyethylene (HDPE) drainage net, and a 40-mil HDPE liner. All of these cover components are proposed to be emplaced over the current landfill at Los Alamos, after adding compacted soil layers to level out the preexisting land surface.

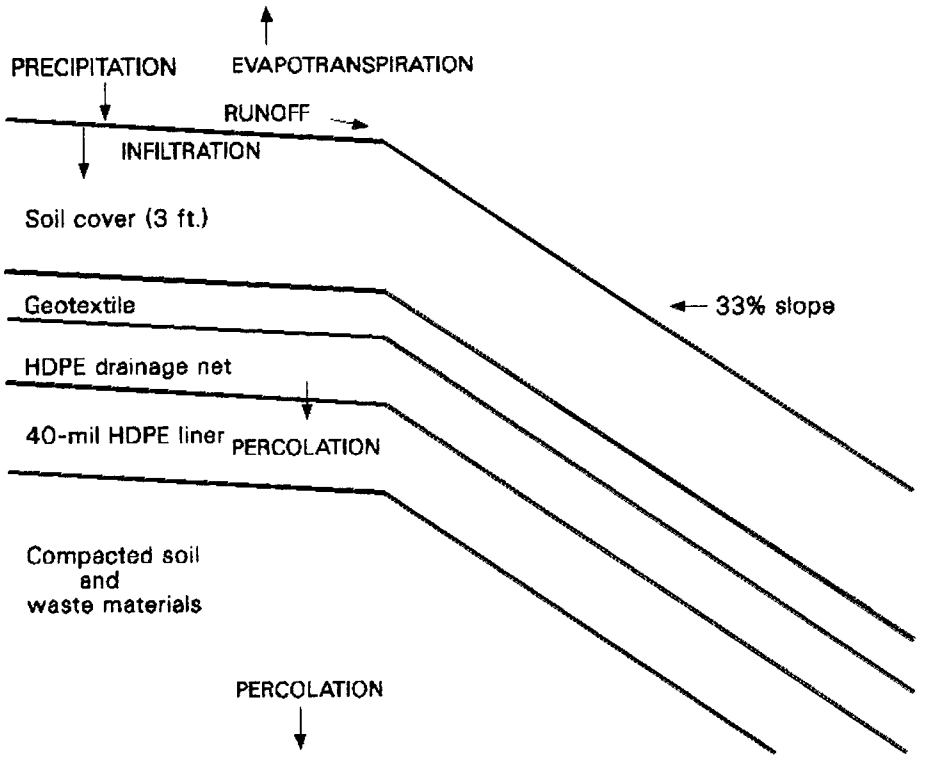

Fig. 3. One prototype closure plan for Waste Disposal Area P.

III. SITE DESCRIPTION AND WASTE USE HISTORY OF THE AREA P LANDFILL

Waste Disposal Area P (Figs. 4 and 5) is located in a saddle of a short, eastern-trending, narrow mesa. The saddle is near the south rim of Cañon de Valle, just north of the TA-16 thermal treatment area's pad number 387. Figure 6 shows the results of a recent land survey conducted to characterize Waste Disposal Area P compared with a prelandfill survey to determine the area influenced by the landfill (Delta H Engineering, Ltd. 1985). The general area impacted is a half-ellipse, roughly 170 ft (north/south) by 400 ft (east/west). Within this area are two areas of fill, one to the west and the second to the east. The estimated landfill volume is 13,000 yd^3. Landfilling progressed from west to east. The west portion was closed by leveling the landfill and covering the soil. The leveling overflowed the rim in the northwest quadrant of Waste Disposal Area P, as witnessed by the elevation changes determined by the survey. As shown in the cross sections, large quantities of the wastes are located on the steep canyon slope. The landfill depth at the rim is 12 to 14 ft, thinning both to the south and down the slope to the north. While there is a disturbance back to the 7450 ft elevation, much of the elevation change is only 1 ft and is probably the result of leveling the site, not of waste burial. The cross section indicates that deposition of wastes reaches only 30 to 40 ft back from the rim, and extends down the slope. Large items, such as blocks of foundation concrete and pieces of structural steel, did roll to the canyon floor. A few empty cans were also found on the canyon floor.

The west portion of the landfill has revegetated with grasses, wild rose, wormwood, and oak brush. There are occasional protrusions of concrete rubble, pipe, and steel, which aid in binding the mass. However, the east landfill area was the most recently active portion of the site. Fill has progressed from south to north with cover soil being spread as the fill advanced. Wastes on the north face are exposed.

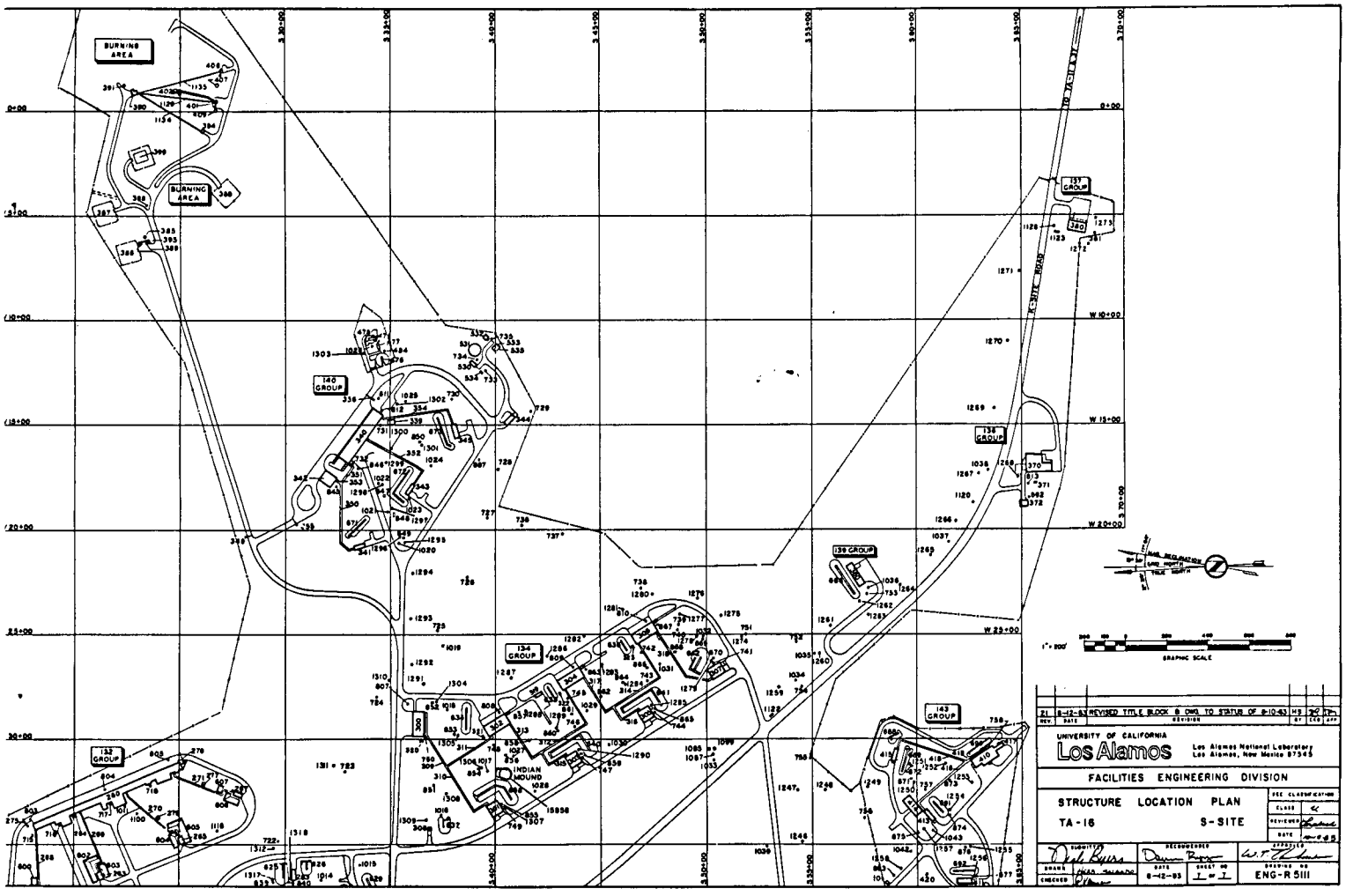

Fig. 4. Map of TA-16 showing burning areas.

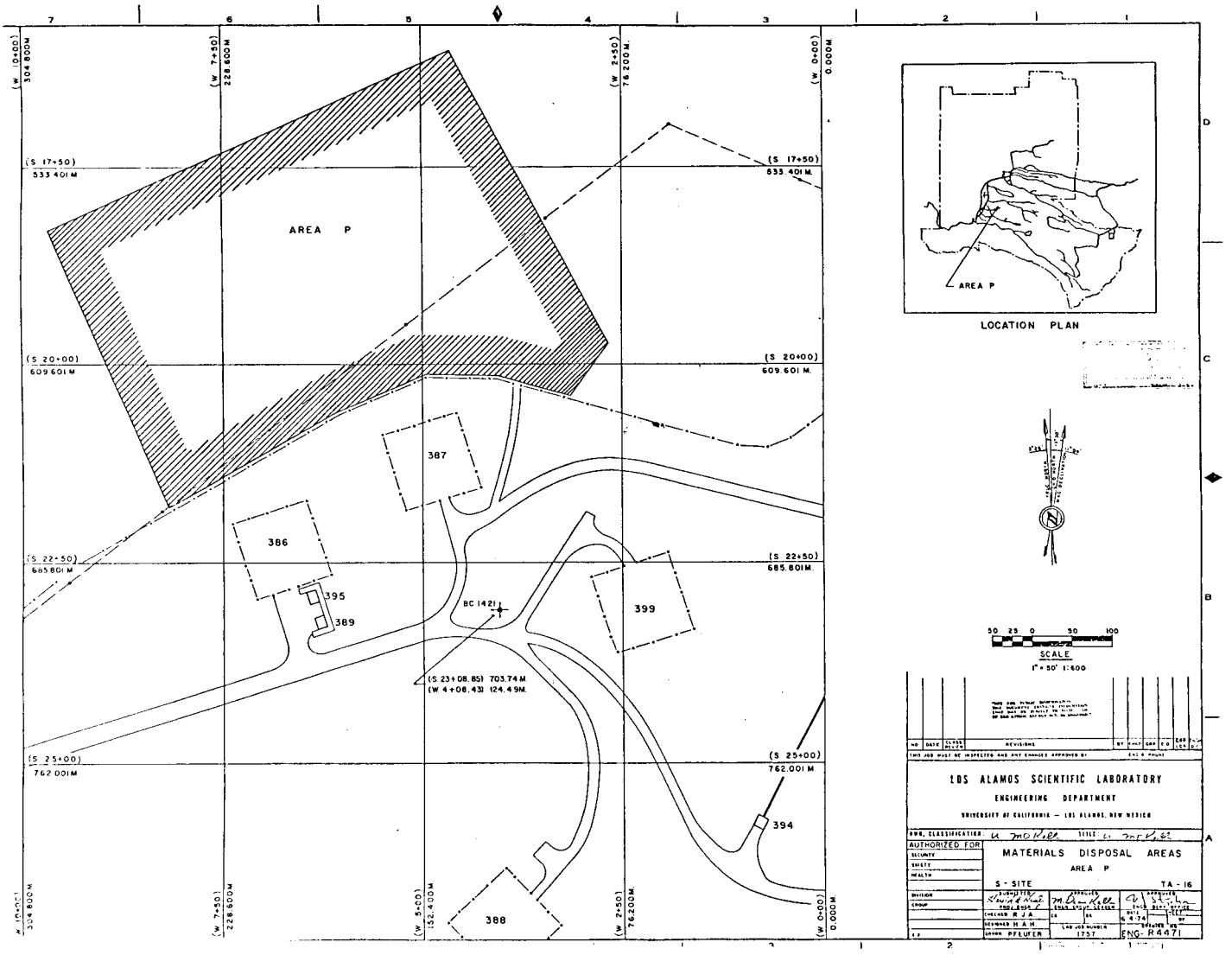

Fig. 5. Map of Waste Disposal Area P.

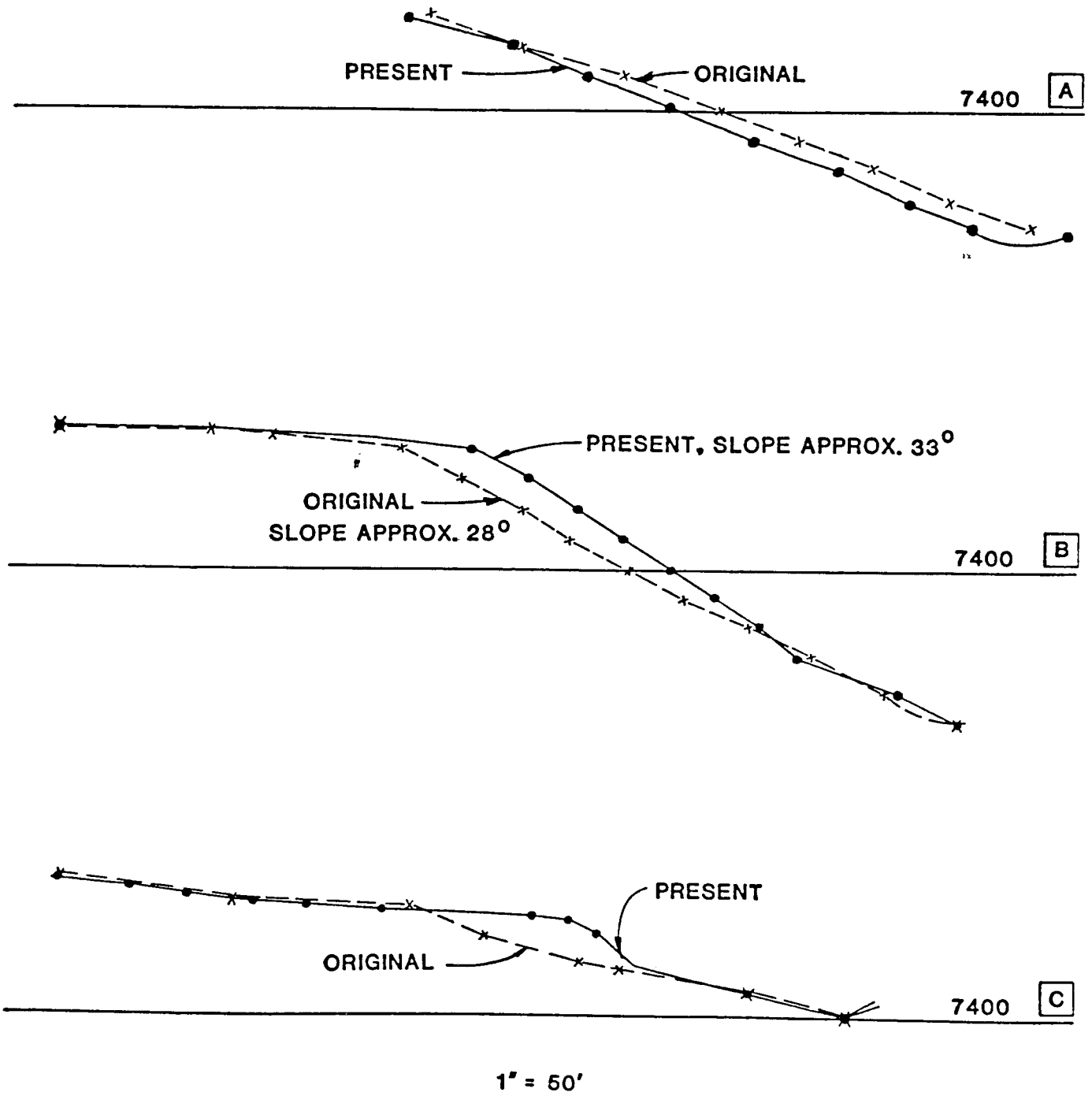

Fig. 6. Map of three cross sections of Waste Disposal Area P showing locations of original and present land surfaces relative to an elevation of 7400 feet. Cross sections A, B, and C are roughly north-south transects located immediately west of the landfill, through the middle of the west portion of the landfill, and through the middle of the east portion of the landfill, respectively (Delta H Engineering, Ltd. 1985).

The covered portion has no appreciable vegetation, and surface drainage cuts through this portion of the landfill.

Waste Disposal Area P is a regulated landfill because it has been used for disposal of residues that exceed the extraction procedure toxicity limit for barium. Prior to November 1985, high explosive (HE) contaminated wastes and equipment were burned on sand-covered pads at S Site (TA-16), and the sand was then removed after the burn and placed in the landfill. All HE is currently burned on lined trays then the sand and ash residue is collected, placed in metal drums, and sent to the Laboratory's Waste Management Group for treatment and disposal as nonhazardous waste. The source of barium in the residue is barium nitrate used in the formulation of some HE. The concentration in the pad sand varies with the barium nitrate concentration in the HE and the HE concentration in the waste.

There is very little documentation of the types or quantity of wastes buried at Waste Disposal Area P (Delta H Engineering, Ltd. 1985). The site was initially used in the early 1950s to dispose of burned equipment that had been HE-contaminated and rubble from building demolition. Known wastes include concrete rubble, structural steel, burn-pad sand, burned equipment, and empty solvent cans.

The procedure for handling HE-contaminated equipment was to disassemble it and to clean the surfaces as well as possible. The equipment was then taken to the burn pad and flashed, along with other combustible material needed to support the fire. After the thermal treatment, the equipment was inspected and determined to be free of HE. Because of the hazard associated with HE, the burned equipment was buried at Waste Disposal Area P, rather than salvaged or shipped to an off-site landfill, to protect the public in case any HE residue had not burned and was not found during the final inspection. Equipment buried at Area P includes several large items, including two trucks and large pieces of concrete rubble from building demolition.

Empty solvent containers have been placed in Waste Disposal Area P. A majority of these containers are quart metal cans and glass bottles. Larger containers, as large as 55-gal. drums, were also in the landfill. During a site inspection, an empty acetone and an empty methanol can were found in the landfill. Both acetone and methanol are regulated as ignitable hazardous wastes, but both containers found were empty as defined by the regulations.

IV. EVALUATION OF CLIMATIC INPUT PARAMETERS TO BE USED IN THE HYDROLOGIC MODELS

The main climatic data required by the CREAMS water balance model are daily rainfall, mean monthly temperature, and mean monthly solar radiation. As discussed earlier, precipitation is the input to the water balance equation and is used in the computation of all the other terms. Mean monthly temperature and mean monthly solar radiation are fitted with Fourier series and then interpolated to daily values for use in the evapotranspiration calculations.

A major problem with performing hydrologic modeling at the Area P landfill is that long-term climatic data are not available specifically at Area P. Precipitation in the area usually increases with elevation and proximity to the Jemez Mountains. Thus, for the entire county, the precipitation records available at the S Site weather station (elevation of 2338 m) are the weather data collected closest to the landfill, but these records are only available from 1977 (with the 1978 data missing). The next closest weather data has been collected at the Occupational Health Laboratory (OHL) at Technical Area 59 (TA-59), which is located at an elevation of 2248 m, but is farther away from the Jemez Mountains. However, the OHL data base is excellent because its weather records go back to 1911. The only other weather station with a record of any substantial length is located in White Rock, but it is located the farthest distance away from Waste Disposal Area P and has an elevation of 1944 m.

A triple-mass plot of the precipitation data available from 1977 through 1987 was constructed to determine differences between the precipitation received at the S Site, OHL, and White Rock stations (Fig. 7). This plot clearly shows that the temporal precipitation pattern at S Site is similar to that at OHL, but both of these stations receive a different precipitation pattern than that observed in White Rock. The average annual precipitation received at the S Site station was 20.50 in., only 1.23 in. more than that observed at OHL for this time period. The White Rock station, in contrast, exhibited an annual average precipitation of only 12.80 in.

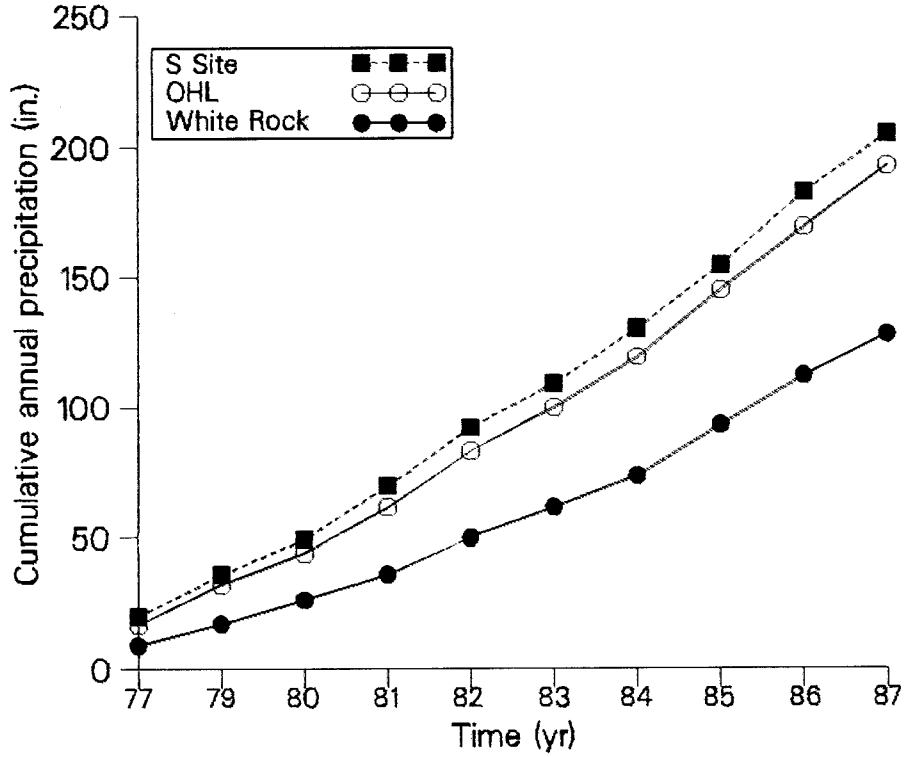

Fig. 7. Triple mass precipitation plot for three meteorological stations.

However, past modeling experience has demonstrated that seasonal inputs of precipitation can have a big effect on water balance components, such as seepage. For example, two locations could potentially have the same annual precipitation, but the location having the heaviest winter precipitation would probably have a larger amount of seepage. Therefore, we also analyzed the precipitation data for seasonal differences (Fig. 8). The results of this analysis show that there are no significant differences in the seasonal distribution of precipitation between OHL and S Site, but that the White Rock station seems to receive substantially less precipitation from July through September than do the other two stations.

Because performance requirements for site closure are specified for time periods like 100 yr (Table I), we utilized a graphical and statistical analysis of the annual precipitation data collected at OHL (Nyhan *et al.* 1989) performed for use with another hydrologic modeling study (Nyhan and Barnes 1988). The statistically calculated values for the 10-yr, 100-yr, and 200-yr events (25.0, 32.9, and 35.0 in., respectively) matched the corresponding graphically derived values for annual precipitation (25.9, 32.9, and 35.0 in., respectively). We also calculated the 95% one-sided tolerance intervals for these estimates (Table II) to provide estimates of the variation about these mean values. The 95% tolerance intervals for the 10-yr, 100-yr, and 200-yr annual events were 27.0, 36.8 and 41.3 in., respectively. The interpretation of this statistical analysis for the 100-yr event, for example, is that 95% of all the 100-yr precipitation events will be less than 36.8 in., with the average 100-yr event being 32.9 in.

Monthly air temperature data were also used as an input parameter in CREAMS. Although temperature data were not available from S Site (Fig. 9), we were able to make a comparison between the OHL and the White Rock stations. The average annual temperatures for OHL (1951-1980 data) and White Rock (1965-1987 data) were 48.2 F and 49.2 F, respectively. The major seasonal difference between these two locations seems to be that White Rock has relatively warmer summers. Thus, because there was such a small difference between White Rock and OHL, we decided it was safe to use the OHL data to represent the Area P landfill in the hydrologic modeling.

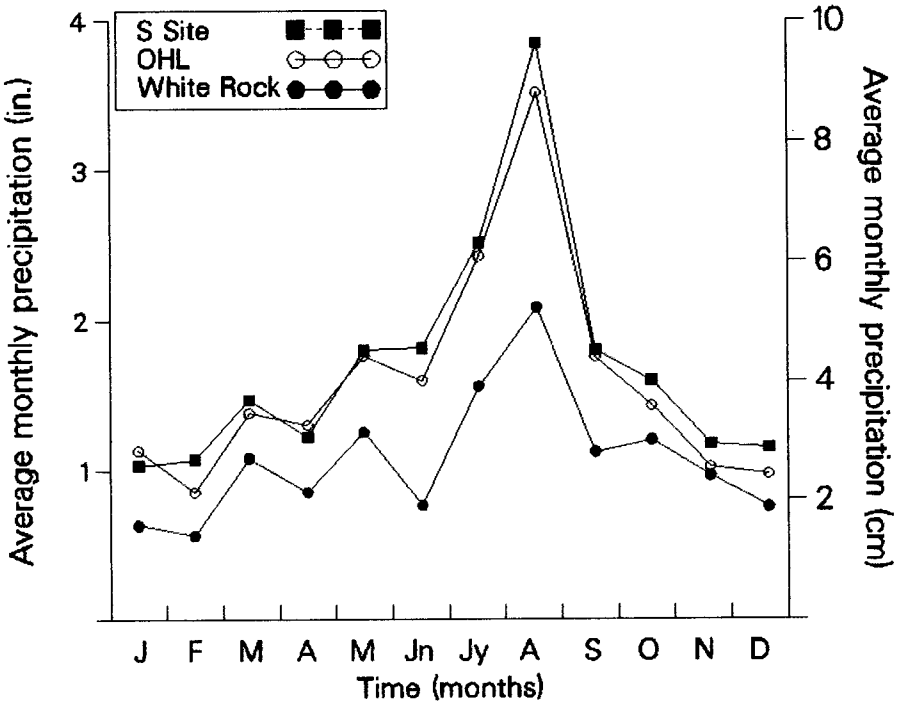

Fig. 8. Monthly precipitation for three meteorological stations (1977–1987).

TABLE II. Precipitation Estimates for Los Alamos (OHL data: 7373 ft elevation)

Time Period	Annual Precipitation Estimate (in.)	95% Tolerance Interval
10 year	25.0	27.0
100 year	32.9	36.8
200 year	35.0	41.3
500 year[a]	39.9	– –

[a]Derived from tree ring index data.

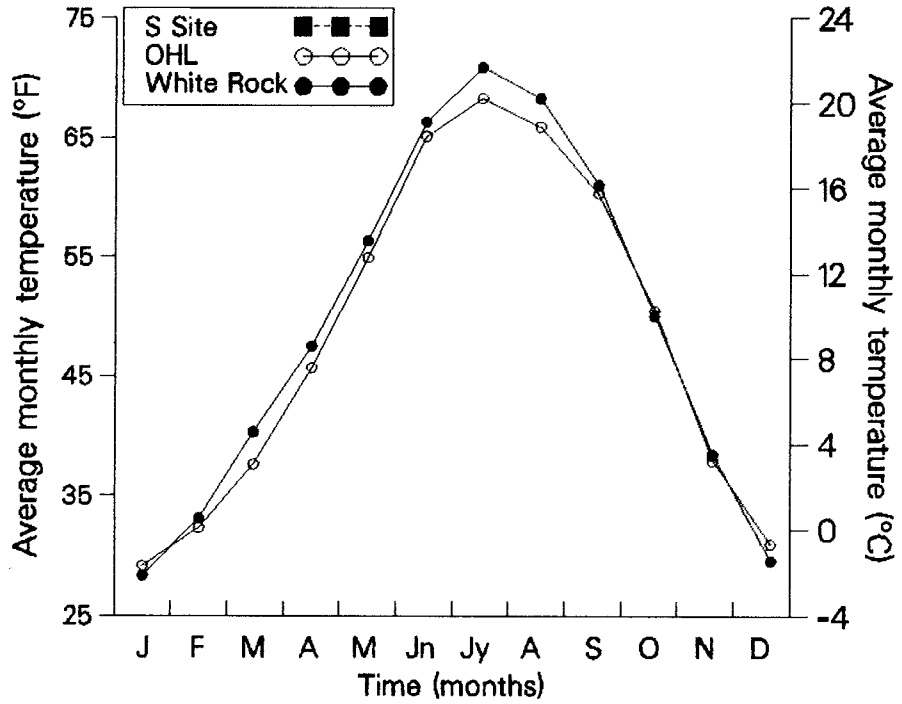

Fig. 9. Monthly air temperature for three meteorological stations.

V. EVALUATION OF THE VOLUMETRIC WATER CONTENT DATA COLLECTED AT WASTE DISPOSAL AREA P

The volumetric water content of several sampling areas around the Area P landfill was evaluated before the hydrologic modeling was performed, for several reasons. First, this data base represented the only source of hydrologic information available for modeling purposes, even though no information was available within the landfill boundaries. Initially, it was hoped that something might be gained by examining the overall site dynamics of the water balance equation, such as changes in soil water content with time, even though no field information was available for evapotranspiration, seepage, and runoff changes with time. The other reason for evaluating the data was that each access tube emplaced adjacent to the landfill had an invaluable geologic log associated with it. With this knowledge of the geology of the site, gross estimates of site hydrologic properties could be made from experience (Abeele 1984, Abeele *et al.* 1981, Abrahams 1963).

The most informative data were collected at sampling locations P-12, P-13, and P-16 within TA-16 (Fig. 10). Sampling location P-12 was located over 1000 ft southeast of the landfill, whereas sampling locations P-13 and P-16 were situated less than 30 ft immediately to the south of the landfill (Fig. 10). Thus, the P-12 location acted like a "background," with the other two sampling locations sharing a portion of the temporary, crushed-tuff cover that had been emplaced over the entire landfill.

The volumetric water content data collected in 1987 and 1988 by the Environmental Surveillance Group (HSE-8) personnel are presented in Figs. 11–13. The data for location P-12 is a representative background 100-ft profile, with winter volumetric water contents ranging from about 25%-33% in the soil layers above the tuff, 4%-7% in the Unit 3d tuff, and 5%-7% in the underlying Unit 3c tuff (Fig. 11). Slightly elevated levels of tuff water content were observed near the contact zone between tuff units, as should be expected in these lower conductivity layers.

Both sampling locations adjacent to the landfill exhibited elevated levels of volumetric water content (Figs. 12 and 13) relative to the location P-12 data. The samples collected from location P-13, for example,

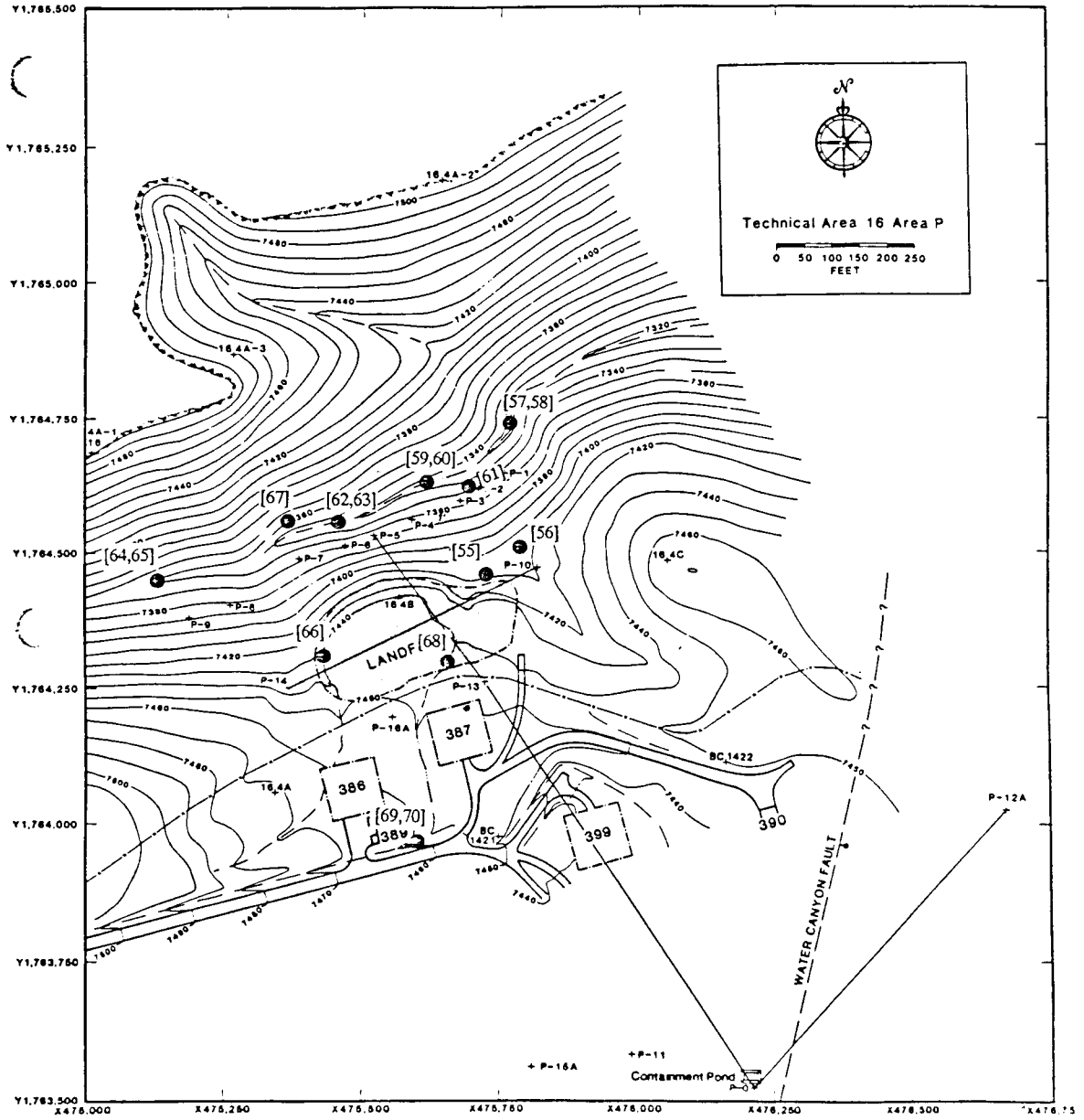

Fig. 10. Map of Waste Disposal Area P showing locations of neutron probe access tubes.

exhibited volumetric water contents greater than 40% in the top 7 ft of coarse-textured tuff backfill, 21%-24% in the underlying Unit 3d tuff, and 20%-26% in the lowest Unit 3c tuff.

The elevated volumetric water content in the undisturbed tuff units beneath the landfill can be appreciated even further by comparing the water content profiles in the three locations in March 1988 (Fig. 14). A calculation of the inventory of water in each of these three profiles to a depth of 90 ft was determined to further demonstrate this point. Whereas the entire profile at location P-12 contained a total soil water inventory of only 100.9 in., locations P-16 and P-13 adjacent to the landfill exhibited similiar inventories of 275.3 and 318.7 in. of water, respectively.

This data base, combined with a knowledge of the hydrologic properties of the temporary tuff backfill cover at the landfill, allowed us to derive the following scenario as to what could be happening at the landfill. First, the crushed-tuff cover was emplaced across the top of the site with minimum compaction, probably resulting from the difficulty in successfully compacting a layer of crushed tuff over a loosely packed assortment of metallic rubble. Thus, there is a crushed-tuff backfill layer (7 ft thick) at the surface

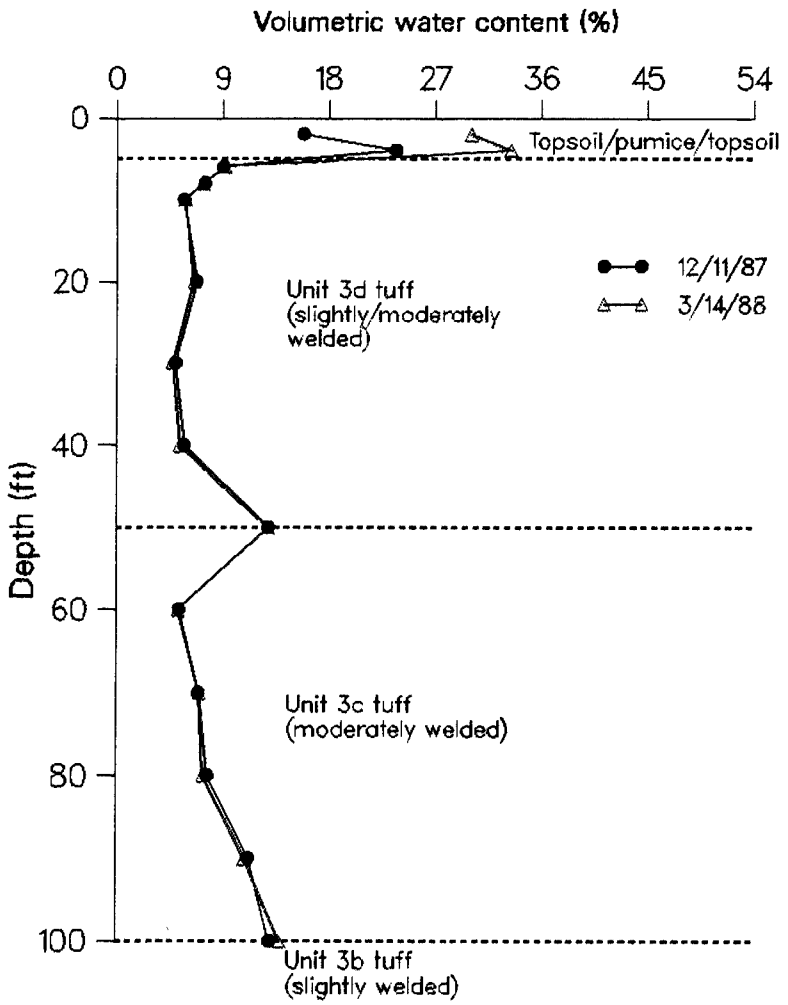

Fig. 11. Volumetric water content data for location P-12.

of the landfill with a very high porosity and saturated conductivity, two factors that would contribute to very low runoff rates and very high infiltration rates. However, the data (Figs. 12 and 13) demonstrated that volumetric water contents in excess of 40% were observed in the tuff backfill, which suggests that the undisturbed Unit 3d tuff layer beneath the backfill (or a layer of fine-textured soils materials) is acting as a barrier to vertical soil water movement in the profile. This makes good sense because the saturated hydraulic conductivity of this tuff unit (or the layer of fine-textured soils materials) is surely orders of magnitude lower than that of the backfill.

However, the above explanation may account for some of the soil water inventory differences observed earlier (Fig. 14), but not a difference as large as about 200 in. of water as discussed previously. The only way to account for a difference this large is to have a water input to the landfill (locations P-13 and P-16) beyond the infiltration of precipitation occurring at all three sampling locations. A field inspection of the landfill immediately provided us with the major probable culprit: the unlined drainage ditch that traverses the southern landfill boundary. This ditch collects runoff from a large area above the landfill, and this runoff undoubtedly infiltrates into the coarse-textured backfill along the southern border of the landfill. This would act the same as making a five- to ten-fold increase in the precipitation input to the landfill area. Of course, other "culprits," such as horizontal subsurface flow of soil water into the site from upland regions, could also be found to play a role once more information is known about this site.

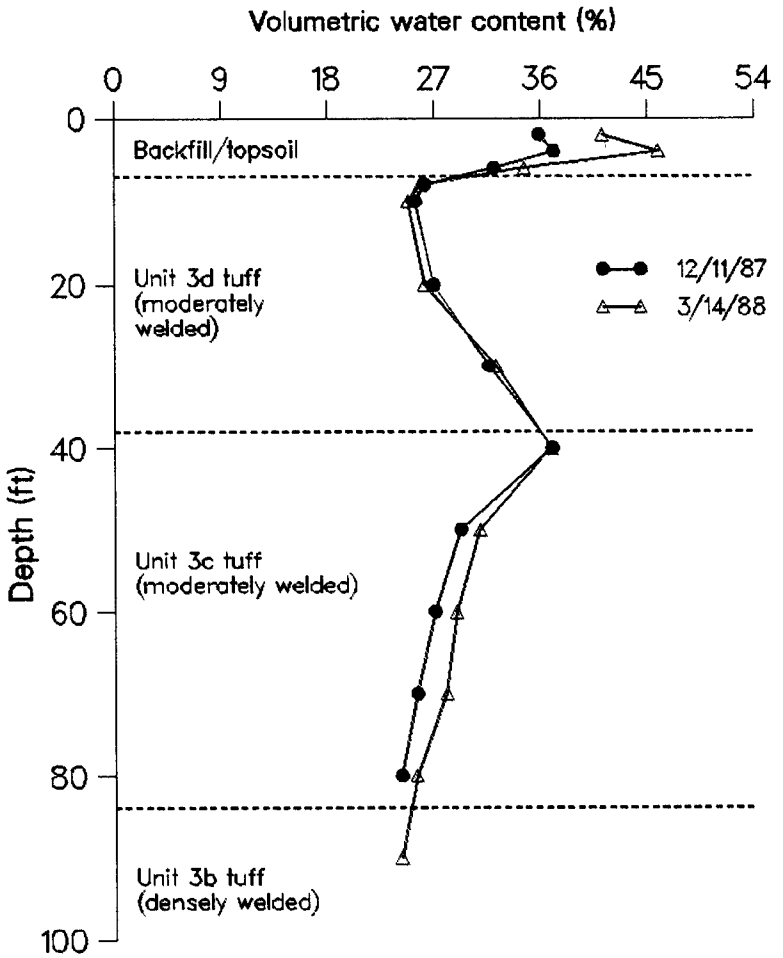

Fig. 12. Volumetric water content data for location P-13.

VI. HYDROLOGIC MODELING AT THE AREA P LANDFILL

The CREAMS modeling activities for the Area P landfill had two general objectives. The first objective was to estimate soil and plant modeling parameters to model the Area P landfill as it currently exists without implementation of a closure cover. The southeast and southwest portions of the landfill currently have no vegetation and sparse vegetation, respectively, so both of these scenarios had to be modeled. The second objective was to use a field-calibrated CREAMS model to help evaluate cover features, such as cover thickness, to help improve a final approved closure plan for this landfill.

A. Area P Landfill Scenario Without a Closure Cover

The CREAMS modeling scenarios in this subsection involved modeling the 7-ft-deep backfill at the landfill for the vegetated and nonvegetated portions of the site. Model parameter estimates were initially chosen using past experience (Nyhan 1989, Nyhan and Barnes 1989, Nyhan and Lane 1982) and other instructions on how to use CREAMS (Lane 1984). The daily precipitation input file used was the 1977-1987 data collected at S Site by Group HSE-8 personnel.

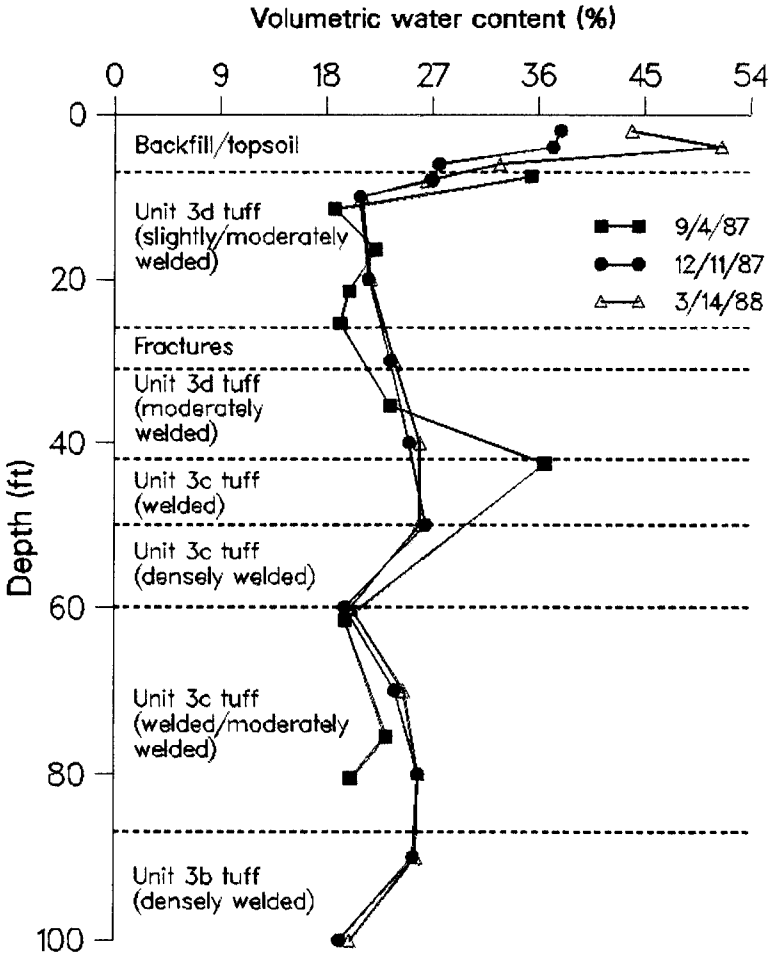

Fig. 13. Volumetric water content data for location P-16.

Because the only real site data for this time period consisted of volumetric water content data collected in December 1987, clearly, this was an attempt to extrapolate and estimate hydrologic variables to the maximum! However, after several CREAMS simulations, parameter optimization techniques lead to the estimation of volumetric water content with time while varying the saturated hydraulic conductivity (RC) in the model. The CREAMS RC parameter represents the slowest estimated hydraulic conductivity of either (1) any layer in the crushed tuff profile considered in the simulation at the Area P landfill, or (2) a layer immediately beneath the crushed tuff profile, such as a layer of either undisturbed tuff or fine-textured soil particles. The results are presented in Fig. 15 for the bare backfill scenario and in Fig. 16 for a cover with poor range-grass cover.

Two important conclusions resulted from these initial CREAMS simulations. First, as we discussed at the end of the last section, RC values as large a 0.070 in./hr and greater (which would be characteristic values for crushed tuff backfill alone) resulted in CREAMS-estimated volumetric water contents that were much lower (Figs. 15 and 16) than those observed in the field (Figs. 12 and 13). Thus, the rate-limiting saturated hydraulic conductivity that finally used in CREAMS simulations of the tuff backfill had to match the ra in RC factors known for the less-conductive underlying tuff (or a fine-textured soil layer immediately above the tuff), *i.e.*, 0.003 to 0.070 in./hr! Even within this range of conductivity values, field-observed

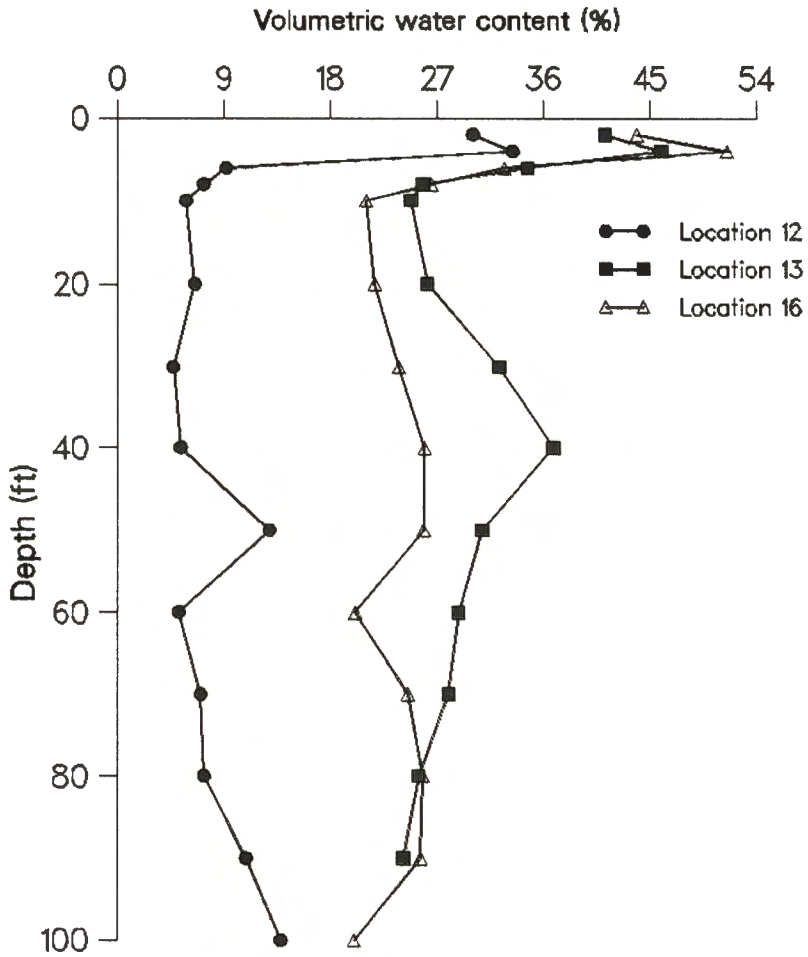

Fig. 14. Volumetric water content data for three sampling locations in March 1988.

water contents were not simulated in 10 yr until RC values closer to 0.003 in./hr were used (Figs. 15 and 16).

The second major conclusion reached was a verification that even a poor range-grass cover seemed to enhance simulated evapotranspiration, thus reducing volumetric water content (Fig. 16) predicted by CREAMS over that observed in the bare-backfill scenario (Fig. 15). Although CREAMS-predicted volumetric water content does gradually increase with time in the backfill, this occurs dramatically slower with time with a small amount of vegetation present.

These CREAMS simulations are summarized in Fig. 17 in terms of the volumetric water content predicted by the model in December 1987 and the average annual seepage as a function of the saturated hydraulic conductivity. Again, the point is made that as the saturated conductivity for the cover profile decreases, the volumetric water content increases and the average annual seepage through the fill cover decreases.

From the simulation results shown in Fig. 17, we decided to set the final RC factor at 0.003 in./hr and simulate seepage production over the 10 yr of precipitation observed at S Site (Figs. 18 and 19). CREAMS predicts annual seepage ranging from 0 in. to almost 7 in. from the 7-ft profile either with or without vegetation. Notice that there seems to be a lag period in maximum seepage production of about a year after a year with high-precipitation.

The simulation results presented in Figs. 17 to 19 are examples of what could be learned when a field-calibrated hydrologic model is developed for the Area P Landfill in the future. Current experience

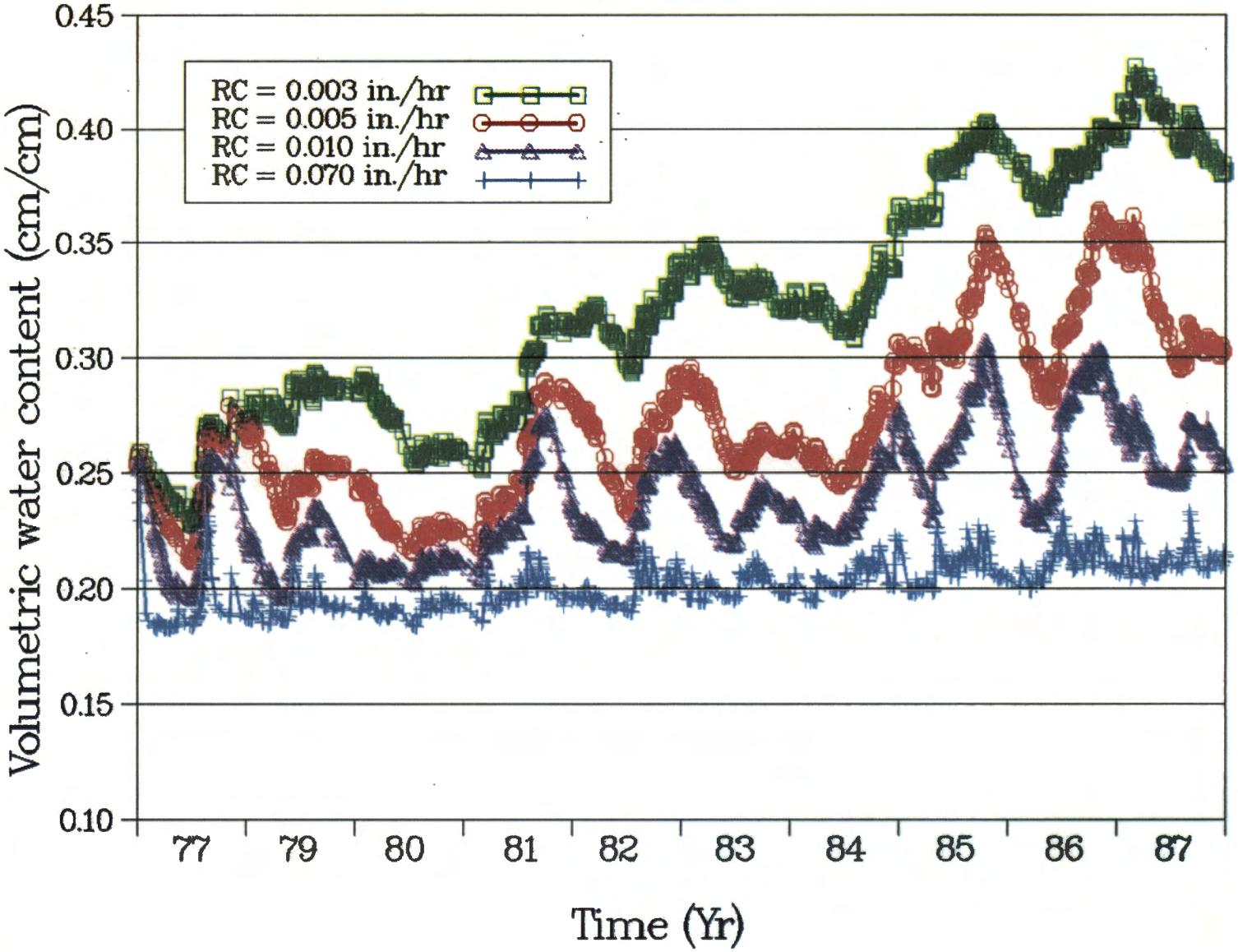

Fig. 15. CREAMS—predicted soil water content at Waste Disposal Area P (bare backfill cover scenario).

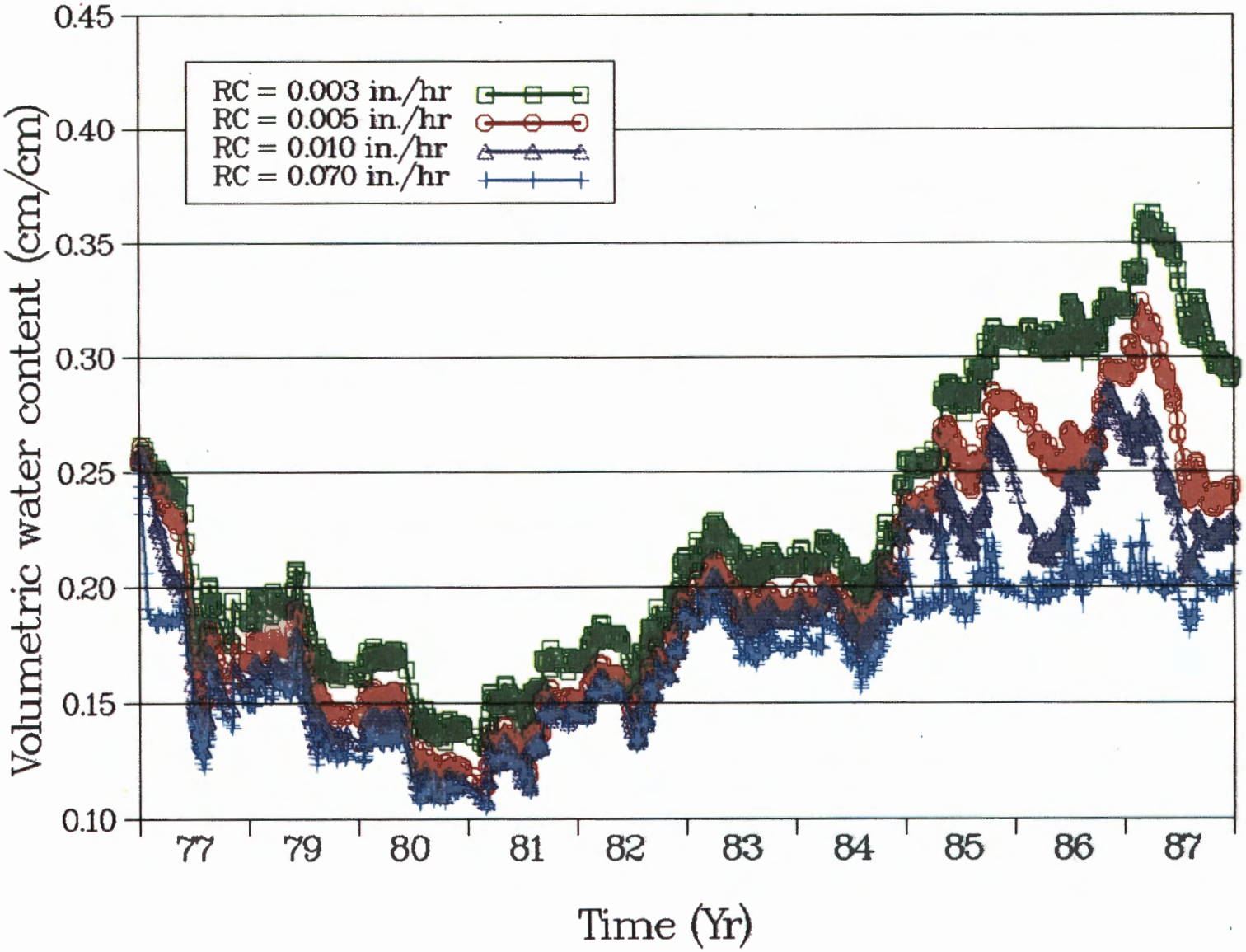

Fig. 16. CREAMS—predicted soil water content at Waste Disposal Area P (poor range grass cover scenario).

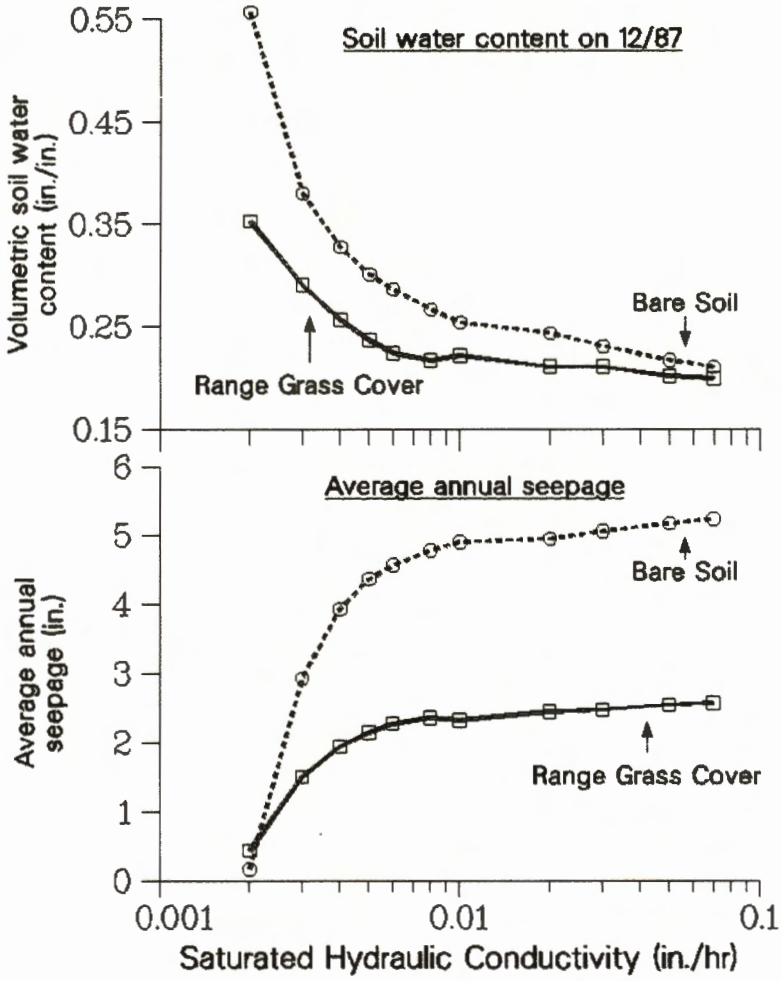

Fig. 17. CREAMS 10-yr simulation at Waste Disposal Area P.

with the CREAMS model at the Laboratory only involves modeling of land areas similar to the upper, flat portions of the Area P Landfill. The model also does not have the ability to describe two-dimensional unsaturated flow of soil water through the landfill, as could currently occur as a result of either runon or subsurface downhill transport at the interface between the tuff backfill and the undisturbed tuff at this site.

B. Area P Landfill Scenarios With a Closure Cover

This entire exercise was based on two field-calibrated models developed in previous research sponsored by the DOE National Low Level Waste Management Program. The integrated test plot (ITP) cover demonstration involved a comparison of water balance on a conventional Los Alamos landfill cover design (15 cm of topsoil emplaced on top of 76 cm of crushed tuff backfill) with that of an improved design containing a capillary barrier (Nyhan *et al.* 1989). The CREAMS model was calibrated for the conventional design (Nyhan and Barnes 1989), and was just calibrated for the improved design (Nyhan 1989).

As was pointed out earlier in this report, SLB design characteristics such as landfill cover thickness do not have to be arbitrarily chosen. Now that a field-calibrated hydrologic model existed that described

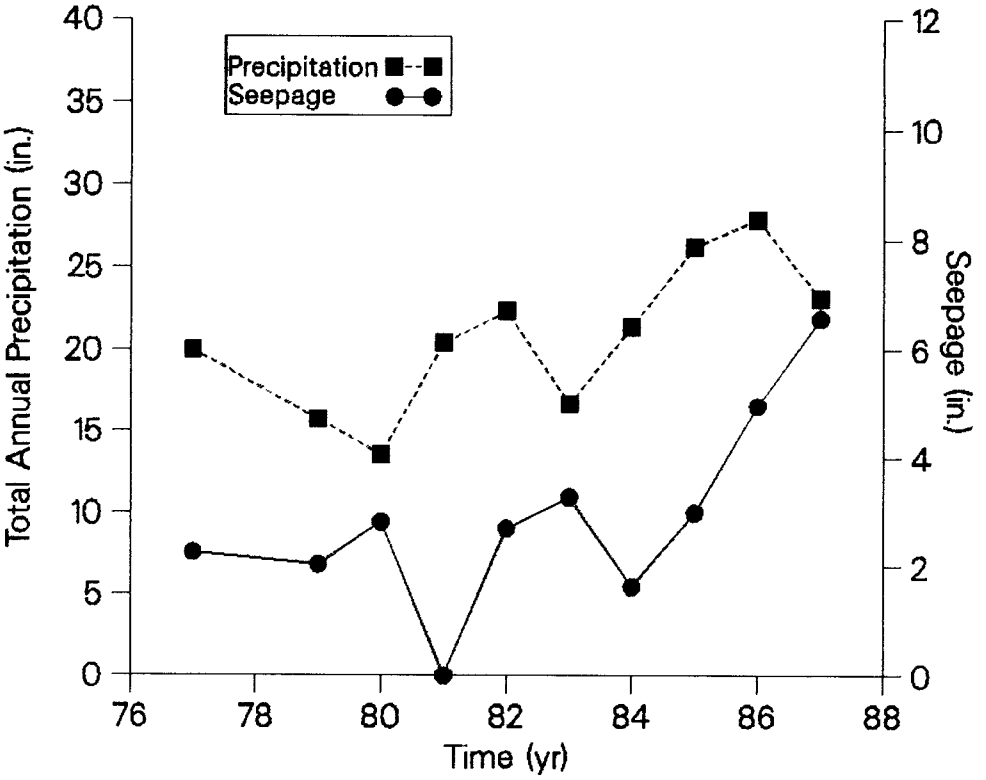

Fig. 18. Precipitation vs seepage predicted by CREAMS at Waste Disposal Area P (bare backfill cover scenario).

water balance relationships for the improved SLB design configuration at Los Alamos, CREAMS was used as a tool to improve the design of SLB.

Before the modeling activities for the design of the closure cover were initiated, a comparison was made between a CREAMS simulation (with a 1977-1987 daily precipitation data) of S Site and OHL. One of the 7-ft-thick scenarios was arbitrarily used (Fig. 16) with RC = 0.004 in./hr. The average annual amounts of precipitation varied from 19.2 in. at OHL to 20.7 in. at S Site during this time period. The simulation results demonstrated a negligible increase in soil water content and only a 5% increase in annual evapotranspiration using the S Site data base rather than the OHL data. There were 1.5 in. more annual precipitation received at S Site than at OHL, which resulted in only 0.6 in. of increased seepage production. Thus, it was felt that it was acceptable to use the longer OHL precipitation data base for the hydrologic modeling at the Area P Landfill because the simulation results using the two precipitation bases were so similar.

Using daily OHL precipitation data from 1968 to 1987, a series of CREAMS simulations were performed by varying the thickness of the landfill cover and determining the predicted amount of seepage occurring for both the average year and the wettest year for each thickness. The parameters used in this effort were the same as those used for the improved plots in the ITP experiment, with the exception that the 1985 plant leaf area index distributions were used for the entire simulation period. One CREAMS simulation was performed for each of nine landfill cover thicknesses (0.31, 0.46, 0.61, 0.91, 1.30, 1.52, 1.83, 2.13, and 2.52 m).

One of the first major discoveries made in the use of CREAMS for SLB landfill cover designs at Los Alamos was the influence of vegetative cover on decreasing seepage through the SLB landfill cover (Nyhan and Lane 1982). Because these early efforts were performed without the field-calibrated CREAMS model, it was decided to repeat this exercise with our field-calibrated model. The results of these CREAMS simulations are presented in Fig. 20, where the performance of a landfill cover with a bare soil surface

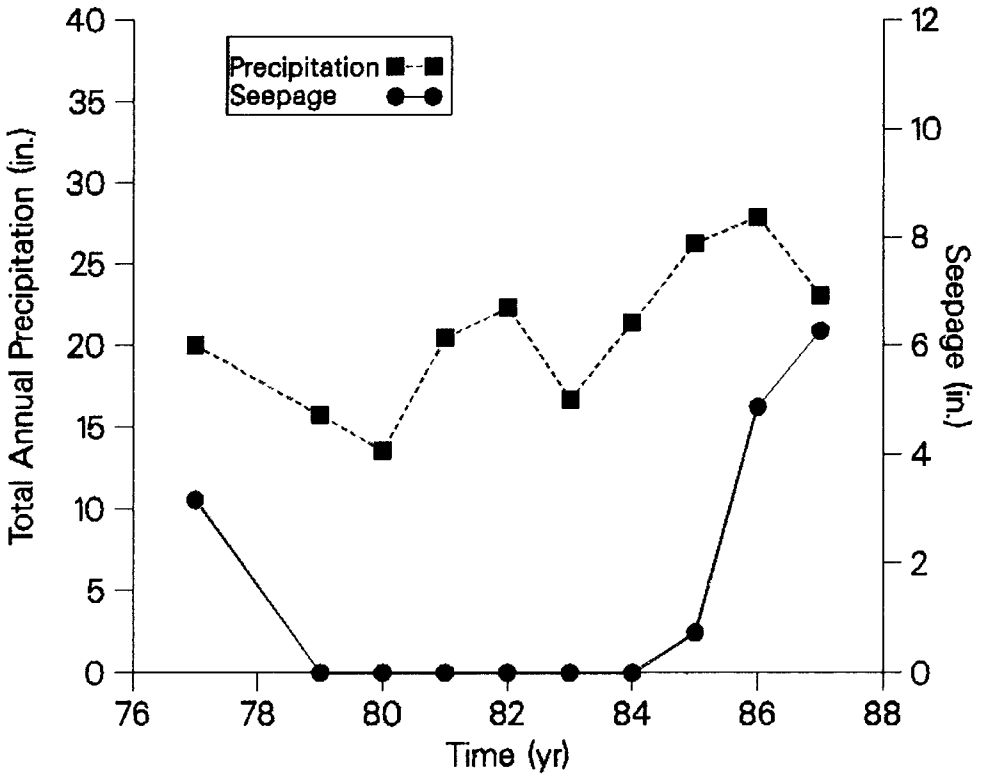

Fig. 19. Precipitation vs seepage predicted by CREAMS at Waste Disposal Area P (poor range grass cover scenario).

with a 70% cover of gravel is compared with one similar to that found on the ITP improved plot design (one with a 70% cover of gravel and a good cover of range grass).

The results of this comparison (Fig. 20) show that the bare soil/gravel cover consistantly produces about 10 cm of annual seepage in the average year and about 23 cm of annual seepage in the worst case (wettest year), regardless of the thickness of the landfill cover. In contrast, the good range grass/gravel cover produces average annual seepage that ranges from 5.6 to 0.27 cm as the landfill cover thickness increases from 0.31 to 2.5 m. In the wettest year, the good range grass/gravel cover produced from 14 to 5.4 cm of annual seepage as the landfill cover thickness increased from 0.31 to 2.5 m. The major factor causing this observed difference between these two cover designs revolves around the effort to use vegetation to enhance evapotranspiration, and thus decrease annual seepage, during the plant growing season. Thus, as the landfill cover with the good range-grass cover becomes thicker, the effective plant rooting depth increases, allowing increased plant interception of infiltrating precipitation.

If the results from the good range grass/gravel cover CREAMS simulation were used to design a landfill cover for long-term repository closure, we can see (Table II) that about 7.4 cm of annual seepage is predicted to occur in the wettest year (1987) with the thickness of one proposed landfill cover closure configuration (3 ft thickness: see Fig. 3). However, regardless of whether the CREAMS seepage predictions for the good range grass/gravel cover (Fig. 20) are for the 0.30 cm cover thickness (15 cm) or the 2.5-m-thick landfill cover (5.4 cm), the amounts of annual seepage predicted for the wettest years between 1968 and 1987 are usually about tenfold larger than the annual seepage occurring on the average year. The reason for this, of course, is that the wettest years (*i.e.*, 1968 and 1987) are years when snowmelt dominates the seepage production temporal pattern and times when plant transpiration does not occur to help reduce seepage production. This is a very important observation because neither the winter of 1968 nor 1987 was even a 10-yr event, in which 15 cm of precipitation would be received by the landfill cover let alone a 100-yr winter, in which even more precipitation would have occurred (Table II). Because our CREAMS simulations generally underestimated seepage occurring in the field, the implications for the

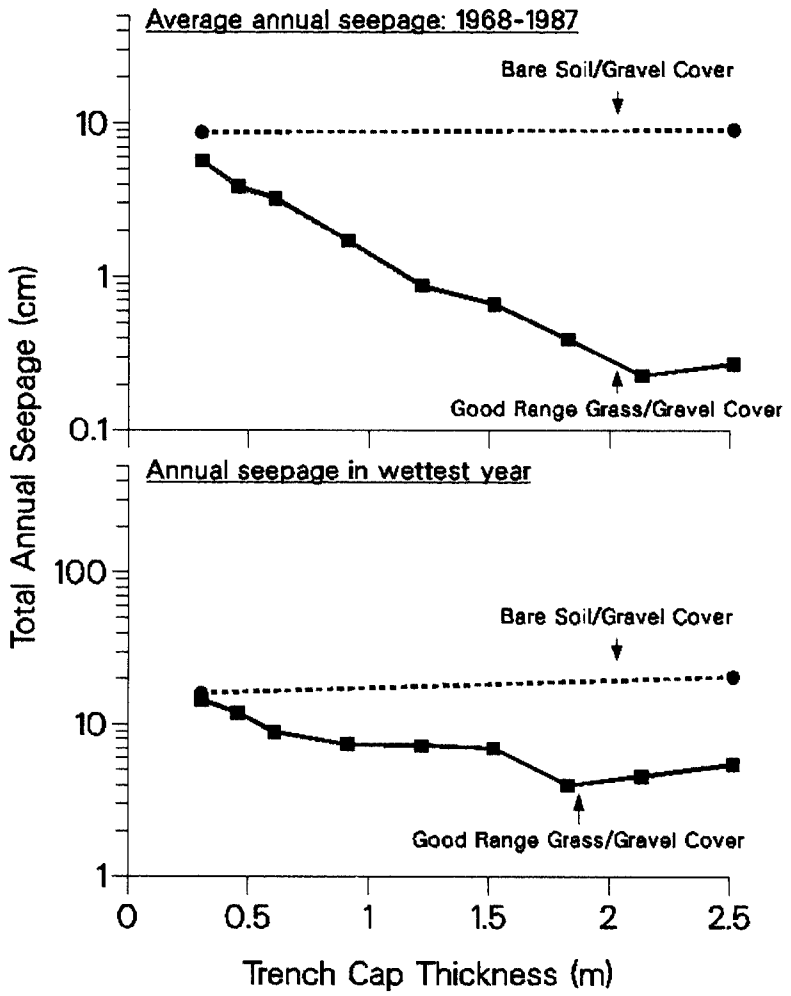

Fig. 20. CREAMS 20-yr simulation at Waste Disposal Area P.

waste management site operator are that large amounts of percolation could occur in 10-yr and 100-yr winters, especially when antecedent fall soil moisture levels are high.

VII. RECOMMENDATIONS FOR FUTURE STUDIES AND SPECIFIC WASTE MANAGEMENT PRACTICES AT WASTE DISPOSAL AREA P

An ongoing field study at Waste Disposal Area B is currently studying runoff/infiltration characteristics of landfill covers consisting of shrubs, grasses, and shrub and grass covers with partial gravel cover. One area for highly recommended future modeling activities would be to investigate the influence of reducing the bare soil evaporation parameter (C) in CREAMS simulations of disposal site hydrologic dynamics and design. The ITP modeling activities performed in previous studies indicated that C values should be decreased dramatically from those suggested (Lane 1984) when a gravel cover was involved. Further field validation of this effect would greatly enhance the accuracy of the CREAMS predictions of seasonal seepage in SLB designs, especially if a partial gravel cover is used in the Area P landfill designs to reduce erosion of the closure cover. The near-surface field studies performed at Waste Disposal Area B will also greatly enhance our ability to predict soil loss rates for different cover treatments using the erosion component of CREAMS.

Another recommendation can be made as a result of the overall modeling efforts in this study. Since appreciable annual seepage is predicted to occur in the wettest years, capillary barriers should be used in the long-term closure designs of all SLB facilities. More specifically, this would mean that the Delta H Engineering, Ltd., closure plan approach to essentially leave the western portion of the Area P landfill as is could be improved; it could also be improved because a portion of the water infiltrating the western portion of the landfill would infiltrate horizontally into the eastern portion of the landfill, with its proposed concrete cover. Since the improved plot design in the ITP experiment contained capillary barriers that dramatically reduce annual seepage, this data base should be further expanded by collection of field data at Waste Disposal Area P in the future. The field data and the modeling expertise are unique to Los Alamos and do not exist anywhere else in the US.

Several recommendations can be made in terms of what types of moisture, or capillary, barriers could be emplaced as part of the landfill cover at Waste Disposal Area P. First, as was mentioned earlier, synthetic liners have limited expected lifetimes (Fig. 2). This automatically eliminates closure covers made of concrete and polyethylene. This would leave either a rock barrier type of moisture barrier or a clay admixture barrier as the alternative. Of these two, the potential health hazards at Waste Disposal Area P from uptake of contaminants by plants growing on the cover do not warrant the expense of the gravel cobble biointrusion-moisture barrier. Thus, the recommendation would be to construct a landfill cover using a moisture barrier consisting of a mixture of crushed tuff and 4% bentonite in the final approved cover design (Abeele 1984a and 1984b, Abeele 1986a and 1986b, Abeele *et al.* 1986).

A possible alternative to the use of capillary barriers alone might be to dramatically reduce winter seepage using conifers in conjunction with capillary barriers. Using an evergreen cover on the trench cap, in addition to a good cover of range grass, could greatly enhance evapotranspiration in the winter and early spring, thus reducing seepage in the wettest years (worst case) described in this study. This would probably make a good waste management decision, but would necessitate further studies of capillary/biointrusion barriers to prohibit conifer roots from penetrating waste materials beneath the trench cap.

Finally, additional future field research and concurrent hydrologic modeling should be performed in three other areas involved in the water balance equation. First, transpiration studies of various grass, shrub, and tree species need to be performed in the field on a scale larger than the 3- by 10-m plots used in the ITP experiment. Ultimately, the precision of a model like CREAMS to predict evapotranspiration will depend on our ability to accurately describe both seasonal transpiration and evaporation processes involved. The second area that needs further research involves further field investigations into seepage production in SLB configurations. Without seepage field data, both evapotranspiration and runoff parameter estimates need to directly measured, which may not be possible with the technology currently at hand. Finally, a reliable technique needs to be developed and evaluated for determining the saturated hydraulic conductivity for the field soils that agrees with the model estimates of RC in a generic sense. A good field estimate of RC representing a large field area would take a lot of guesswork out of CREAMS parameter estimation, resulting in greatly enhanced accuracy in model predictions.

Several additional waste management suggestions should be made specific to ultimately deriving a final approved closure plan for the Area P landfill:

1. Based on our hydrologic modeling of the site, the first thing to be done immediately (before site closure) is to relocate and to line the runoff diversion ditch located on the south side of the landfill. The runoff diversion ditch should also be relocated so that it takes the runoff coming from the total area uphill and to the south of the landfill and sends it northeastward down the road into the canyon (around the landfill).
2. Collect neutron moisture gauge data inside of the Area P landfill, and collect soil samples for contaminant assays when the holes are drilled for the access tubes.
3. Perform a flood frequency analysis in the canyon (to the north of the site) to determine if the current, or future, landfill cover will undergo water erosion.
4. Before the final closure cover is emplaced on the landfill, be sure to compact the final subsurface layer under the cover (using approved safety procedures) to avoid subsidence problems. The extremely high volumetric water content in the current crushed tuff backfill cover will greatly enhance subsidence of these layers in the future, resulting of course, in subsidence of soil layers placed on top of the current cover.

5. Set up the final approved closure cover so that its performance can be both successfully monitored with time with a minimal manpower requirement and successfully modeled with time. This will allow HSE Division and the Laboratory to be in a better position to design covers for future waste disposal areas to undergo site closure.

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