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W. J. Waugh
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December 1988

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
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ABSTRACT

Pacific Northwest Laboratory (PNL) and Westinghouse Hanford Company convened a workshop in January 1987 to define key issues regarding the impacts of climatic variability on the performance of protective layered soil and rock barriers proposed for possible use at Hanford. Workshop participants concluded that the sensitivity of vegetation and evapotranspiration to climate must be better understood before climate-change impacts on drainage through the barrier and groundwater recharge can be adequately modeled. As a result of this conclusion, workshop participants proposed measuring evapotranspiration and other water balance parameters in lysimeters constructed around monoliths of undisturbed soil and mature vegetation, and located at sites analogous to late-Quaternary pluvial and altithermal conditions. Climate-analog sites would be selected based on reconstructions of late-Quaternary vegetational patterns and model projections of future climatic variability in the region. The lysimeter data would be input into a simulation model of soil-water movement in barriers. The distribution of pedogenic carbonates and radionuclides from nuclear weapons testing fallout would be analyzed as independent indicators of past water movement in analog-site soil profiles.

EXECUTIVE SUMMARY

A defensible evaluation of near-surface waste disposal strategies at Hanford would account for climate-change impacts. Earthen protective barriers, which are designed to impede water infiltration and biointrusion into buried waste for up to 10,000 years, may be particularly sensitive to climatic variability. A technical workshop was convened in January 1987 to better define climate issues and key parameters that will be used in barrier performance analyses, and to outline a recommended approach for quantifying key parameters.

Workshop discussions focused on the problem of estimating climate-induced variability in drainage through a barrier and the subsequent transport of contaminants to the groundwater. It was hypothesized that drainage across fine-coarse layer interfaces in the barrier occurs as a threshold response to changes in soil-water storage. If this is true, drainage would be relatively insensitive to climatic variability as long as soil-water storage remained below the saturation threshold. Evapotranspiration (the evaporation from soil and plant surfaces) would maintain soil-water storage below the saturation threshold. Participants concluded that the sensitivity of evapotranspiration to climate is a key issue that must be resolved before climate-change impacts on drainage and groundwater recharge can be quantified.

A preliminary task plan was developed that proposes a sequence of studies needed to estimate evapotranspiration and to model soil-water movement for a predictable range of climate changes over the next 10,000 years. The first set of studies would reconstruct late-Quaternary Hanford vegetational and climatic patterns from pollens preserved in datable lake sediments within and around the Pasco Basin. Second, if it can be shown, using climate-forecast models, that late-Quaternary vegetation and climate bound forecasts of future conditions, then a reconnaissance would be conducted to identify sites at Hanford that are potentially analogs of pluvial and altithermal conditions. Evapotranspiration and other parameters required for modeling soil-water movement would be measured in mature vegetation at these wet and dry climate-analog sites using monolith lysimeters. Finally, indicators of past soil-water movement, such as pedogenic carbonates and chlorine-36 from fallout from nuclear weapons testing, would serve as independent checks of soil-water balance model simulations.

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1.0 INTRODUCTION

Pacific Northwest Laboratory (PNL) and Westinghouse Hanford Company (WHC) convened a workshop January 29 and 30, 1987, in Richland, Washington, to identify and discuss key issues and parameters for investigating climate-change impacts on the near surface disposal of certain of Hanford's defense wastes. A protective barrier (a layered soil and rock cover engineered to impede biointrusion, erosion, and leaching of buried radioactive waste) is a critical component of several waste disposal alternatives (USDDE 1987). The Protective Barrier and Warning Marker System Development Plan (Adams and Wing 1987) describes the tasks necessary to develop, test, and model a barrier intended to isolate waste for up to 10,000 years. Convening a climate-change impact workshop was one task of the multiyear Protective Barrier Development Program managed by WHC for the U.S. Department of Energy (USDOE).

Recent models correlating climatic variability with periodicity in the earth's orbital parameters suggest that the earth's climate may be moving into another ice age during the next 10,000 years (Imbrie 1985). Such climatic change could have a major influence on the long-term performance of a layered earthen barrier at Hanford. Water movement within and between barrier layers would be sensitive to changes in precipitation, temperature, and the water extraction behavior of plants inhabiting the barrier soil (Figure 1.1). The likelihood of biointrusion would be tied to climate-induced changes in the abundance and distribution of plants and burrowing animals. Subtle changes in precipitation and wind regimes could impact the stability of the barrier surface. Also, the recurrence of catastrophic glacial flooding could entrain and disseminate wastes stored in sediments deposited during previous flood episodes (Craig and Hanson 1985).[a]

(a) Citing Milankovitch-based climate forecasts by Craig (1983) and Imbrie and Imbrie (1980), the U.S. Department of Energy (USDOE 1987) discounted glacial flooding as a disruption scenario for in-place waste disposal within the next 10,000 years. However, large measures of uncertainty are associated with climate-change forecasts, and recent global models suggest that the transition toward a glacial state may be more rapid than previously thought (Imbrie 1985).

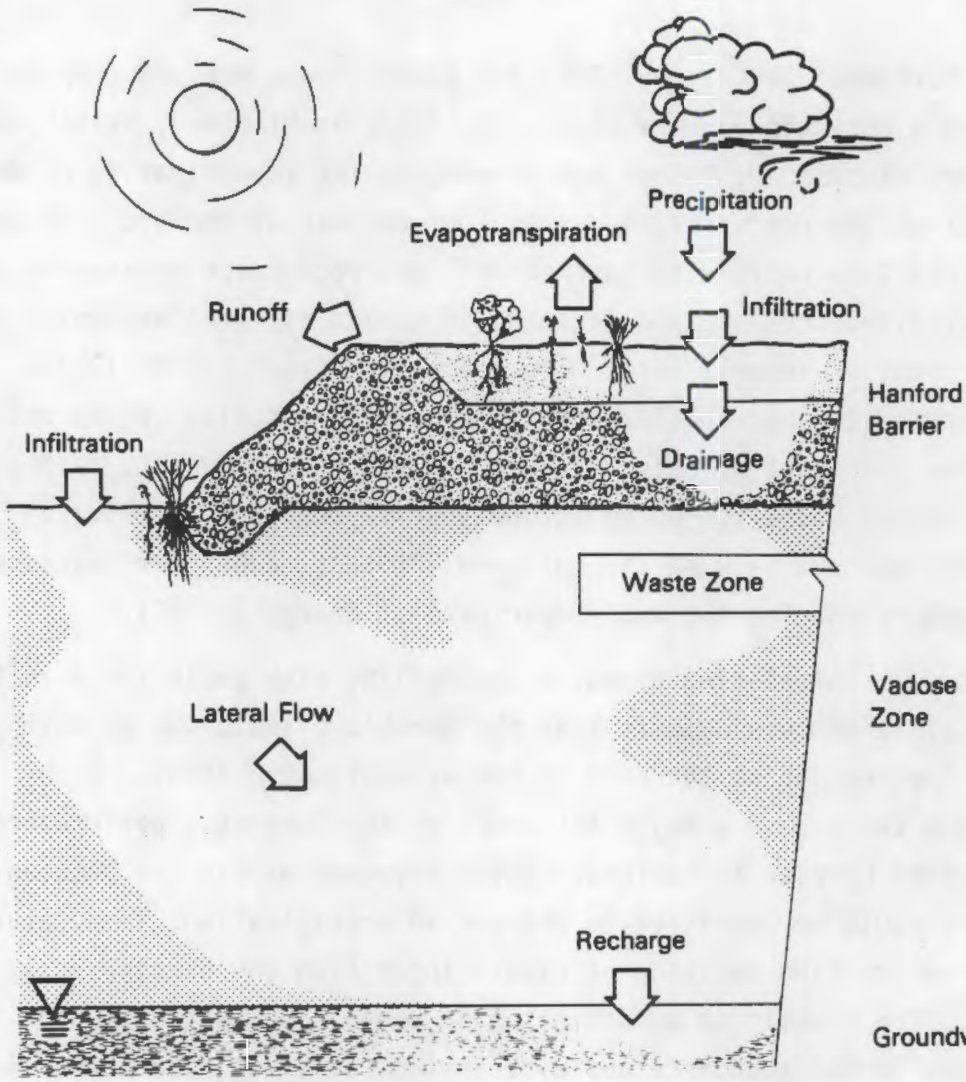

FIGURE 1.1. Soil-Water Balance Parameters Potentially Impacted by Climate Variability

The workshop was intended to address the following objectives:

- define climate issues and key parameters to use in barrier performance analyses
- assess the sensitivity of the Hanford disposal system and performance assessment models to climate variability
- critically examine prior assumptions about the impact of climate variability on moisture movement into and through the vadose zone

- develop a suggested plan to resolve climate-variability issues and quantify relevant parameters
- determine which defense waste disposal issues and parameters are not adequately addressed in climate characterization tasks proposed by the Basalt Waste Isolation Project (BWIP) and the Performance Assessment Scientific Support (PASS) program for commercial waste repositories.

Simulation models are the principal tools for predicting long-term barrier performance at Hanford. Predictive models of water movement, biointrusion, and erosion all may eventually be needed for an adequate performance assessment. The model development effort to date has focused primarily on simulating water movement. Consequently, the discussion of climate-input parameters during the workshop and the planning of tasks to acquire needed information both centered on this issue. (The planning of studies to acquire climate-change data to analyze biointrusion and surficial erosion awaits guidance from model developers in those areas.)

This report summarizes the format, results, and conclusions of the workshop. It also presents a preliminary task plan for acquiring climate data needed to evaluate water movement in barriers. This information will be incorporated into climate-change impact study plans during FY 1988.

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2.0 WORKSHOP FORMAT

The Climate-Impact Workshop was run as a facilitated brainstorming session. To keep the workshop group small (see Table 2.1), the technical scope of the workshop focused on the problem of estimating drainage variability at Hanford induced by climate changes. A minimum number of participants were selected to cover the required disciplines. A facilitator was used to enhance communications, promote creative technical exchanges among the participants, and to focus discussions by summarizing, synthesizing, and limiting digressions.

At the beginning of the 2-day workshop, each participant listed climatological issues thought to be important for the discipline he represented. Group participation at this stage was limited to amplifying the lists as they were presented to tie them to other disciplines. After listings were completed, participants combined them to summarize the direction the issues seemed to be moving and to define the key issues from which to develop a proposed issues hierarchy (see Section 3.0).

The remainder of the 2-day workshop was spent developing an issues hierarchy, defining workshop conclusions, and constructing a preliminary task plan.

TABLE 2.1. Climate-Impact Workshop Participants

Participant	Organization	Discipline Represented
PA Beedlow	PNL	Ecophysiology, plant ecology
MJ Fayer	PNL	Soil-water balance modeling
MG Foley	PNL	Quaternary geology (Facilitator)
GW Gee	PNL	Soil physics, evapotranspiration
GA Sehmel	PNL	Eolian processes
RL Skaggs	PNL	Surface-water hydrology
WH Walters	PNL	Global climate modeling
WJ Waugh	PNL[a]	Applied ecology, barrier design (Sponsor)

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(a) At the time the workshop was held, W. J. Waugh was employed by PNL.

3.0 ISSUES, PARAMETERS, AND RESULTS

During initial workshop sessions, participants listed all known or potential modeling parameters and a compendium of data-gathering and modeling-related issues. The lists were used to identify a key issue: the sensitivity of plant communities and evapotranspiration (ET) to climatic variability. The lists are not included here because they did not lead to an issues hierarchy and an ordered list of parameter needs, as was originally envisioned.

On the second day, the six climate-related issues of concern to the Protective Barrier Development Program were presented. Presentation of these issues was delayed until the second day so as not to bias the participants' thinking during the initial brainstorming sessions. The workshop only briefly discussed the fourth issue and did not address either the fifth or sixth issues.

1. Are available soil-water balance, erosion, and biointrusion models adequate for barrier performance assessment?

2. How sensitive is the waste disposal system to climatic variability? How sensitive are the performance assessment models to climatic variability?

3. What climate parameters are required to simulate water movement, biointrusion, and erosion on a Holocene time scale?

4. Will the commercial waste repository project's climate models produce satisfactory estimates of the variability of these parameters (i.e., are climate models capable of forecasting rainfall seasonality and intensity)?

5. Is it realistic to attempt to make probabilistic statements about future climate impacts?

6. Can measures of uncertainty in forecasts of continental glaciation and glacial flooding be reduced?

Initially, there was a general consensus among participants that the key issue to address was the sensitivity of site-scale recharge to climatic variability. It became apparent after the first sessions, however, that conceptual and computer models and supporting data for water extraction from the active (root) zone were lacking. Without this information, it was not possible to develop a hierarchy that defined the relative importance of climatic, sedimentologic, and hydrologic parameters. As is discussed below, participants concluded that there may be little climate-change impact on drainage from the active zone through the deeper vadose zone at Hanford. Because of this uncertainty, a decision-analysis-based issues hierarchy could not be developed. The active zone issues will have to be resolved before deeper vadose-zone issues can be addressed.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Based on workshop discussions, the following conclusions were made:

1. Regional and global climate-forecast models to be developed by the commercial waste repository project[a] will forecast climatic variability at 1,000 to 3,000-year intervals. The temporal resolution of these models will be inadequate to support barrier runoff, infiltration, and evapotranspiration models, which require monthly and diurnal data for many climate parameters.

2. As long as climate changes do not significantly alter the distribution of vegetation types, the key control on drainage below the root zone at Hanford may not be climate, but moisture storage and removal from the root zone.

3. Root-zone storage may cause a threshold effect for drainage.

4. The threshold effect may be variable and could be a function of soil properties, soil moisture profile, and plant-community dynamics. Workshop participants recommended measuring these variables and testing the threshold concept using high-precision weighing lysimeters.

5. Because no engineered barrier can credibly withstand a Missoula flood, glacial flood recurrence is considered to be a Performance Assessment Program, not a Barrier Development Program, issue.

In summary, modeling alone cannot be used to estimate the impact of climatic variability on barrier performance. Instead, large-scale lysimeter tests are needed to evaluate the moisture-recycling behavior of the root zone under current climate conditions for undisturbed areas and multilayer barrier

(a) In December 1987, the U.S. Congress directed that the Basalt Waste Isolation Project (BWIP) at Hanford be closed. As a result, the BWIP Climate Study Program was discontinued. However, regional and global climate modeling in support of siting a commercial waste repository at Yucca Mountain, Nevada, continues as part of the Performance Assessment Scientific Support (PASS) Program.

designs and to validate computer models for predicting the impact. Also, paleoclimate and paleovegetation studies must be performed to determine the late-Quaternary climate and vegetation history of the Hanford area and to identify potential sites at Hanford that are analogs of full-glacial climate conditions (temperature, precipitation, and vegetation) at Hanford's waste sites. Finally, global/regional/local climate modeling must be performed to evaluate the use of Hanford paleoclimate and vegetation data to bound future climate and vegetation variability for the 10,000-year period.

5.0 PRELIMINARY TASK PLAN

Based on the workshop conclusions, we propose the following technical tasks to obtain information needed to evaluate climatic-change impacts on water movement in protective barriers over the next 10,000 years. Figure 5.1 depicts the flow of information among tasks. This preliminary task plan will be further developed during FY 1988 into a set of study plans that will guide all future barrier climate research.

- Task 1 - reconstruct Pasco Basin vegetational patterns
- Task 2 - determine whether past climatic variability bounds forecasts of future climatic variability at Hanford
- Task 3 - locate sites with vegetation and climate analogous to the bounding scenarios
- Task 4 - install and monitor monolith lysimeters at climate-analog sites to obtain water-balance model input data
- Task 5 - validate model simulations of soil-water balance at climate-analog sites
- Task 6 - analyze chlorine-36 distribution in climate-analog site soil profiles as a tracer test of 30-year water movement patterns
- Task 7 - model carbonate distribution as a pedogenic indicator of water movement in soil profiles at climate-analog sites.

A rationale for and descriptions of these tasks are provided in Sections 5.1 and 5.2.

5.1 TASK RATIONALE

The model that would be used to simulate the impacts of climate changes on water movement in barriers, UNSAT-H (Fayer, Gee, and Jones 1986), requires hourly and diurnal input of certain climate and climate-related parameters. Climate models to be developed for the commercial waste site characterization

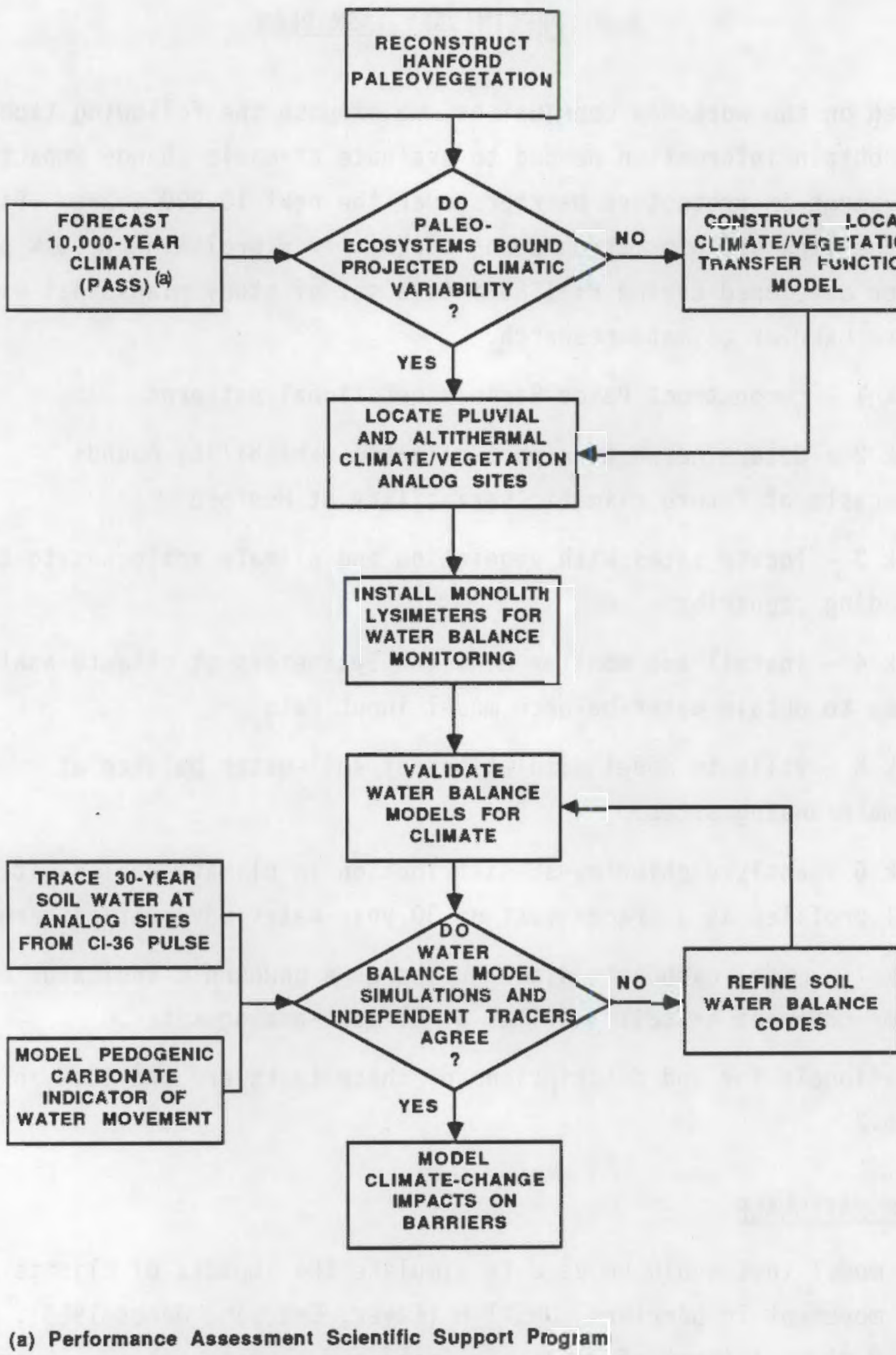

FIGURE 5.1. Information Flow Among Tasks Proposed for Assessing Climate-Change on Protective Barriers

would forecast many of these parameters, but only at 1,000 to 3,000-year time steps; an adequate resolution to capture glacial and interglacial impacts on the groundwater system, but grossly inadequate for vadose zone modeling. As concluded during the workshop, this insuperable disparity in resolution dictates an alternative approach -- measure water-balance model-input parameters at two or more locations that bound the range of climatic and vegetative variability expected during the next 10,000 years.

Drainage across the fine-coarse layer interface within a barrier (of adequate lateral extent) would be the primary source of water for radionuclide transport toward the groundwater. Drainage could occur as a threshold response to soil-water storage changes; drainage may not take place until the fine soil at the layer interface approaches saturation. If this hypothesis is true, then drainage would be relatively insensitive to climatic variability as long as water storage remained below the saturation threshold. Therefore, drainage, although ultimately a key barrier performance issue, is not a key parameter for measuring climate-change impacts.

In contrast, moisture removal from the root zone, evapotranspiration, is highly sensitive to climatic variability. In an operational barrier, evapotranspiration would maintain water storage levels below the saturation threshold. Because evapotranspiration is tied to plant-community composition and abundance, climate-induced changes in the vegetation could pose a salient climatic impact on barrier performance. Therefore, the selection of climate-analog sites for obtaining water-balance model input data should be based on vegetation type.

Just as contemporary vegetational distributions reflect modern climatic patterns, former vegetational distributions reflect past climatic patterns. Former vegetational patterns are also analogs of future patterns. The selection of climate-analog sites for water-balance model calibration would be based on a reconstruction of changes in Late Pleistocene and Holocene vegetation of the Pasco Basin. Paleovegetation patterns would be reconstructed from fossil pollen preserved in datable lake sediments and packrat middens. Before climate-analog sites are selected, however, these reconstructions would be compared with the commercial waste repository project's climate forecasts to determine whether climatic variability that caused former vegetational patterns bounds model-projected climatic variability for the next 10,000 years.

Currently, weighing lysimeters provide the most reliable measurements of evapotranspiration. To measure evapotranspiration from mature vegetation, monolith-type lysimeters that little disturb root systems and surrounding soil are needed. Such lysimeters would be constructed at wet and dry climate-analog sites to measure evapotranspiration as well as other water balance parameters needed for modeling climate-change impacts on water movement. Model calibration and validation would involve comparing simulated water storage changes in climate-analog site soils with actual soil-water profile data.

Water movement indicators such as pedogenic carbonates and chlorine-36 from bomb fallout would be examined as corroborative evidence for the model simulations. The distribution of each in soil profiles adjacent to the monolith lysimeters would be analyzed to obtain estimates of the depths and rates of water movement over the last 30 and 10,000 years, respectively. Carbonate and chlorine-36 distribution also could, conceivably, provide direct measures of long-term barrier performance, if layered soils that resemble engineered barrier configurations exist at selected climate-analog sites.

5.2 TASK DESCRIPTIONS

5.2.1 Task 1: Reconstruction of Pasco Basin Vegetational Patterns

The purpose of this task is to reconstruct changes in Pasco Basin vegetation during the Late Pleistocene and Holocene periods from an eastern Washington network of fossil pollen data. The selection of climate-analog sites, where monolith lysimeters would be constructed to monitor soil-water balance, would be based on this reconstruction.

Fossil pollen dating (palynology) is the principal technique for reconstructing terrestrial vegetational patterns and paleoclimates. Palynology is the only technique for reconstructing paleoclimates that has been widely and successfully applied in the Pacific Northwest (Baker 1983). The technique involves 1) extracting sediment cores from a network of lakes within and surrounding the target area, 2) age-dating the sediments using radiocarbon dating or tephrochronology (the use of distinctive volcanic ash layers of known age for relative age-dating), 3) estimating pollen percentages in dated strata, and 4) constructing maps of temporal and spatial vegetational patterns. A similar approach can also be used for fossil packrat middens.

Most existing pollen records from sites in and around the Columbia Basin extend back through the Holocene period, but no earlier because Late Pleistocene glacial floods destroyed earlier Quaternary sediments. Many of the sites are also distant from boundaries between major vegetation types, and thus may be relatively insensitive to shifts in plant distribution. For these reasons, existing pollen records may not provide a defensible analog of Pasco Basin vegetational patterns for the next 10,000 years. If existing post-glacial pollen data are judged to be inadequate records of Holocene and Late Pleistocene shifts in vegetation distribution, then the Barrier Development Program would fund the collection and analysis of additional fossil pollen cores. These cores would be extracted from sediments found in climate-sensitive locations and outside the influence of Missoula floods.

5.2.2 Task 2: Comparison of Past Climates Inferred from Paleovegetation and Climate Forecasts

This task would use the commercial waste repository project's climate-model forecasts to determine whether Holocene/late-Pleistocene climatic variability bounds climatic variability for the next 10,000 years. This bounding study would be critical in establishing the validity of the analog-site concept and finding analog sites at Hanford.

5.2.3 Task 3: Selection of Climate-Analog Sites

Assuming that Task 2 shows the analog-site concept to be valid, the goal of this task would be to select one or more sites that mimic what has been determined to be the pluvial climatic and vegetative conditions at the low-land waste sites. Similarly, altithermal analog sites would be used, if possible, to mimic the global greenhouse effects. Again, this task would rely heavily on paleovegetation studies for Hanford and on modeling the relationship between proxy data (e.g., fossil pollen) and paleoclimate.

5.2.4 Task 4: Installation and Monitoring of Monolith Lysimeters

The purpose of this task is to install monolith weighing lysimeters at the sites chosen as analogs of pluvial and altithermal vegetation/climate conditions at potential Hanford waste disposal sites. The lysimeters would be constructed large enough to contain the majority of the root zone, so that measured water losses closely reflect evapotranspiration from adjacent undisturbed sites. The lysimeters would be installed in pairs at each location (Figure 5.2) and the data would be networked and radiotelemetered to the laboratory for near real-time analyses. Plant and soil characteristics needed to run UNSAT-H would be measured for the monoliths and for adjacent areas. In addition, physiological parameters needed by UNSAT-H such as

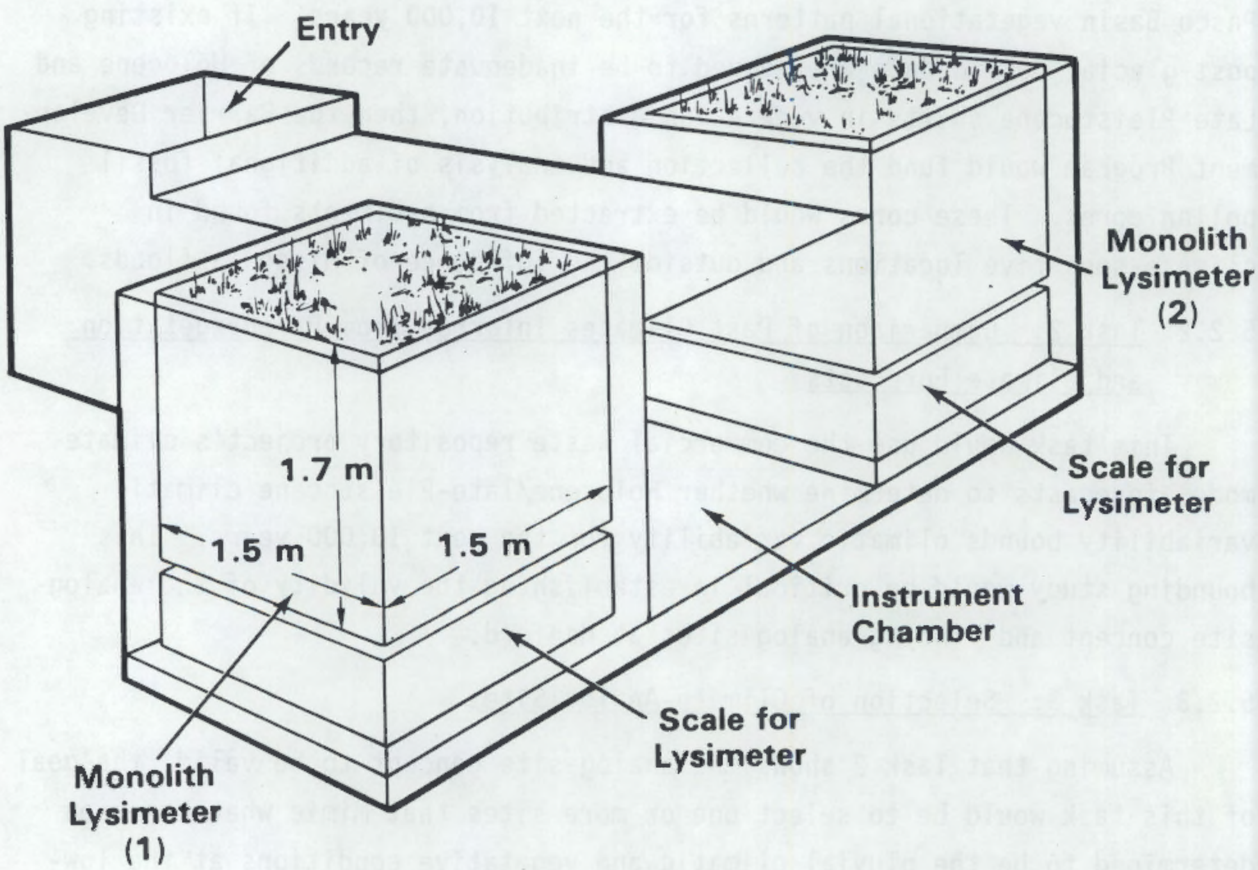

FIGURE 5.2. Paired Monolith Lysimeters for Monitoring Soil-Water Balance at Selected Climate-Analog Sites

stomatal resistance and leaf water potential, and phenological responses to temperature and other climatic variables (precipitation, vapor pressure, photosynthetically active radiation, and wind speed) would also be monitored.

5.2.5 Task 5: Climate-Analog Site Water Balance Simulation and Model Validation

In this task, data obtained with the monolith lysimeters would be used to validate UNSAT-H and, subsequently, to explore the possibility of detecting drainage pulses through barriers for a range of vegetation and climatic conditions. This model extended to two dimensions, or an alternatively suitable two-dimensional model, would be developed if significant heterogeneity were found in soil-moisture profile data from the vicinity of the altithermal- and pluvial-analog sites. If shown to be valid and if supported by field data, the two-dimensional model would be coupled with the one-dimensional models of evapotranspiration to enhance the credibility of estimates of the impacts of future climatic variability.

5.2.6 Task 6: Chlorine-36 Tracer Investigation

The purpose of this task is to investigate chlorine-36, released from nuclear weapons testing, as an indicator of water movement in layered soils at selected climate-analog sites. During the mid-1950s, surface thermal-nuclear tests injected relatively large amounts of chlorine-36 into the atmosphere. Within 10 years, most of this pulse was distributed globally on land and ocean surfaces. Given the hydrophilic nature of chloride, this fallout pulse would represent a 30-year tracer test for estimating net infiltration and recharge.

The method would involve extracting cores from selected soil profiles, leaching chloride from the samples, and then contracting with a lab to measure chlorine-36 in the extracted chloride with a tandem accelerator mass spectrometer (TAMS). The TAMS technique is highly sensitive. Phillips et al. (1984) analyzed chlorine-36 from desert soils in central New Mexico on a TAMS and estimated 0.02 mm/yr net infiltration at a 5-m depth.

Soil cores from disturbed and undisturbed plant communities at the wet and dry climate-analog sites would be analyzed for chlorine-36 distribution.

These analyses would be equivalent to 30-year tracer tests for recharge under the expected range of vegetation and climatic conditions to which barriers may be subjected.

5.2.7 Task 7: Pedogenic Carbonate Modeling

The objective of this task is to develop and validate a model of calcium carbonate accumulation as a function of soil-water balance variables. The model would be used to estimate long-term drainage through layered soils at selected climate-analog sites.

Calcic horizons and other caliche layers (layers of carbonate accumulation) have been observed in many Hanford sediment profiles. The distribution of carbonates in these sediments may be indicative of water movement patterns over hundreds and thousands of years. If not of lithogenic origin, these caliche layers are likely the product of bicarbonate equilibrium: carbonate dissolution, bicarbonate translocation, and the reprecipitation of carbonate

$$CO_2 + H_2O + CaCO_3 = Ca^{2+} + 2HCO_3^- \qquad (1)$$

If CO_2 concentrations remain relatively high in these sediments, then the depth of carbonate reprecipitation should be closely related to soil hydraulic properties -- water is removed by evapotranspiration and the reaction moves to the left. Therefore, the depth of caliche accumulation is likely strongly dependent on soil-water flow and, thus, sensitive to changes in mean annual precipitation and evapotranspiration.

The first phase of this task would be to characterize and confirm the origin of carbonates in the selected soil profiles. This would include descriptions of soil morphology and measures of bulk density and particle-size distribution for samples with and without carbonates. Soil-moisture parameters (hydraulic conductivity, plant-available water), elemental homogeneity of the parent material, carbonate distribution, and other chemical indicators of pedogenic carbonates would also be measured. Micromorphological features would be examined for evidence of carbonate precipitation, desiccation and CO_2 loss. It may also be possible to distinguish pedogenic and lithogenic carbonates using carbon-isotope analysis (Rabenhorst, Wilding, and West 1984).

A compartmental model, in which the soil column is represented by a vertical sequence of compartments of equal thickness, would likely be used to estimate water movement (McFadden and Tinsley 1985). Porosity, water-holding capacity, CO_2 content, and temperature would be specified for each compartment. Water movement would be calculated as a function of carbonate solubility, carbonate influx rates, and carbonate dissolution.

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