Assessment of Effectiveness of Geologic Isolation Systems

AEGIS Technology Demonstration for a Nuclear Waste Repository in Basalt

September 1982

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

Pacific Northwest Laboratory
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AEGIS TECHNOLOGY DEMONSTRATION FOR A
NUCLEAR WASTE REPOSITORY IN BASALT

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EXECUTIVE SUMMARY

The Office of Nuclear Waste Isolation (ONWI) directed the Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) Program to conduct a technology demonstration of current performance assessment techniques as applied to a nuclear waste repository in the Columbia Plateau Basalts. The technology demonstration began in FY 1979 and was completed in FY 1981. Hypothetical repository coordinates were selected for an actual geographical setting on the Hanford Reservation in the state of Washington. Published hydrologic and geologic data used in the analyses were gathered in 1979 or earlier. The following report documents the technology demonstration in basalt.

Available information contained in federal publications, state publications, Rockwell International reports, selected university studies, local consultant reports, and other sources have been used to establish the data base and initial hydrologic and geologic interpretations for this site-specific application. A simplified diagram of the AEGIS analyses is shown in Figure S.1. Because an understanding of the dynamics of ground-water flow is essential to the development of release scenarios and consequence analyses, a key step in the demonstration is the systems characterization contained in the conceptual model (Chapter 2). Regional and local ground-water movement patterns have been defined with the aid of hydrologic computer models (Chapter 3). Hypothetical release scenarios have been developed and evaluated by a process involving expert opinion and a Geologic Simulation Model for basalt (Chapter 4). (The Geologic Simulation Model can also be used to forecast future boundary conditions for the hydrologic simulation.) Chemical reactivity of the basalt with ground water will influence the leaching and transport of radionuclides; solubility equilibria based on available data are estimated with geochemical models (Chapter 5). After the radionuclide concentrations are mathematically introduced into the ground-water movement patterns, waste movement patterns are outlined over elapsed time (Chapter 6). Contaminant transport results are summarized in Chapter 7 for significant radionuclides that are hypothetically released to the accessible environment and to the biosphere.

FIGURE S.1. Simplified AEGIS Analyses

ASSUMPTIONS

The following assumptions used in the AEGIS technology demonstration are organized into six major categories and are annotated to indicate a conservative, nonconservative, or reasonable character. A conservative assumption tends to increase the severity of consequences, and a nonconservative assumption tends to decrease the severity of consequences. In general, the selection of assumptions was conservative; however, technical judgment was used to obtain reasonable estimates when appropriate. This approach does not relieve the eventual need to perform sensitivity analyses.

Assumption	Class	Comments
<u>Conceptual Model</u>		
1) Porous flow equivalent of composite transmissive zones in geologic cross-section	Reasonable	Integrates limited point source data into continuous lumped parameters (nonhomogeneous in areal extent)
2) Porous flow equivalent of composite confining layers in geologic cross-section	Reasonable	Integrates limited point source data into continuous lumped parameters (nonhomogeneous in areal extent)

Assumption	Class	Comments
3) Grande Ronde Formation is hydrologically similar to Wanapum Formation	Conservative	Limits ground-water flow to recharge/discharge within model boundaries
<u>Hydrologic Simulation</u>		
4) No flow boundary in Horse Heaven Hills and Blue Mountains	Conservative	Based on ground-water divide in Wanapum Formation and anticlinal structure
5) Pasco Basin is regional discharge area	Conservative	Topographic low in regional elevations, potentiometric low in Wanapum Formation
6) Vertical and horizontal ground-water flow in Pasco Basin	Conservative	Based on well hydrographs and hydraulic conductivities of basalt formations
7) Hydraulic conductivity increases in vertical direction and decreases in horizontal direction at anticlinal structures	Conservative	Based on interpretations of field data
8) Basalt formations generally discharge ground water to Columbia, Snake, and Yakima Rivers	Nonconservative	Fixed potential boundaries (elevation head)
<u>Geologic Simulation</u>		
9) Natural phenomena considered for one million years	Conservative	No threshold exceedance in first 250,000 yr
10) Natural phenomena consistent with past few million years	Reasonable	Basis for modeling statistics
11) Faulting is the most probable but unlikely natural event	Conservative	Estimated site-specific probability threshold of 10^{-8} or less
<u>Geochemical Simulation</u>		
12) E^H based on ground-water equilibrium with amorphous ferric hydroxide	Conservative	Fixes the maximum E^H value
13) Permissive equilibrium limited to 1/20 of the log of solid solubility product	Reasonable	Interpreted representation of accumulated errors

<u>Assumption</u>	<u>Class</u>	<u>Comments</u>
<u>Source Term</u>		
14) Raw spent fuel	Conservative	Only package geometry considered; no credit taken for canister, overpack, or backfill
15) Congruent leaching	Nonconservative	Rate of oxidation for uranium dioxide could be limiting instead of rate for release of uranium
16) PWR fuel assemblies are 10 yr old at interment	Conservative	Estimated temperature of 152°C at 100 yr for repository heat load of 53 kW/acre
17) 0.5% of the waste packages are released to ground water	Reasonable	Based on thrust faults associated with Umtanum Ridge, Gable Mountain, and Rattlesnake Hills, and repository design orientation
18) 14,000-yr leach duration time	Conservative	No credit taken for overpack, backfill, and additional solubility constraints of near-field environment
<u>Contaminant Transport</u>		
19) Inventory of 46,800 MTHM	Reasonable	Repository design
20) Majority of nuclide travel time confined to Grande Ronde and Wanapum Formations	Conservative	Based on hydrologic simulation and almost vertical pathway
21) Reducing ground-water environment with altered and secondary minerals in Grande Ronde and Wanapum Formations	Reasonable	Based on water quality data, basalt mineralogy, and geochemical simulation
22) Best estimate of sorption coefficients (K_d)	Reasonable	For retarded nuclides, K_d values range from 5 to 500

CONCLUSIONS

The AEGIS technology has been successfully demonstrated. The results of the basalt demonstration indicate that the geohydrologic systems separating the nuclear waste from the accessible environment and the biosphere mitigate

the consequences of the postulated fault intersection event. The analyses also suggests that the basalt system as defined satisfies the 1000- and 10,000-yr proposed standards for release to the accessible environment (limited release of ^{129}I and ^{14}C). However, the results presented are valid only for one particular set of parameters and one postulated release scenario. Sensitivity analyses must be performed to evaluate the range of effects that might be observed under different release conditions and different ranges in parameters.

In addition to establishing the utility of computer codes and assessment methodology, the AEGIS technology demonstration in basalt has produced some practical guidance for field data gathering programs. These suggestions are organized under the major categories of hydrologic simulation, geologic simulation, and geochemical simulation.

Hydrologic Simulation

The hydrologic simulations performed as part of the AEGIS technology demonstration in basalt suggest the following:

1. A better understanding of the nature of the vertical hydraulic conductivity within the basalt systems is needed. Vertical data describing hydraulic conductivity is required to assess potential vertical movement on a large scale. Structural features (if any) that give rise to the increase in vertical hydraulic conductivities (compared to estimates for dense basalt) that were required for model calibration need to be evaluated in more detail.
2. Because little field data exist, porosity measurements are required. Field data are needed to support the concept that horizontally conducting layers having high porosity act together with the low hydraulic conductivities and lower porosity of dense basalt layers to dominate vertical travel time (these dense layers control vertical flux). Field tracer tests required to verify this concept can also provide information on hydrodynamic dispersivity. The high storage coefficients estimated and observed in the basalts support the relatively high range in porosity deduced from this basalt demonstration.

3. Potential head measurements deep within the Grande Ronde are needed to verify the boundary conditions and regional flow effects deduced through this study.
4. A collection of historical records of potentials, pumping, and irrigation data is needed to use historical matching techniques to model, adjust, and determine vertical and horizontal distributions in hydraulic conductivity.
5. The measurements of recharge in the Rattlesnake Hills and Horse Heaven Hills are needed to affirm or refute the character of these boundaries.
6. Further field evidence is necessary to quantify the relationship that hydraulic conductivity decreases in the horizontal direction and increases in the vertical direction as the axis of an anticline is approached (also deformation zones associated with synclines).

Geologic Simulation

The AEGIS Geologic Simulation Model (GSM) has been operated in the Monte Carlo mode to generate several hundred possible futures of the geologic and hydrologic systems of the Columbia Plateau. Results of these analyses are plausible but not yet defensible because they are based on insufficiently documented and peer-reviewed input data and code. The GSM is completely developed as a research tool, but needs substantial review before it will be useful as a licensing tool. An important benefit of this review process is that it will help focus detailed site-characterization studies and will provide a framework in which to test the consistency of geologic and hydrologic field data.

Additional work can be divided into two categories: studies that will require substantial original scientific investigation, and studies that can be pursued through innovative application of current knowledge and a limited amount of additional work. Areas requiring the greatest amount of original work are 1) the prediction of future climate and climate-related effects such as continental glacier growth, glacially induced fracturing and isostatic deformation of bedrock, and Missoula-type flooding, 2) the estimation of changes in hydrologic properties of bedrock, which may be induced by folding and faulting.

The climate submodel of the GSM acts as a driver to other submodels, particularly those handling geomorphology, sea-level changes, glaciation, and the hydrologic system. Besides tectonics, climate is the principal dynamic component of the GSM, contributing to about half of the complexity of the model. Initial runs of the GSM suggest that climatic changes may have profound effects on the ground-water system in the Pasco Basin, both beneficial and deleterious at different times in the "future." Thus, the components of the climate submodel need careful review.

Input data to characterize the climate states can probably be developed from paleoclimatic parameters. Some parameters, such as the orographic effects of changes of relative elevation between the Pasco Basin and the Cascade and Rocky Mountains or of changes of sea level, may require limited original work by outside consultants, but not on a scale of generality to be excluded from the scope of site characterization work.

A related area of effort concerns the growth of the Cordilleran Ice Sheet and its relation to the Laurentide Ice Sheet (or global continental glacial activity) and to sea level. The present glaciation submodel represents the Cordilleran Ice Sheet as circular and synchronous with global glacier advance/retreat behavior. Such a representation probably would have been adequate if future glaciers had not been predicted to cross the Pasco Basin repeatedly. A more sophisticated representation is needed, and can probably be approached from a site-specific basis.

Missoula-type flooding, as modeled in the GSM, will cause net deposition in the Pasco Basin, or net erosion if Wallula Gap is seriously affected by future glacial advances. Results of the recent modeling effort suggest that net erosion by Missoula floods will not directly threaten a repository in the Pasco Basin, but will change potentiometric gradients in the confined ground-water system affecting such a repository. Topics needing further work in the GSM simulation of Missoula floods include the timing of floods relative to glacial advances; the probable magnitudes of the floods in relation to their timing; amounts of deposition of glacio-fluvial sediments in the Pasco Basin as a function of flood volume and the state of Wallula Gap; more detailed

work on the relation between flood volume, flow parameters, and erosion to be expected; and an estimate of how the hydraulic damming characteristics of Wallula Gap will change with time.

Changes in bedrock hydrologic properties from deformation, faulting or seismic shaking, and glacially induced stresses have been significant in the GSM simulations. However, treatment of these phenomena has been inconsistent because different consultants were responsible for parameterizing and characterizing different aspects of stress- or deformation-related changes. A uniform approach is necessary to analyze the hydrologic characteristics of fractured rock as well as how those characteristics vary with changes of stress or with deformation of the rock. This information is necessary for the GSM and for more detailed hydrologic modeling, and should be a multidisciplinary effort involving geologists, geophysicists, and hydrologists.

Geochemical Simulation

The ion speciation-solubility WATEQ2 model is a useful tool for determining the solid phases that limit the concentrations of dissolved constituents in ground waters. An extensive, thermodynamic data base and accurate and comprehensive analytical data for the ground water are necessary prerequisites of the successful application of this geochemical model to diverse aqueous systems. Without the inclusion of solubility data for amorphous solids and metastable minerals, identification of permissive solubility controls would be limited.

Based on the modeling results, calcite is at equilibrium with the basalt ground waters. In addition, amorphous phases, such as ferric oxyhydroxide, allophane, and SiO_2 (glass), apparently play an important role at ambient temperatures in limiting the maximum concentration of dissolved Fe, Al, and Si in the ground waters. Detailed mineralogical studies are needed to ascertain if solid phases such as gibbsite, dolomite, sepiolite, and MnHPO_4 (unnamed)--which similarly compute to be in equilibrium with these water samples--are in fact present as secondary minerals of the altered Columbia Plateau Basalt.

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CHAPTER 1

INTRODUCTION

In FY-1979, the Office of Nuclear Waste Isolation (ONWI) directed the Waste Isolation Safety Assessment Program (WISAP) to perform a reference site initial assessment (RSIA) of a hypothetical nuclear waste repository in the Columbia Plateau Basalt as a demonstration of the capabilities of WISAP and to assist in methodology development. The Basalt Waste Isolation Program (BWIP) provided data from sources already on hand, and the staff of WISAP developed preliminary release scenarios using a modified Delphi procedure. A preliminary repository simulation model was developed and documented (Stottlemire et al. 1981), and the evaluation of hydrologic data to be used for consequence analysis was initiated.

At the beginning of FY-1980, WISAP was divided into two separate projects according to the different management and technical needs for site applications and long-term basic research. The Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) Program continued the WISAP methodology development for scenario and consequence analysis and performed site applications; the Waste-Rock Interactions Technology (WRIT) Program continued the WISAP geochemical and related studies concerning waste-form leaching and sorption, and supported AEGIS site applications.

ONWI directed AEGIS to continue the technology demonstration in basalt that was initiated in FY-1979 and to issue a draft report for internal review by Department of Energy (DOE) contractors during the first quarter of FY-1981. On 1 February 1980, an agreement between Battelle and Rockwell was completed for a coordinated team approach to the basalt demonstration of AEGIS and the Site Characterization Report (SCR) of BWIP (see Appendix A). The completed AEGIS technology demonstration was to accomplish a more careful and detailed release scenario analysis, including use of the Geologic Simulation Model (GSM) for basalt, and a detailed consequence analysis commensurate with the available data, funds, and time. On 1 April 1981, the draft report was submitted to DOE as a programmatic milestone.

CONTEMPORARY STUDIES

Two contemporary studies were conducted at the Pacific Northwest Laboratory (PNL) that contributed to the basalt demonstration. They involved remote sensing within the Columbia Plateau and a detailed evaluation of hydrometeorological characteristics for the Pasco Basin. The results of both studies were used to develop an estimate of aquifer recharge for the hydrologic simulation. Aquifer recharge calculations provided an estimate of the amount of ground water conducted through transmissive zones in the basalt. Also, the recharge calculations were instrumental in providing boundary conditions needed to estimate transmissivity distributions for the deeper basalt systems. Both studies were funded through a shared Rockwell-Battelle arrangement designed to meet the joint technical needs of AEGIS and BWIP.

Remote Sensing Within the Columbia Plateau

In FY-1979, Rockwell Hanford Operations (RHO) sponsored a project at PNL to perform a land cover classification of 41,000 square miles of the Columbia Plateau using 1975 digital Landsat multispectral scanner data. This initial effort set the stage for a follow-on project that was initiated in FY-1980 to perform a more up-to-date analysis of the same area using 1979 Landsat digital data.

The original intent of the new study was to use most of the computer analysis routines developed during the FY-1979 project. However, recent changes in the format of the USGS-supplied Landsat tapes, as well as project emphasis on determining selected land cover changes between 1975 and 1979 (especially for the irrigated cropland), required extensive software revision and development. Because of the potential applicability of these selected land cover data to regional hydrologic modeling, support for the software developmental efforts was provided by the AEGIS program. Whereas project time and funding elements permitted only a preliminary land cover classification to be performed for the four 1979 Landsat scenes (e.g., only irrigated cropland and water classes were edited), efforts to develop and test a computer program for monitoring land cover dynamics were extremely successful. Accordingly, project results obtained relative to changes in irrigated cropland between 1975 and 1979 are considered

to be accurate within 10%. The remote sensing study contributed to the determination of regional recharge, as discussed in Appendix B.

Pasco Basin Hydrometeorological Study

The objective of the hydrometeorological study was to analyze available meteorological data and to prepare a new precipitation distribution (isohyetal) map of the Pasco Basin that included the effects of local topography on the distribution contours. The more detailed mapping primarily related variations in precipitation to changes in elevation. The study contributed to the evaluation of ground-water dynamics beneath the Hanford Reservation for RHO and to the determination of regional recharge for the basalt demonstration at PNL. Statistical correlations among the parameters of precipitation, evaporation, evapotranspiration, and snowfall were performed. The hydrometeorological study contributed to the determination of regional recharge, as discussed in Appendix B.

AEGIS TECHNOLOGY DEMONSTRATION

The performance assessment of long-term waste isolation involves a number of distinct analytical steps. Initially, the specific nature of the engineered components in the repository and of the surrounding geologic and hydrologic systems must be adequately understood. Because natural geologic processes and future human activities may alter these systems, an evaluation must also determine if there are plausible disruptive processes and events, in geologic time, for affecting the integrity of the repository. If such a process or event is identified, the transport of radionuclides from the repository to the environment, and the environmental impacts, can be estimated. AEGIS currently has the methods for performing these analytical steps.

The AEGIS approach is applicable at various levels of sophistication, depending on the analytical need and the amount of information available. The analytical methods are continuously improved to overcome deficiencies identified during technology demonstrations and as the site selection and licensing processes develop. The AEGIS approach for evaluating the effectiveness of a geologic repository has been discussed by Silviera et al. (1980). An appreciation

for the AEGIS methodology can be obtained from the schematic diagram of the AEGIS analysis followed during the technology demonstration in basalt, as shown in Figure 1.1. The dashed lines indicate existing or future capabilities not used in the basalt analysis.

Conceptual Model Development

The analysis begins with a search and compilation of the available geological, hydrological, and geochemical information for the region being studied. This information is usually obtained from sources such as Federal and state publications, DOE-sponsored programs, Landsat imagery (Stephen et al. 1979), other government agencies (e.g., USGS), and general scientific literature. RHO has summarized the available information for the Columbia Plateau Basalt. Because ground water is the most probable transport mechanism for radionuclides released from deep underground repositories, the local and regional geology and hydrology must be understood. This involves identifying the various aquifer systems and their hydrologic characteristics; the hydraulic connections between deep confined aquifers, shallow unconfined aquifers, and surface-water systems; and aquifer recharge and discharge locations.

The preparation of a conceptual model of the hydrologic and geologic systems requires the participation of scientists who are actively involved with identifying and characterizing the geological and hydrological properties of a particular site. The result is a composite description of the region, which includes interpretations of potentiometric surfaces, structural contours for the various geologic and hydrologic units, pumping distributions, and boundary conditions. Often this information must be interpolated from sources such as drilling logs, static well measurements from the same aquifer, topographic maps, meteorological measurements, and stream flow records. Usually, specific information must be interpreted from incomplete field data. Extensive data tabulations will require the use of a computer storage and retrieval system such as the Comprehensive Information Retrieval and Model Input Sequence (Friedricks 1980).

Geologic understanding of the natural processes of the region contributes to the preparation of a conceptual model. The geologic history of the region is determined through studies of the various rock types, their distribution in

FIGURE 1.1. Schematic Diagram of AEGIS Analysis

the area, and the regional and local structural features. Additional information involving the influence of geochemical effects on the integrity of the repository includes a chemical analysis of the ground water and the mineral types that may contact the ground water, as described by Deutsch (1980). This additional information can provide insight into the origin and source of ground water, residence time, and chemical evolution of the ground-water system. The conceptual model forms the common basis necessary to obtain compatibility between the hydrologic systems simulation and the geologic process simulation.

Hydrologic Systems Simulation

After the conceptual model of the hypothetical repository site and region has been developed, computer codes are used to simulate flow patterns within the hydrologic system. The hydrologic codes used as part of the AEGIS methodology include the Variable Thickness Transient (Reisenauer 1980), the Finite-Element, Three-Dimensional Ground-Water code (Gupta et al. 1980a), and CFEST (Gupta et al. 1980b). Information obtained from the hydrologic models is then used for input into the source term model and the radionuclide transport model.

An important characteristic of the AEGIS computer code usage is the interactive computer system. Interactive computer systems allow the user to receive immediate response from the computer, greatly enhancing code and model development. Because the AEGIS computer codes must be adapted to model the conceptual description of the particular repository region, the interactive computer system makes that process efficient and, more importantly, increases the involvement of hydrologists and geoscientists in the AEGIS computer operations. Thus, the output from these codes can be readily used to evaluate and refine the conceptual model of the regional and local hydrogeologic systems, and to plan future data gathering activities.

Geologic Process Simulation

The geology and environment surrounding a repository will continue to change over geologic time. Projections of the possible evolutionary paths can be made from knowledge of the geologic history of the region, the existing states of the geologic and hydrologic systems, and the scientific understanding of the geologic processes in effect. AEGIS staff use the conceptual description

of the existing hydrogeology as a focus for evaluating future states of the system. The expertise of a team of consultants is employed to help characterize the natural processes that could affect the repository. A computer model is used to assist the AEGIS staff and consultants in the analysis and in keeping track of the potentially large numbers of natural processes and interactions.

Based on these considerations, AEGIS methodology identifies and quantifies geologic states that result in a loss of repository integrity and, thus, need to be further analyzed (Stottlemire et al. 1981). Development of AEGIS technology has been driven by the need to provide an auditable method for the derivation and quantification of these geologic states of interest, with estimates of the plausibility and time of occurrence. In this process, the justification can be developed for discarding other implausible future projections.

If the Geologic Simulation Model (GSM) identifies a process or series of events that cause a loss of repository integrity (Petrie et al. 1981), then the input data for the hydrologic models are modified to reflect the boundary conditions surrounding that geologic state. The information obtained from the GSM is further used as input into the development of a source term model.

Geochemical Modeling

Geochemical modeling aids in the identification of geochemical processes that regulate the concentration of dissolved radionuclides released and transported from a repository. Computer simulations involve both near-field and far-field aspects of performance assessment, and help to quantify the effects of temperature, speciation, sorption, and solubility on the concentrations of dissolved constituents. Two types of geochemical models are available at PNL. The WATEQ speciation-solubility model estimates the closeness to equilibrium of dissolved constituents and solid phases (Truesdell and Jones 1973, 1974; Plummer et al. 1976; Ball et al. 1979, 1980). The EQ3/EQ6 reaction path model predicts the resulting composition when ground water of a given chemical composition reacts with a specific mineral or mineral assemblage (Wolery 1978, 1979). Geochemical models provide information for source term development and the selection of distribution coefficients for transport modeling.

Source Term Modeling

Analysis of ground-water transport of radionuclides from a nuclear waste repository depends on an appropriate definition of a "source term"--a projection of the rate of release of radionuclides from the repository (Kuhn 1980). Development of the source term is influenced by a detailed release scenario, aquifer interconnections, and the near-field flow regime. In addition, local ground-water chemistry, canister and backfill materials, and temperature profile from the heat generated by the nuclear waste must be considered. Ground water that hypothetically contacts the waste may be an oxidizing or a reducing agent and may affect the waste leach rate and solubility limit. The WRIT Program at PNL supports AEGIS applications by defining a source term; however, the development of a useful model requires a multidisciplinary approach incorporated into AEGIS methodology demonstrations on an ad hoc basis. The source term model provides radionuclide concentration profiles to the transport model.

Transport Modeling

The codes used for radionuclide transport, like the ground-water codes, are multi-dimensional and interactive. These codes include the Multicomponent Mass Transport code (Washburn et al. 1980) and the GETOUT code (DeMier et al. 1979). Radionuclide migration as affected by the geologic medium is simulated by a distribution coefficient (K_d). The K_d is a measure of the ability of a geologic medium to retard a given radionuclide. A storage and retrieval system for experimental data on sorption/desorption analyses for a wide variety of radionuclides, ground-water compositions, rocks and minerals is the Sorption Information Retrieval System (Hostetler et al. 1979, 1980). In addition to distribution coefficients, other code input includes:

- ground-water flow velocity
- longitudinal dispersivity
- flow path length
- dimensions of the stream tube
- nuclide half-lives
- a matrix describing radionuclide chain decay
- porosity
- leach rate information.

After the radionuclide concentrations are mathematically introduced into the ground-water movement patterns, waste movement patterns are outlined over elapsed time. Contaminant transport results can be summarized by profiles of point-source concentration versus time profiles of concentration versus arrival distribution for significant radionuclides that are hypothetically released to the biosphere. When appropriate, dose models are used to calculate radiation doses to man directly or to man through his food chain.

Dose Modeling

When radionuclides are released to the atmosphere or to surface waters, they may disperse or they may accumulate in the environment. Even short-term (acute) releases can lead to long-term environmental contamination, which in turn leads to long-term irradiation of individuals and populations. Pathways of these radionuclides to human exposure include direct radiation from contaminated air, water, sediment, and soil; ingestion of contaminated drinking water, aquatic food products, terrestrial farm crops, and farm animal products; and inhalation of airborne materials. These exposure pathways are evaluated by AEGIS staff using computer codes such as KRONIC, SUBDOSE, DACRIN, and PABLM (Streng and Watson 1973; Streng et al. 1974, 1975; Napier et al. 1980). Site-specific information about demography, local crop production practices, eating habits, and recreational activities is required as input for these codes. Dose modeling was not included in the basalt demonstration.

Future AEGIS Capability

AEGIS methodologies will ultimately be used for design, site selection, and licensing analyses. The geologic simulations will use models of waste form behavior and engineered barriers to describe some of the boundary conditions, initial conditions, and source terms for the ground-water flow and transport. As more data on engineered barriers, leaching rates and solubility limits of the waste form become available, and the near-field codes from the Waste Isolation Performance Assessment Program (WIPAP) become operational, they will be incorporated into the AEGIS consequence analysis. This analysis will eventually include:

- changes in local and regional conditions to reflect the bounds of the GSM
- realistic modeling of the waste- and repository-induced effects
- more complex modeling of the waste form leaching, solubilities, and engineered barriers for the perturbed conditions postulated from the geologic simulations
- prediction of the radiation dose levels for humans and their environment, where those calculations are appropriate
- predictions of the variances on the flow, transport, and dose results, as the uncertainty analysis methodology develops.

Waste-induced effects (near-field phenomena) will be included in AEGIS performance assessment methodologies of the future. The path leading to this operational capability must take into account the predominantly far-field focus of previous performance assessment efforts at PNL. A major change in scope from principally far-field to balanced far-field and near-field was initiated in the latter half of FY-1981. In addition, recent ONWI directives indicate a broader AEGIS scope, including all facets of waste isolation (i.e., waste package, repository, site, and system). In FY-1982, the AEGIS project will establish capabilities needed in near-field methodology and evaluate in-house and incoming computer codes from the SCEPTER Program (INTERA Environmental Consultants, Inc.).

CHAPTER 2

BASALT CONCEPTUAL MODEL

Initial considerations in characterizing the regional ground-water flow in the Columbia Plateau Basalt included a three-level conceptual system proposed by RHO (Deju and Fecht 1979). In this preliminary characterization, the stratigraphy of the Columbia Plateau Basalt was grouped into shallow, intermediate, and deep ground-water flow zones, as has been generally suggested by Toth (1963). However, the regional flow regime was more recently grouped according to the major basalt formations (Saddle Mountains, Wanapum, and Grande Ronde) by Gephart et al. (1979a). Available information is most abundant for the Saddle Mountains Formation and least abundant for the Wanapum and Grande Ronde Formations. The apparent lateral boundary for the lower hydrologic system consists of the Spokane River to the north, the Idaho batholith to the east, the Blue Mountains to the southwest, and the Cascade foothills to the west (see Figure 2.1).

Computer modeling of the Columbia Plateau Basalt by the U.S. Geological Survey (USGS) was discussed by USGS and AEGIS staff in Tacoma, Washington, on 29 November 1979. The USGS uses a three-layered transmissive configuration that generally conforms to the known basalt stratigraphy to characterize the ground-water flow system. The three layers used in the Columbia Plateau modeling are not conceptually identical to those proposed by RHO for Pasco Basin, and they include a representation of the transmissive zones in the basalts located below the Grande Ronde--called "Picture Gorge." The Saddle Mountains and Wanapum Formations in composite form the top layer; the middle layer represents transmissive zones in the Grande Ronde Formation. In general, the northern, northeastern, and eastern boundaries of the modeled region follow the perimeter of the Columbia Plateau Basalt, as shown in Figure 2.2. The Craigmont monocline and Limekiln fault appear to form the southeastern boundary. Ground-water divides in the Blue Mountains and the Horse Heaven Hills

FIGURE 2.1. The Columbia Plateau Basalt

anticline form the southern boundary. Anticlines of the Yakima fold belt sub-province form the western boundary, and seepage faces at the edge of the basalt plateau form the northwestern boundary.

Various basins within the Columbia Plateau Basalt have been studied individually through the use of numerical computer methods. Some of these studies are listed by way of introduction to the conceptual model proposed by Lawrence Berkeley Laboratory (Apps et al. 1979). Because of the early interest in storage of defense wastes on the Hanford Reservation, the Pasco Basin contains the largest number of shallow and deep exploratory boreholes on the basalt plateau.

FIGURE 2.2. Regional Ground-Water Model Boundaries [The map shows location of geologic structures and outline of basalt plateau digitized from a tectonic map by Newcomb (1970). Ground-water flow directions and approximate model boundaries were obtained from discussions with the USGS Hydrologic Division, Tacoma, Washington.]

Figure 2.3 shows a significant decrease in the number of documented wells that penetrate to successively greater depths below land surface in the Pasco Basin. More than 90% of the wells are contained in the upper 600 ft of the Columbia River Basalt (Schalla and Leonhart 1981). This may be compared to the minimum thickness of 5000 ft for basalt within the Pasco Basin.

FIGURE 2.3. Distribution with Depth of Pasco Basin Wells for which Drillers Logs were Available (Schalla and Leonart 1981)

Lawrence Berkeley Laboratory has proposed a two-level system to describe the ground-water flow in the Pasco Basin: the shallow sedimentary system (including the Ringold Formation and other alluvial materials), and the basalts of the Columbia River Basalt group. The contact between the shallow sedimentary system and the basalt group is the Saddle Mountain Formation, and the lower boundary of the deep basaltic system is considered to be a few thousand feet below the Umtanum member of the Grande Ronde Formation. The lateral limits of the deeper ground-water system in the Pasco Basin was not clearly defined (Apps et al. 1979).

Four hydrologic systems that are operative within and beneath the Pasco Basin are described by RHO: surface water bodies, the unsaturated zone, unconfined aquifer, and confined aquifer systems (Gephart et al. 1979a). The Columbia, Snake, and Yakima Rivers converge in the southern portion of the

Pasco Basin. The unconfined aquifer beneath the Hanford Site includes saturated sediments of the Ringold Formation and other fluvial and glaciofluvial sands and gravels (see Figure 2.4). The lateral boundaries of the unconfined aquifer are identified by the basalt structures that rim the Pasco Basin. These structures include the Saddle Mountains to the north, Umtanum and Yakima Ridges on the west, Rattlesnake and Horse Heaven Hills on the south, and a broad monocline on the east (Gephart et al. 1979a). The confined aquifers are divided into an upper and lower set of flow systems. The upper-most confined aquifers include transmissive zones within the lower Ringold Formation and the Saddle Mountain Basalt. The lowermost confined aquifers include transmissive zones within the Wanapum and Grande Ronde Formations.

AEGIS CONCEPTUAL APPROACH

Available data and interpretations of hydrology and geology applicable to the Columbia Plateau Basalt and particularly to the Pasco Basin have been summarized to establish a conceptual model or systems characterization that is common to both the hydrologic and geologic simulations. The purpose of hydrologic modeling on the basalt demonstration is to simulate the hydrogeology of the deep basaltic system beneath the Hanford Site at the horizon where the hypothetical waste repository would be located. To establish the boundary conditions for such a localized model, it was first necessary to understand the hydrogeology of the surrounding basin and of the surrounding region, and finally to define a ground-water unit. In particular, the ground-water unit must reflect an understanding of the recharge and discharge mechanisms of the deep basalts that include: 1) the locations and amounts of recharge and discharge at the basalt outcrops and perimeters, 2) the hydraulic connection between the various basalt flows, 3) the hydraulic connection between the confined aquifers in the basalts and the shallow unconfined aquifer systems as well as between the basalts and the Columbia, Snake, and Yakima Rivers, and 4) the hydraulic connection across the lower boundary of the deep basalt layer.

To overcome some of the difficulties presented by a lack of detailed knowledge about the deep ground-water regime of the Columbia Plateau Basalt,

FIGURE 2.4. Hydrogeologic Column for the Pasco Basin (Gephart et al. 1979a)

modeling for release scenario and consequence analysis was based on steady-state representations of the surface and ground-water systems. The steady-state approach has also been the basis for regional hydrologic modeling performed by the USGS in Tacoma, Washington.

The overall strategy for hydrologic simulations has been to develop a regional model of the major portions of the Columbia Plateau Basalt that serve as a source of recharge waters or in other ways influence the flow or movement of circulating ground water within the more local Pasco Basin. As shown in Figure 2.1, the Columbia Plateau Basalt extends over southeastern Washington, northeastern Oregon, and parts of west-central Idaho. Hydrologic and geologic data and interpretations indicate that boundary conditions can be defined for a regional simulation of ground-water flow in the portion of plateau basalts that are located in southeastern Washington. However, because of a lack of hydrologic and geologic data with increasing depth, reasonable assumptions regarding hydrologic similarities with overlying stratifications are necessary. A regional hydrologic model using the multiaquifer, two-dimensional VTT code (Reisenauer 1980) was implemented to simulate the recharge and discharge mechanisms and the flow characteristics of the deep basalts over most of southeastern Washington. For more detailed modeling of the Pasco Basin, a finer-grid subregion model using the fully three-dimensional FE3DGW code (Gupta et al. 1980a) and boundary conditions established by the regional hydrologic model was implemented to more closely define ground-water flow patterns for transport modeling (see Chapter 3).

The current systems characterization of the Columbia Plateau Basalt produced a reduction in the initial complexity of the Geologic Simulation Model (GMS) envisioned for release scenario analysis (Petrie et al. 1980). Review of a simplified cross section of the regional hydrogeology proposed by the USGS allowed for the elimination of the alpine glacier submodel from the GSM and the incorporation of all hydrologic considerations into a single submodel. The computer model is designed to permit simulation of the geologic and hydrologic system response, as a function of disruptive phenomena and time, for a period of a million years. The time frame chosen is long enough to accomodate future

requirements for analyses for thousands, tens of thousands, or even hundreds of thousands of years. It is not, however, so long that the model must consider significant changes in the details of global tectonic activities and rates. Eleven submodels, each of which addresses a class of disruptive phenomena compose the computer model: 1) Climate, 2) Continental Glaciation, 3) Deformation, 4) Geomorphic Events, 5) Hydrology, 6) Magmatic Events, 7) Meteorite Impact, 8) Sea-Level Fluctuations, 9) Shaft-Seal Failure, 10) Sub-Basalt Basement Faulting, and 11) Undetected Features. These submodels address the disruptive natural phenomena that may, alone or in concert, affect the safety of a waste repository located in a layered basalt geologic system (see Chapter 4).

The GSM is designed to be flexible enough to incorporate objective and subjective input from a variety of geoscience disciplines, and is operated in single-run and Monte Carlo modes. The single-run mode provides for user selection of desired disruptive events and associated rates and magnitudes. The Monte Carlo mode involves pre-established distributions for individual phenomenon occurrences, rates, magnitudes, and phase relations. This technique generates a large number of disruptive event sequences, which may then be analyzed by geoscientists for plausibility. The ones found plausible are assessed for likelihood by a statistical package, and those which exceed regulatory probability standards (e.g., those of the Nuclear Regulatory Commission) become the design disruptive sequences for consequence analysis (Petrie et al. 1980).

Input from geoscientists is critical at all stages of the disruptive sequence selection and consequence analysis. The computer model is designed to complement the efforts of the geoscientist by providing broad outlines of long-term geologic and hydrologic changes that might occur in the vicinity of the repository. The geoscientist abstracts this information, identifies patterns and trends, classifies histories, and provides detail where needed. The geoscientist may also change the input data to test any insights gained in the abstraction process (Petrie et al. 1980).

The AEGIS conceptual model for the basalt demonstration has a regional aspect characteristic of the Columbia Plateau Basalt and a local aspect similar to Pasco Basin. Definition of the hydrology and geology of both aspects depends on the information obtained from current and planned field programs of RHO and others. Thus, details within the conceptual model will continue to improve with time, but the frame-work of regional and local aspects should remain constant. Geologic and hydrologic characteristics of the conceptual model are summarized to provide an overview useful for mathematical modeling.

GEOLOGIC CHARACTERISTICS

The Columbia Plateau Basalt covers an area of approximately 78,000 square miles and contains an estimated basalt volume of 41,000 cubic miles. The topographic low occurs in the approximate location of Pasco Basin where the accumulation of flows from the Columbia River Basalt and the interbedded sediments attain their maximum known thickness of over 4500 ft. Flows range in thickness from a few inches to more than 300 ft with an average thickness of 90 to 120 ft (Myers et al. 1979).

Physical Geometry

The regional aspect of the conceptual model covers approximately 21,000 square miles in southeastern Washington, as shown in Figure 2.5. The northern and eastern model boundaries follow the perimeter of the Columbia Plateau Basalt. Seepage faces form the northwestern boundary where the Columbia River is incised into the basalts. The remainder of the northern boundary and the eastern boundary follows the Spokane River and the Idaho border, respectively. The conceptual model boundaries are essentially the same as the regional boundaries used by the USGS.

The western and eastern model boundaries cut across the Columbia Plateau rather than follow the basalt perimeter. The southeastern boundary follows the Craigmont monocline and the Limekiln fault. These geologic structures, discussed in Bond (1963), are probably a very effective barrier to ground-water flow. To the southeast of the Craigmont monocline and the Limekiln fault, the basalt becomes thin and highly folded and faulted. It is unlikely that significant volumes of ground-water flow laterally through these structures.

FIGURE 2.5. Geologic Map of the Central to Northeast Portion of the Columbia Plateau Basalts

Ground-water divides on the Horse Heaven Hills anticline and the Blue Mountains form the southern boundary. Composite water elevations of the Saddle Mountain and Wanapum Formations (Gephart et al. 1979a) show a no-flow boundary in the Horse Heaven Hills. Insufficient data exists to establish the same ground-water divide for the Grande Ronde Formation; however, it is reasonable to assume that a similar no-flow boundary is present.

East-west trending anticlines of the Yakima Fold Belt Subprovince form the western boundary along the Columbia River between Wenatchee and Priest Rapids Dam. Mackin (1961) describes a structural axis (called the Hog Ranch axis) that trends nearly north-south and follows the high points on the east-west trending anticlines of the Yakima Fold Belt. Well data collected from the local area support a ground-water divide near the Hog Ranch axis that appears to be a low, broad anticlinal structure.

Regional stratigraphy in the conceptual model has been grouped according to the simplified geologic and hydrologic cross-section shown in Figure 2.6. The Ringold Formation is mostly limited to the Pasco Basin. The Saddle Mountains Formation generally outcrops in the southwestern portion of the model area where it probably causes confining conditions in the upper Wanapum basalt flows. To the southeast, the Saddle Mountain Formation mantles some of the interstream divides and may contain some perched water or shallow ground-water systems. Within the modeled area, the Wanapum Formation is exposed more than any other formation. The Wanapum Basalt thins northward and eastward so that the Grande Ronde Basalt occurs near the surface at the northern and eastern margins of the basalt plateau. The Grande Ronde Formation is exposed in the Blue Mountains and in the vicinity of Table Mountain Anticline where Wanapum Basalt was either not deposited or removed by erosion. In general, the basalt sequences have a southwesterly dip such that the Grande Ronde may be included, at least in part, within the shallow or intermediate flow systems along the Washington-Idaho border, but within the deep or regional flow system at the Hanford Site.

Confining layers separate the composite transmissive layers, as shown in Figure 2.6; however, the total vertical movement of ground-water is quite

FIGURE 2.6. Simplified Conceptual Model of Regional Ground-Water Flow (Section AA' from regional aspect shown in Figure 2.2)

significant over most of the model region. The Grande Ronde is largely confined over the entire model area while the Wanapum is mostly unconfined in the north-eastern portion of the region. Composite confining layers in the hydrologic model were represented by interaquifer transfer coefficients (vertical hydraulic conductivity divided by the effective thickness of the confining layer) or leakance (Lohman 1972). A confining layer below the Grande Ronde Formation (unspecified horizon) acted as the bottom surface of the conceptual model.

Rock Properties

Data describing the material properties of the various layers within the model region are limited. Lack of detailed stratigraphy makes the thickness of basalt formations difficult to determine. Therefore, general transmissivity values will be used in the hydrologic and geologic simulations rather than specific hydraulic conductivities and formation thicknesses. Based on specific capacity tests, transmissivity values for the Wanapum Basalt range from 10,000 gpd/ft to 70,000 gpd/ft, with the average being about 30,000 gpd/ft. The limited data indicate that the typical Grande Ronde transmissivities in the Columbia Plateau may be twice as large as those for the Wanapum. Seepage face transmissivities have been selected to be about 100 gpd/ft.

Information regarding general trends in hydraulic conductivity may be helpful in calibration of the hydrologic and geologic models. Basalt permeability may be largely a result of cooling joints and other fractures (LaSala and Doty 1971). LaSala et al. (1973) believe the average hydraulic conductivity in basalt to be much greater in the direction concordant with the dip than in the cross-bed direction and, in areas uncomplicated by structural features, that ground water tends to move more readily in a horizontal rather than vertical direction. Typical ranges of hydraulic conductivities are shown in Table 2.1, and estimates of effective porosity are shown in Table 2.2.

Values of storage coefficient for confined basalt aquifers in the Columbia Plateau range from 1.5×10^{-3} (Luzier and Burt 1974) to 1.6×10^{-4} (Eddy 1976). Few tests of separate basalt formations have been made individually; therefore, the same average value of storage coefficient will be used initially in the regional hydrologic model for the confined portions of the Wanapum and Grande Ronde Formations.

TABLE 2.1. Ranges of (Horizontal) Hydraulic Conductivities Observed for Various Lithologies Within Formations of the Columbia River Basalt Group (Summers and Weber 1978)

<u>Formation</u>	<u>Dense Interiors (ft/day)</u>	<u>Interflows (ft/day)</u>	<u>Interbeds (ft/day)</u>
Saddle Mountains	0.01 to 0.1	0.1 to 40	0.1 to 60
Wanapum	0.001 to 0.01	0.01 to 10	0.1 to 40
Grande Ronde	0.001 to 0.01	0.0002 to 300	0.003

TABLE 2.2. Estimates of Effective Porosity for Various Lithologies Within the Columbia River Basalt Group and Associated Interbeds (La Sala and Doty 1971).

<u>Lithologic Character</u>	<u>Estimated Effective Porosities (%)</u>
Sedimentary Interbed	20 ^(a)
Fractured Basalt Zone	16
Vesicular Basalt	5
Dense Basalt	1 or less

(a) This value is probably very high. Actual values are probably less than 10% (La Sala and Doty 1971)

Knowledge of the basalt stratigraphy improves considerably within the boundaries of the Pasco Basin and particularly within the Hanford Reservation. Selected hydraulic parameters for the Pasco Basin are listed in Table 2.3. A summary of hydraulic conductivity across low-density zones and across columnar zones of the Grande Ronde Basalt is shown in Figures 2.7 and 2.8, respectively.

TABLE 2.3. Summary of Hydraulic Properties in the Pasco Basin (Deju and Fecht 1979)

Material	Hydraulic Conductivity (ft/day)	Storage Coefficient	Porosity (%)	Remarks
Unconfined Aquifer Glaciofluvial sediments	1,200 to 12,000 (6,000)	5×10^{-2} to 4×10^{-1} (3×10^{-2})	Estimated 5 to 20	Mostly dry (above water table)
Unconfined Aquifer Upper and middle Ringold sediments	1 to 200 (60)	8×10^{-4} to 2×10^{-1} (1×10^{-3})	Estimated <12	---
Confined Aquifer Lower Ringold	0.10 to 7 (2)	Estimated $\sim 10^{-3}$	Estimated 5 to 20	Extremely clayey material
Saddle Mountains Basalt Dense basalts Brecciated basalts Interbeds	0.030 to 10 (0.030) (0.030) (2)	2.7×10^{-5} to 1.2×10^{-3} (1×10^{-4})	1.00 to 3.95 (2.00)	Most of the hydraulic conductivity is through the interbeds
Wanapum Basalt Dense basalt Brecciated basalts Interbeds	0.020 to 10 (0.020) (0.030) (1)	2.7×10^{-5} to 1.2×10^{-1}	1.00 to 4.00	Most of the hydraulic conductivity is through the interbeds
Grande Ronde Basalt Umtanum Dense basalt Brecciated basalts Interbeds	7.3×10^{-7} to 1×10^{-2} (1×10^{-6}) (0.003) (0.01) (0.003)	1×10^{-5} to 1×10^{-3} ($<1 \times 10^{-4}$)	1.00 to 25.00 ^(a) (3.00)	Lowest hydraulic conductivities found

(a) High value in one sample of brecciated basalt

DATA FROM BOREHOLES
DC-1, DC-6, AND RSH-1

FIGURE 2.7. Range of Hydraulic Conductivity Across Low-Density Zones Within the Grande Ronde Basalt in the Pasco Basin (Gephart et al. 1979a)

DATA FROM BOREHOLES
DC-1, DC-2, AND RSH-1

FIGURE 2.8. Range of Hydraulic Conductivity Across Columnar Zones Within the Grande Ronde Basalt in the Pasco Basin (Gephart et al. 1979a)

HYDROLOGIC CHARACTERISTICS

Regional flow of ground water tends to be southwestwardly across the model area, as shown in Figure 2.2. Exceptions to this general flow appear to be:

- at the northern perimeter of the Columbia Plateau Basalt where ground water may be flowing toward the edge of the plateau because of potentiometric highs within the model boundary
- north of the Blue Mountains where ground water tends to flow northward toward the Snake River
- in the western portion of Pasco Basin where ground water tends to flow generally eastward toward the Columbia River.

Boundary Conditions

The boundary conditions for both the Wanapum and Grande Ronde Basalts are very similar. A major source of recharge to both aquifers is the area along the northern and eastern perimeter of the plateau where the basalt flows are closer to the ground surface and the regional precipitation is greatest. A significant amount of recharge to the basalts still occurs over much of the model region as a result of infiltration by precipitation, by irrigation water, and by storm runoff in channels crossing the basalts. Because the surface layer is hydrologically modeled as a constant head condition only along the major surface-water systems, a fraction of the precipitation and irrigation recharge will input directly to the Wanapum Basalt in the model region.

Recharge is considered to be minimal in portions of the Pasco Basin where:

- precipitation is lowest, regionally
- irrigation is not practiced
- Ringold Formation clays are present.

The Snake and Columbia Rivers directly contact different basalt formations as they flow toward the Pasco Basin. The Snake River is initially entrenched to the Grande Ronde Formation from the southeastern portion of the model region to Walker Canyon. From Walker Canyon to a few miles northeast of Ice Harbor Dam, the Snake River is only in contact with the Wanapum Formation. From the Ice Harbor Dam to the confluence with the Columbia River, the Snake River flows

through the Saddle Mountains and Ringold Formations. The Columbia River is entrenched to the Grande Ronde Formation from the basalt entry point near Wenatchee to the Saddle Mountains Anticline. From the Saddle Mountains Anticline to the Hanford Site, the Columbia River flows through the Wanapum Formation except along the Umtanum Ridge where Grande Ronde Basalts are exposed. Within the Pasco Basin, the Columbia River flows on the Ringold Formation.

The predominant discharge regions for transmissive zones in the Wanapum Formation occur along major surface-water systems. The same is probably true for the Grande Ronde Formation. Thus, nearly all reaches of both the Columbia and the Snake Rivers within the model region serve as discharge areas for the deep basalts. Figure 2.9 is a cross-sectional view of regional discharge in the vicinity of a river channel. The ground-water flow in the various layers beneath the streambed is seen to be directed upward at different lateral locations. The deep ground water ultimately reaches the more permeable sands and gravels in the river channel and is conducted toward the river to discharge as base flow. To allow for such a discharge, the major surface-water systems will become held potential boundaries in the direct contact layer of the hydrologic model. For example, the Snake River between Lewiston, Idaho, and Central Ferry, Washington is a held potential boundary in the Grande Ronde Formation. From Central Ferry to the confluence with the Columbia River, the Snake River is a held potential boundary in the Wanapum Formation. Similarly, the Columbia River from Wenatchee, Washington to Crescent Bar is a held potential boundary in the Grande Ronde Formation, and the Columbia River from Crescent Bar to Wallula Gap is a held potential boundary in the Wanapum Formation. It is assumed that discharge of regional aquifers does not occur west of Wallula Gap (i.e., all ground water in the model area discharges into the surface-water system upstream of the Horse Heaven Hills Anticline).

Initial Conditions and Interconnections

The general hydrologic system for the regional aspect and for the Pasco Basin is shown in Figures 2.10 and 2.11, respectively. The general hydrologic system for the Pasco Basin (Figure 2.11) includes more layers than that of the region. The interconnections between the Wanapum, the Grande Ronde, and the

FIGURE 2.9. Cross-Section View of Regional Discharge

other surface and ground-water systems are indicated by solid and dashed lines. The dashed flow lines imply a probable but unknown hydraulic connection. Most of the precipitation is lost to evapotranspiration because of the predominantly desert climate. Whereas the region contains a great quantity of ground water from a volumetric point of view, the overall flow of ground water is small in comparison with the surface flows in the Columbia and Snake Rivers. In the hydrologic model, a constant value for leakance will be assigned to each confining layer except in the discharge zones for the Columbia and Snake Rivers--where a higher transfer coefficient will be used.

Generalized potential contour maps are available for the Wanapum and the combined Wanapum and Saddle Mountains Formations (Gephart et al. 1979a). The

FIGURE 2.11. General Hydrologic System for the Pasco Basin

water-table aquifer in the Ringold Formation beneath the Hanford Site is well documented. A key assumption in the hydrologic model is that the Grande Ronde is hydrologically similar to the Wanapum.

Ground-Water Quality

Data on the chemistry of ground water can be used to corroborate hydrologic inferences on discrete flow units and to establish a geochemical computer model of the ground-water system. Chemical data for ground water in the Columbia Plateau have been compiled by RHO (Gephart et al. 1979a). The analyses are grouped into the following special categories: Columbia Plateau exclusive of Pasco Basin; Pasco Basin, unconfined aquifer; Pasco Basin, Mabton and Saddle Mountains Basalt transmissive zones; Pasco Basin, Grande Ronde transmissive zones; and Rattlesnake Hills springs.

Eighty-three chemical analyses are available for the Columbia Plateau exclusive of the Pasco Basin from the U.S. Geological Survey's ground-water quality data files. These analyses do not represent data for a single aquifer sampled at a well site, but rather for a composite of several aquifers intercepted by the well. Consequently, the information is only useful in a general sense to characterize the ground water of the basalt sequence. This water has a generally low total dissolved solids content (average equals 325 mg/l) with the principal constituents being bicarbonate, silica, sodium, and calcium. Ground water affected by irrigation practices shows an increase in sulfate, chloride, nitrate, and calcium. Carbon-14 age data are only available for two areas in the southeastern portion of the Columbia Plateau. The carbon-14 ages range from modern to greater than 32,000 yr and, in general, increase in age with depth.

Definite trends occur in the composition of the ground water with respect to distance from the presumed recharge areas (Gephart et al. 1979a) and with respect to the consequent increase in residence time within the basalt transmissive zones. As a function of distance and residence time, these trends include: 1) an increase in concentrations of Na, K, Cl, SO_4 , and F; 2) a decrease in Ca and Mg, whereas, 3) the Si and $\text{HCO}_3^{1-} + \text{CO}_3^{2-}$ concentrations are variable. These trends are displayed in Table 2.4, which represents a subset

TABLE 2.4. Chemical Analyses Representative of Ground Waters Close to Natural Recharge Zone (Spokane Area) and Far from Recharge Zone (Moses Lake Area) from Van Denburgh and Santos (1965)

	Ca (ppm)	Mg (ppm)	Na (ppm)	K (ppm)	Cl (ppm)	SO ₄ (ppm)	HCO ₃ (ppm)	F (ppm)	SiO ₂ (ppm)
Spokane Area									
	29	8.7	16	2.9	6.2	19	153	0.3	43
	33	10	5	2.2	3.5	14	142	0.2	18
	29	9.4	18	1.3	6.8	5	152	0.4	48
	20	11	15	1.2	5.5	7.8	141	0.4	44
	26	14	14	2	6.2	11	168	0.4	46

Moses Lake Area									
	5.6	3.2	86	26	14	50	212	1	36
	3	0.8	81	12	14	27	176	2.8	62
	18	8	46	17	12	62	142	0.6	34
	13	7.2	55	5	12	25	177	1.6	30
	22	11	33	8.3	9	25	176	0.7	40

of the analytical data given in Van Denburgh and Santos (1965). The analyses in Table 2.4 have been subdivided into a set characteristic of ground water from the basalt transmissive zones near the recharge area (Spokane) and a set from the vicinity of Moses Lake, which is situated down the ground-water flow path. Similar relationships between major constituents in the ground water and distance from recharge zone have been noted by Gephart et al. (1979a) for the Pasco Basin. A notable exception is that SO₄ in the Pasco Basin decreases along the flow path, apparently in response to sulfate reduction by bacteria.

Relatively complete chemical analyses of individual well samples are available for the unconfined aquifer in the Pasco Basin. The range of values is quite large, but in general the water has low total dissolved solids and is of a calcium-bicarbonate type.

Nineteen acceptable analyses are available for the Mabton interbed and other Saddle Mountain transmissive zones. The transmissive zones should be

sampled individually. The water has low total dissolved solids (average less than 500 mg/l) and is of a sodium-bicarbonate type. The following patterns are noted with distance from the assumed recharge area:

- calcium, magnesium, and sulfate decrease
- sodium, potassium, and total dissolved solids increase.

These changes are caused by precipitation of carbonates, reduction of sulfate, and cation exchange. The chemical computer model, WATEQ, was used to analyze ground water of the Mabton interbed (see Chapter 5).

In the eastern part of the Pasco Basin, the chemical character of the ground water was affected by irrigation practices of the Columbia Basin Irrigation Project. This resulted in generally higher concentrations of nitrate, calcium, magnesium, sulfate, and chloride. The flow direction of ground water in the Mabton interbed (as inferred from the distribution of total dissolved solids, carbon-14 ages, tritium levels, and $\delta^{18}\text{O}$ measurements) conform to that established by the piezometric head distribution.

Chemical data for ground water are currently available for 12 well sites that intersect the Wanapum. Coverage does not extend to the lower Wanapum. The available data show that for a given site the upper Wanapum ground water is chemically similar to the Saddle Mountain Basalt ground water. This may be because of interconnections between the transmissive zones or because of similar chemical evolution of the ground water. More work needs to be done to distinguish which of these possibilities is correct and to better characterize the Wanapum according to region and depth of transmissive zones.

Data for the Grande Ronde are available for only one or two transmissive zones from four Hanford Site wells. No data are available offsite for the Pasco Basin. The data presented are for a zone immediately below the Umtanum unit and a composite primarily from 600 ft below the Umtanum unit. The ground water has a total dissolved solids content of greater than 500 mg/l and is a sodium-chloride-bicarbonate type. Carbon-14 ages have not been determined for this water. Compared to overlying aquifers, $\delta^{18}\text{O}$ values show a heavier trend, indicating an older flow system. Chemically, this water is distinctly different from the ground water in the aquifers above it. No regional trend can be determined from the small number of samples available.

Eighty springs were sampled in the Rattlesnake Hills area. The analyses show them to all be of a similar calcium-bicarbonate type. The spring waters have the same characteristics as the ground water from the upper confined transmissive zones. The radioisotopic data establish that the water is of meteoric origin and has not been appreciably mixed with other ground waters.

In summary, the limited data currently available allow for a tentative ground-water chemical differentiation of the Pasco Basin aquifers. This is shown in Table 2.5. No data are available for the lower Wanapum or the Grande Ronde above the Umtanum unit.

TABLE 2.5. Summary of Ground-Water Quality in the Pasco Basin

<u>Aquifer</u>	<u>Formation</u>	<u>Number of Analyses</u>	<u>Areal Distribution of Samples</u>	<u>Chemical Type</u>	<u>Age</u>
Unconfined	Hanford and Ringold	62	fair	calcium-bicarbonate	modern
Upper Confined	Saddle Mtn. Upper Wanapum	19 12	fair	sodium-bicarbonate	11,000 to 23,000 yr
Lower Confined	Grande Ronde below Umtanum	5	poor	sodium-chloride-bicarbonate	not dated

CHAPTER 3

HYDROLOGIC SIMULATION

The hydrologic simulation used in the basalt demonstration was divided into three major parts: 1) aquifer recharge calculations, 2) a regional hydrologic model, and 3) a local hydrologic model of the Pasco Basin. The basic techniques used by Gutknecht et al. (1980) in the hydrometeorological study of Pasco Basin were applied to the larger area defined by the regional hydrologic model. Because ground water is the most probable transport mechanism for radionuclides to reach the biosphere, estimates of water quantities, patterns of ground-water flow, and interconnections (surface and ground water) are necessary for the eventual simulation of contaminant transport. The hydrologic simulation, summarized in this chapter and discussed in detail in Appendix B, was the most complex hydrogeologic modeling task attempted to date on the AEGIS project. Although there are always many assumptions included in any mathematical approximation of a physical system, three major assumptions used in this modeling task are noteworthy of highlight:

- Porous flow equivalents are valid characterizations for composite transmissive zones in the geologic cross-section (Figure 2.6).
- Porous flow equivalents are valid characterizations for composite confining zones in the geologic cross-section.
- The Grande Ronde Formation is hydrologically similar to that of the Wanapum Formation.

Published hydrologic data used in this analysis were gathered in 1979 or earlier. Interpretation of available data has generally emphasized a conservative evaluation. Ground-water investigations within the Hanford Site are still continuing, and the interpretation of more recent data may suggest changes to the potentiometric surfaces, transmissivity maps, and boundary conditions used in the basalt demonstration.

AQUIFER RECHARGE CALCULATIONS

Recharge from precipitation and irrigation constitutes the major source of water for the ground-water system of any given basin. In ground-water modeling, this input is either ignored or implied through held potential boundaries. The held boundary condition for ground-water potential serves as an infinite source or sink.

Definition of the flow volumes in and out of the hydrologic system, in conjunction with observed potential distributions, provides a tool that can be used to bound the transmissive properties of the ground-water system. Along with the available data on the hydraulic properties of the system, the use of recharge values that were independently determined at each grid point provided a means to predict ground-water potentials as a function of estimated flow. The model-predicted potentials were in agreement with the measured potential distributions (agreeing in actual shapes and elevations), and confidence in the accuracy of the regional ground-water model was enhanced. The transmissivity values ultimately play an important role in transport calculations for consequence analysis.

Information Sources

The net recharge reaching ground water from precipitation and irrigation depends on many parameters. Some of the important factors are precipitation, topography, soil type, vegetation type, irrigation, stream runoff, and potential evapotranspiration. The sources of information used were as follows:

Precipitation

Precipitation data were taken from a series of Washington Climate Circulars prepared for groups of counties by Washington State University in cooperation with the U.S.D.A. (Donaldson 1979; Donaldson and Ruscha 1975; Phillips 1965, 1970). These circulars list monthly and annual data in inches for each station, along with locations (latitude and longitude) and elevations. Figure B.8 shows the location of 115 weather stations used in the calculations.

Topography

The topography for the modeled area was acquired from Digital Terrain Tapes, obtained from the U.S. Department of the Interior, Geologic Survey (USGS), National Cartographic Information Center. Figure B.10 is the topographic output produced by Pacific Northwest Laboratory (PNL).

Soil Type

The soil type distribution was obtained from a "General Soil Map for the State of Washington" (prepared for the U.S.D.A. by Ray W. Chapin 1968). For use in this study, the soil types have been organized into the categories listed in Table 3.1. The general soil descriptions were condensed from the State map (U.S.D.A. 1968), and the resulting soil distributions are shown in Figure B.12.

TABLE 3.1. Soil Classification and Description (condensed from a "General Soil Map for the State of Washington" U.S.D.A. 1968)

<u>Class</u>	<u>Soil Type</u>	<u>General Description</u>
1	Scabland soils	Shallow and moderately deep, loam and silt loam soils formed in wind-laid silts (i.e., loess), glacial outwash, volcanic ash, pumice and bedrock.
2	Loessal Upland soils	Very shallow to deep, silt loam, loam and clay loam soils, some of which are gravelly or stoney, formed in wind-laid silts, weathered basalt, glacial outwash and colluvium.
3	River Bottom soils	Deep, silt loam, sandy and sandy loam soils, some of which are gravelly or stoney, formed in colluvium, alluvium, glacial outwash, and wind-laid silts.
4	Sandy soils	Deep, sandy soils formed in wind-laid sands.
5	Glacial Deposit soils	Moderately deep and deep, sand, sandy loam and loam soils, some of which are gravelly or stoney, formed in glacial outwash and fill, alluvium, lake sediments, and wind-laid silts.
6	Upland soils	Shallow to deep, silt loam soils, many of which are stoney or cobbly, formed in wind-laid silts and weathered basalt.
7	Forest soils	Shallow to deep, mildly alkaline to strongly acid, sandy loam to silt loam soils, formed in volcanic ash, glacial materials, wind-laid silts, and underlain by basalt.

Vegetation Type

The distribution of vegetation type was obtained from the publication entitled "Well Location and Land Use Mapping in the Columbia Plateau Area" (Stephan 1979). The distribution has been digitized according to the vegetation classes listed in Table 3.2, and a regional map is shown in Figure B.13.

TABLE 3.2. Vegetation Class, Type, and General Description

<u>Class</u>	<u>Vegetation Type</u>	<u>General Description</u>
1	Semiarid Grassland	Rangeland covered with sagebrush and dry/grass (cheatgrass) vegetation
2	Forest	Mixed conifer, dominated by Ponderosa and Lodgepole pine
3	Dryland	Dominantly dryland wheat farming
4	Irrigated	Irrigated farmland

Irrigation

Irrigation water requirements for various crops were taken from the U.S.D.A. SCS Irrigation Guide for the Columbia Basin (1973). Annual requirements were determined by subtracting the 50% change effective rainfall from the consumptive use for the crops. Effective rainfall is the "precipitation falling during the growing period of the crop that is available to meet the consumptive water requirements of the crop" (U.S.D.A. 1973). Monthly percentages of application during the growing season were taken from a study performed for the U.S. Army Corps of Engineers (1978).

Stream Runoff

Annual runoff was obtained from a map of "Distribution of Mean Annual Runoff in Inches within the Washington State Portion of the Columbia Plateau" (prepared by the U.S.D.A. 1972). Figure B.11 shows the digitized version of this map.

Potential Evapotranspiration

Potential evapotranspiration values are given for a more limited number of stations than the precipitation data in the Washington Climate Circulars.

The monthly and annual potential evapotranspiration values are estimates calculated using the Thornthwaite equation, based on climatic and weather data. Data from 37 weather stations were used. Figure B.9 shows the location of these stations.

Estimation of Ground-Water Recharge

The three-mile grid used in the regional hydrologic model was also used for the estimation of ground-water recharge. For the Columbia River Basalt, the grid consists of 55 x 55 regular three-mile spacings centered at 118.6286 degrees longitude and 47.0292 degrees latitude. A generalized mercator projection was used to develop the Cartesian coordinate system.

Interpolation of Precipitation

From the actual data on precipitation at the weather stations (Figure B.8), some appropriate interpolation, or fitting scheme, is required to estimate precipitation at each grid point by accounting for location and elevation of the grid point and the actual measurements at the nearest stations. The dependence of precipitation distribution on elevation is a well established phenomenon (Chow 1964). Because of effects of more global weather factors such as the rain shadow of the Cascades and the rise of the Rockies, no unique or approximate basin-wide elevation effects could be obtained.

A four-parameter interpolation, or fitting procedure, was selected to estimate precipitation at each model grid point or node. A computer code was developed to obtain a precipitation estimate for each grid point based on different values of the following four parameters.

1. Minimum Number of Stations (MINSTA): the minimum number of stations required for use of the selected interpolation procedure. A maximum of the eleven closest stations to the node are used.
2. Neighborhood Radius (RADIUS): the number of stations that lie within the neighborhood radius. If this number is less than the minimum number (MINSTA) required for weighing or correlation, the neighborhood radius is expanded until at least the minimum number of stations obtained.

3. Minimum Correlation Coefficient (CORMIN): minimum correlation coefficient required for use of the precipitation-elevation correlation method. The annual precipitation at the stations within elevations is fitted with the best straight line, and the correlation coefficient is determined. When this correlation coefficient is greater than the minimum correlation coefficient (CORMIN), annual precipitation at the node is determined from the node elevation and the parameters of the straight line fit (Figure B.14). If the correlation with elevation is less than CORMIN, the selected base method out of the following three methods ($1/d$, $1/d^2$, or Tobler) is adopted.

4. Base Methods Used for Interpolation (BASE): If the best fit straight-line does not satisfy the CORMIN requirement, one of the following weighting methods is used:

a. $1/d$ Method:
$$V_n = \left(\sum_{i=1}^m V_{s_i} W_i \right) / \left(\sum_{i=1}^m W_i \right)$$

where,

V_n = value at node

V_s = value at the station

m = number of stations used

W = weight factor = $1/d$

d = distance between node and the rain gage station.

b. $1/d^2$ Method:

Same as $1/d$ method except $W = 1/d^2$.

c. Tobler Method (Turner 1968):

$$V_n = 0.5 \left(V_{cs} + \sum_{i=2}^m V_{x_i} W_i \right) / \left(\sum_{i=2}^m W_i \right)$$

where,

V_{cs} = value at the closest station

$W = 1/d$

Of the three weighting procedures, the Tobler method places greatest emphasis on the closest station.

The selected base method is invariably used for predicting the monthly rainfall from predicted annual rainfall at the node. Monthly rainfall quantities are normalized according to the annual total rainfall at each station, and these monthly fractions are then weighted, using the selected base weighting method to determine the monthly expected fraction of the total annual rainfall at the model node.

When any interpolation procedure is used some estimate of the error associated with the interpolation scheme should be obtained. For a multi-parameter interpolation technique such as this, an additional procedure is used for determining the optimum values for these parameters to get the best fit. Both a biased and an unbiased method for estimating this error, as well as a parameter optimization method, were developed. An unbiased estimate of error was developed by predicting the observed annual rainfall at a given weather station using only the data from the surrounding stations. Statistics on the average absolute, negative, and positive error, as well as the root mean square error (rms), were developed. A biased estimate of the error was also made by estimating the annual precipitation predicted for the station from the station location and the matrix of annual precipitation values determined for the nodes.

The optimum fitting parameter selection program was developed to use the unbiased error estimate (rms) to derive the optimum values of CORMIN and RADIUS for a given value for MINSTA and a selected base fitting method. The limited range of values for BASE (1,2,3) and MINSTA (4-10) allowed a simpler two-parameter optimization program to determine the optimum values.

The basic time step in terms of data is monthly. For each model node or grid point, estimates of monthly precipitation and potential evapotranspiration (PET) from weather station data are made (Thornthwaite-Mather). These PET estimates are converted to Blaney-Criddle PET estimates for the reference crop of pasture grass with the scaling factor (1.14). The estimated are then adjusted according to the vegetation type for the node by the ratio of the appropriate crop coefficient for that month to the crop coefficient for pasture grass (Table B.3, B.10, B.11, B.12). The root-zone water capacity is determined from Table B.17 according to the soil type and vegetation.

If the node is an irrigated one, the application amounts are selected from Table B.9, according to the assumed irrigation crop type and irrigation efficiency. The actual evapotranspiration recharge plus runoff amounts are determined with a daily time step, according to the selected actual evapotranspiration (AET) method. Some initial January 1 estimate (0.9 times the root-zone water capacity) is used to start the cyclic annual calculations. The cycle is continued until the initial condition for January soil-water status does not vary by more than 0.01 in. from the previous January 1 initial condition. This indicates that the calculations have converged. Table 3.3 illustrates the results from this converged calculation summarized on a monthly basis.

TABLE 3.3. Results from the Converged AET Calculation Summarized on a Monthly Basis for a Typical Model Node

Line = 1 column = 31

Thornthwaite-Mather Method (soil capacity = 8.55 in.)
January 1 soil moisture + 6.34 in.

<u>Month</u>	<u>Rain</u>	<u>Irr</u>	<u>Pe</u>	<u>Ae</u>	<u>Soil</u>	<u>Recharge + Runoff</u>
January	2.6315	0.0000	0.0000	0.0000	8.5500	0.4220
February	2.2754	0.0000	0.1622	0.1621	8.5500	2.1133
March	2.3782	0.0000	1.4814	1.4814	8.5500	0.8968
April	2.0078	0.0000	3.6673	3.5206	7.0372	0.0000
May	1.9827	0.0000	5.6117	4.4306	4.5893	0.0000
June	1.8826	0.0000	5.5546	3.4942	2.9777	0.0000
July	0.4251	0.0000	2.6685	1.1150	2.2879	0.0000
August	0.4352	0.0000	2.0243	0.8243	1.8987	0.0000
September	1.0950	0.0000	2.0390	1.2938	1.6999	0.0000
October	2.1663	0.0000	3.2029	2.3607	1.5054	0.0000
November	2.4817	0.0000	0.3976	0.3976	3.5895	0.0000
December	<u>2.8494</u>	<u>0.0000</u>	<u>0.0983</u>	<u>0.0983</u>	<u>6.3406</u>	<u>0.0000</u>
TOTAL	22.611	0.0000	26.9078	19.1787		3.4321

Annual Rainfall = 22.61; Annual Irrig. = 0.0000; Annual PET = 26.91
Annual AET = 19.18; Annual Runoff = 0.4694; Annual Recharge = 2.963

Total annual recharge for the node is then determined by subtracting the estimated annual runoff, as determined from Figure B.11, from the annual sum of the recharge plus runoff column. For areas that are planted in dryland wheat, a two-year cycle is used rather than a one-year cycle, because in one season the wheat is grown and in the second season the land is fallowed. During the fallow season, only the upper tenth of the root zone is made available for AET. This upper zone acts as a mulching layer.

Table 3.4 illustrates the results from a converged calculation for a dryland wheat node. Because dryland wheat areas within the modeled area receive almost enough rainfall to support a yearly wheat crop, some logic had to be introduced to determine when a dryland wheat node was fallowed. A fallow factor was introduced to allow this determination to be made. The annual rainfall estimate for a node was compared with the annual PET required for small grain crops at that node times a fallowing factor (0.75). When the annual rainfall was less than the product of the fallowing factor times the PET requirement for small grain, then it was assumed that a two-year fallowing cycle was used.

A variety of studies were performed to determine the sensitivity of the predicted AET and recharge distributions to the various values of input parameters, input distributions, and AET calculation methods. (Table B.22 defines the input parameters, distributions, and AET method used in the two base case predictions for AET and recharge distributions, as well as the 12 sensitivity study predictions.) Two base case predictions were made to bracket the recharge quantity. All irrigated acreage was assumed to grow alfalfa for Base Case A (maximum recharge) and small grain for Base Case G (minimum recharge). Twelve other sensitivity cases were used to investigate the effects of the following:

- fallowing practices (Case 1 and 2)
- irrigation efficiency (Case 3)
- PET fitting method (Case 4 and 5)
- precipitation fitting method (Case 6-11)
- AET calculation method (Case 12).

TABLE 3.4. Results from the Converged AET Calculation Summarized on a Monthly Basis for a Typical Fallowed Dryland Wheat Node

Line = 11 column = 31

Thornthwaite-Mather Method (soil capacity = 8.55 in.)

Mulching layer capacity = 0.1 root zone capacity

January 1 soil moisture in mulch layer = 0.86 in.

January 1 soil moisture in lower layer = 3.51 in.

Month	Rain	Irr	Pe	Ae	Soil 1	Soil 2	Soil	Recharge + Runoff
January	1.8560	0.0000	0.0000	0.0000	0.8550	5.3635	6.2185	0.0000
February	1.4459	0.0000	0.2009	0.2009	0.8550	6.6086	7.4636	0.0000
March	1.4496	0.0000	0.9495	9.495	0.8550	7.1087	7.9637	0.0000
April	1.1883	0.0000	2.0121	1.7222	0.3211	7.1087	7.4298	0.0000
May	1.2411	0.0000	3.4009	1.5392	0.0229	7.1087	7.1317	0.0000
June	1.0649	0.0000	4.4235	1.0875	0.0003	7.1087	7.1091	0.0000
July	0.2771	0.0000	5.7138	0.2775	0.0000	7.1087	7.1087	0.0000
August	0.3761	0.0000	4.9600	0.3761	0.0000	7.1087	7.1087	0.0000
September	0.6882	0.0000	2.0063	1.7062	0.6091	5.4817	6.0907	0.0000
October	1.3576	0.0000	3.1157	2.4932	0.4955	0.4597	4.9552	0.0000
November	1.7056	0.0000	0.4137	0.4137	0.6247	5.6224	6.2471	0.0000
December	1.8201	0.0000	0.0634	0.0634	0.8004	7.2034	8.0038	0.0000
January	1.8560	0.0000	0.0000	0.0000	0.8550	7.6950	8.5500	1.3098
February	1.4459	0.0000	0.1484	0.1484	0.8550	7.6950	8.5500	1.2875
March	1.4496	0.0000	1.3277	1.3277	0.8550	7.6950	8.5500	0.1219
April	1.1883	0.0000	3.4496	3.1830	0.6555	5.8998	6.5553	0.0000
May	1.2411	0.0000	5.4557	3.8085	0.3988	3.5890	3.9878	0.0000
June	1.0649	0.0000	5.3912	2.6588	0.2394	2.1545	2.329	0.0000
July	0.2771	0.0000	2.5854	0.8458	0.1825	1.6428	1.8253	0.0000
August	0.3761	0.0000	1.9849	0.6901	0.1511	1.3602	1.5113	0.0000
September	0.6882	0.0000	3.2261	0.8327	0.0066	1.3602	1.3668	0.0000
October	1.3576	0.0000	1.7312	1.3600	0.0043	1.3602	1.3645	0.0000
November	1.7056	0.0000	0.4374	0.4374	0.8550	1.7777	2.6327	0.0000
December	1.8201	0.0000	0.0903	0.0903	0.8550	3.5075	4.3625	0.0000
TOTALS	28.941	0.0000	53.0878	26.2121				2.7292

	Seasonal Averages	Planting Averages	Fallow Averages
Annual Rainfall =	14.47	14.47	14.47
Annual Irrig. =	0.0000	0.0000	0.0000
Annual PET =	26.54	25.83	27.26
Annual AET =	13.11	15.38	10.83
Annual Runoff =	0.4104	0.4104	0.4104
Annual Recharge =	0.9542	2.319	0.0000

Results of the sensitivity studies are shown in Table 3.5 for recharge. The table summarizes the average and total values predicted for the recharge distributions. The insensitivity of predicted recharge to the precipitation or PET fitting method is demonstrated by the fact that total recharge for Cases 4 through 11 varies by no more than $\pm 5\%$ from Base Case A predictions. Similarly, total AET varies by no more than $\pm 2\%$. A comparison of the predicted variations in total AET and total recharge indicates that AET estimates are less sensitive to parameter variations than is recharge. Variation in AET for all 14 predictions shown in Table B.23 differed by no more than $\pm 9\%$ with all but two of the runs within $\pm 2\%$. Recharge variations range from a high of 11% (Case 3) to a low of -14% (Case 12) with only eight of the 14 runs within $\pm 2\%$.

TABLE 3.5. Sensitivity of Recharge to Parameter Variations

Case	Total Recharge (millions of af/yr)	Nodal Recharge		Total Recharge by Vegetation Type			
		Maximum (in/yr)	Average (in/yr)	Arid (millions of af/yr)	Forest (millions of af/yr)	Dryland (millions of af/yr)	Irrigated (millions of af/yr)
Base A	2.66	23.6	2.87	0.93	0.15	0.36	1.22
Base G	2.38	18.8	2.58	0.93	0.15	0.36	0.94
Case 1	2.48	23.6	2.68	0.93	0.15	0.18	1.22
Case 2	2.82	23.6	3.05	0.93	0.15	0.53	1.22
Case 3	2.95	26.8	3.19	0.93	0.15	0.36	1.51
Case 4	2.64	23.8	2.85	0.94	0.15	0.36	1.19
Case 5	2.68	22.8	2.89	0.93	0.15	0.37	1.23
Case 6	2.66	23.6	2.88	0.93	0.16	0.36	1.21
Case 7	2.67	22.3	2.89	0.94	0.16	0.36	1.21
Case 8	2.67	22.2	2.89	0.91	0.18	0.36	1.21
Case 9	2.68	22.2	2.89	0.91	0.18	0.37	1.21
Case 10	2.68	22.5	2.89	0.94	0.18	0.37	1.21
Case 11	2.54	22.5	2.74	0.89	0.093	0.33	1.22
Case 12	2.30	23.6	2.49	0.86	0.13	0.095	1.22

Figure 3.1 illustrates the areal distribution of recharge for Base Case A predictions. The numbers represent inches per year of recharge at a given node location (55 x 55 grid). Only the nodes within the modeled portion of the basalt aquifers are displayed.

One additional recharge calculation was performed to estimate the presettlement recharge to the basalt. For these calculations, all irrigated and dryland wheat areas were reverted to semi-arid grass and sage brush. The resulting prediction of 3.17 million acre feet per year of recharge was 19% higher than the Base Case A prediction. This increase is mainly caused by additional recharge in the eastern modeled area, which is now primarily dryland wheat.

Recharge sensitivity studies indicate that areal distributions are adequate because recharge estimates ranged only $\pm 15\%$ from the base case estimate. The recharge distributions also appear to support the selection of regional hydrologic model boundaries made on the basis of structural and potentiometric evidence alone.

REGIONAL HYDROLOGIC MODEL

Different levels of hydrologic models are operational at Pacific Northwest Laboratory. These models have the capability to simulate a wide variety of ground-water flow systems, from very simple one-dimensional, homogeneous isotropic, single-aquifer flow conditions to the most complex three-dimensional, anisotropic, multilayer cases. The multiple layer two-dimensional Variable Thickness Transient (VTT) code (Reisenauer 1980) was selected as appropriate for the amount of data available and for the conditions existing in the regional systems. This model uses a finite difference formulation to represent the partial differential flow equation.

A horizontal x-y coordinate grid system was adopted to represent the study area. Model parameters defining the aquifer system are assigned to and evaluated at the center of each grid block (or node) and are considered representative of the whole grid block. Model parameters are made into data files

FIGURE 3.1. Predicted Area Distribution of Recharge in Inches Per Year Throughout the Modeled Area of the Regional Basalt Aquifers for the Base Case A Parameter Values

accessible to the computer. From these grid block values, the computer model calculates the ground-water potential for each grid block. The following is a list of the model parameters and their associated units:

- altitude of the land surface (L above mean sea level)
- altitude of top of the regional aquifer for confined systems (L above mean sea level)
- altitude of the bottom of the aquifer (L above mean sea level)
- initial ground-water surface elevation (ground-water potential) of the aquifer (above mean sea level)
- transmissivity (L^2T) or hydraulic conductivity (L/T) of the aquifer
- storage coefficient (dimensionless) of the aquifer
- recharge (L^3/T) to the aquifer
- discharge (or pumping) rate (L^3T) from the aquifer
- river stage (L above mean sea level).

Adaptation of the VTT Code

The general procedure used to apply the VTT ground-water flow code to the Columbia Plateau region consist of the following steps:

- determination of the boundary conditions for the region (Chapter 2)
- interpretation and refinement of published or unpublished data for input to the model
- use of the data to calibrate the model
- model simulations to predict water flow paths and quantity of water flowing into or out of the Pasco Basin from the regional system.

Available Data and Interpretations

Much of the data used in this modeling effort deals with specific aspects of the hydrogeology of the Columbia Plateau region, or deals with the hydrogeology and stratigraphy of only a small portion of the region. Several of the reports used to provide data specifically address ground-water management

of sub-basins or parts of sub-basins within the regional study area. As can be expected, the best data exist in the more heavily populated areas and in the areas irrigated by ground water. Additional hydrogeologic and stratigraphic data are needed. Among some of the most promising work that will ultimately enable an accurate qualitative and quantitative picture of the regional ground-water flow system of the Columbia Plateau is the stratigraphic definition obtained by integrating surface and subsurface stratigraphic data. Recent work sponsored by the Basalt Waste Isolation Program (Gephart et al. 1979a, Myers et al. 1979) suggest that substantial progress is being made in developing many of the hydrogeologic and stratigraphic cross-sections that are needed.

Similar patterns of geographic distribution of data have been found for all types of hydrologic well data, including: water-level data, geophysical well log data, driller's logs, and transmissivity data. These hydrologic measurements are widespread throughout the Columbia Plateau, but are irregularly distributed except in the Pasco Basin. The concentration of data is restricted to areas that have the greatest amount of irrigation where good soil is available for cultivating crops.

In general, the quality and completeness of the hydrologic and geologic data for the shallower basalt formations (layer 1) are far superior when compared to the Grande Ronde (layer 2) data or maps. The paucity of deep wells and their irregular spatial distribution often necessitates patterning the hydrogeologic surfaces of the Grande Ronde after the layer 1 surfaces.

Many of the published reports are based on information shown on well logs submitted by water well drillers to the DOE model studies and, to a lesser degree, on geophysical log data obtained from Washington State University (WSU). Transmissivity maps presented in these documents are based on water well reports of questionable accuracy. Depending on the completeness of the water well report, information may be provided on both static and dynamic water levels. The dynamic or pumping water level is frequently described on the well reports without indication of the duration of the pumping test. Consequently, reported specific capacity values for most wells are approximate at best. In addition, transmissivity data are often not reliable in cases where the well penetrates several aquifers or formations. Most often the proper steps have not been taken to adequately pump test individual units or layers.

Finite Difference Grid and Boundary Conditions

The regional study area as defined for the VTT model was divided into a 55 by 55 square pattern with each grid 3 miles (15,840 ft) on a side. The regional system was modeled as a held potential surface layer and two underlying basalt layers. The surface layer consists of a composite of held potential nodes representing large lakes; the Columbia, Snake, Walla Walla, and Yakima Rivers; basalt seepage faces; and alluvial water table systems in the Walla Walla, Quincy, and Pasco Basins. For modeling purposes, the potential in the surface layer was held at the levels indicated by the field data. Therefore, the surface layer was simulated to the extent that it acted as a recharge or discharge area for the deeper basalt layers.

Layer 1 consisted of the Saddle Mountain Basalt and Wanapum Basalt. The VTT model region for layer 1 and its associated held nodes in the surface layer is shown in Figure B.24. These held nodes act as recharge or discharge areas for the Saddle Mountains and Wanapum Basalts. The layer 1 boundary representing seepage faces to the north and northwest is defined by the Columbia and Spokane Rivers. In addition to the held river and held lakes nodes, there are held potential nodes representing the Walla Walla, Quincy, and Pasco Basins' alluvial systems.

Layer 2 represents the hydrologic system of the Grande Ronde Formation. The VTT model region for layer 2 and its associated held nodes in the surface layer are shown in Figure B.25. The northern and northwestern portion along the Columbia and Spokane Rivers shares a common seepage boundary with layer 1. The other held nodes are lakes or rivers that are incised into the Grande Ronde.

The remainder of the model area perimeter in both layers 1 and 2 is represented as a no-flow boundary; however, a rate of recharge or discharge can be specified if desired. Existing data indicate that little or no movement of water is occurring across these boundaries. Parameters defining the regional model were made into data files for input to the VTT code.

Interpreted Potentiometric Surfaces and Well Data

Potential, or elevation of the ground water above mean sea level, must be defined at each interior and boundary node of the model region. The interpreted

water table surfaces for the three alluvial basins are shown in Figure B.26. The interpreted composite Saddle Mountain-Wanapum potential surface used to represent layer 1 is shown in Figure B.27. As mentioned earlier, no interpretation of the layer 2 or Grande Ronde potentiometric surface was constructed.

Three sets of water level measurements in wells were obtained from the data base. These measurements were the average water level measurements in the wells for the years 1958, 1968, and 1978. There are 162, 439, and 360 wells in the 1958, 1968, and 1978 data sets, respectively. These well measurements were compared to the interpreted composite potentiometric surface for the Saddle Mountain-Wanapum aquifer system. The average and root mean square (rms) error between the wells and the interpreted surfaces are:

- 1958 average error = 79.2 rms error = 116.4
- 1968 average error = 116.2 rms error = 148.6
- 1978 average error = 108.2 rms error = 146.4

Regional flow of ground water tends to be southwestwardly across the model area, as shown in Figures B.26 and B.27. Exceptions to this general flow pattern occur:

- at the northern perimeter of the Columbia Plateau Basalt where ground water tends to flow toward the edge of the plateau because of potentiometric highs within the model boundary
- in the Blue Mountains where ground water tends to flow northward and eastward toward the Snake River
- in the western portion of Pasco Basin where ground water tends to flow generally eastward toward the Columbia River.

Structural Surfaces

Structural surfaces (aquifer top and bottom) for the regional model layers were not used because of the lack of good data. The principal reason for including these surfaces in the model is so that transmissivity values can be calculated from hydraulic conductivity values and the saturated thickness (transmissivity = hydraulic conductivity x saturated thickness). The need for

the saturated thickness was eliminated by using transmissivity values directly. The purpose of the regional model was to determine flux and not to determine water travel time.

Recharge and Discharge

The VTT model can simulate all types of recharge to, or discharge from, the ground-water system. A detailed presentation of recharge data and calculations is provided in Appendix B (methodology similar to Gutknecht et al. 1980). In summary, recharge includes consideration of weather station data on precipitation, temperature, and potential evapotranspiration, and related data on topography, stream runoff, and irrigation. A combination of these parameter distributions in a water balance relationship results in a distribution of annual aquifer recharge. Total recharge to the model region is estimated to approximately 1.7 million acre-ft/yr, and of this total, artificial recharge represents nearly one half.

For modeling purposes, it is not necessary to calculate the seepage (discharge) to or from the Columbia, Yakima, and Snake Rivers, or the lakes. Instead, the water level at the nodes representing the rivers and lakes is held at the field-determined elevations. The model simulates effluents or influent conditions, depending on how the river or lake level compares to the water table in the adjacent ground.

The major source of recharge to both model layers 1 and 2 is located in the Blue Mountains and in the northern and eastern portions of the Columbia Plateau where the basalt flows are closer to the ground surface and the regional precipitation is greatest. Some recharge to the basalts also occurs over other portions of the plateau as a result of infiltration of irrigation water, precipitation, and storm runoff through incised channels.

Transmissivity

The transmissivity contour map for layer 1 was prepared by adding the transmissivity values for the Saddle Mountains and Wanapum Basalts together. This surface was digitized and input directly to the VTT model (Figure B.28).

An initial transmissivity value of 60,000 gpd/ft was uniformly set over the model region for layer 2 (Grande Ronde).

Model Calibration

Degrees of uncertainty surround even the most carefully measured or mapped physical data. Limited quantities of point data are interpolated to produce maps (potential, transmissivity, aquifer bottom). These maps help form a conceptual model of the system. Filtering of data occurs during this step as well as during the step of moving from the conceptual model to the computer model, where one must digitize the information on a grid system. The calibration process involves a series of computer simulations where the model inputs are modified within the accuracy limits of the data to make the model better represent the observed behavior of the physical system. It is the inherent uncertainty in the model input data, along with the associated uncertainties in the conceptual model, which justifies the necessary changes in the model input or conceptual model during the calibration process.

The parameter most commonly adjusted in the calibration process is transmissivity because it is often the parameter of greatest uncertainty and the parameter for which we have the least amount of data. The amount and distribution of recharge or discharge usually has the greatest influence on the model output; therefore, estimates for these parameters must be made carefully, as was done for the basalt demonstration. Changes are sometimes made in the boundary conditions and/or the aquifer top and bottom surfaces, if the conceptual model is refined or if errors are detected or additional data are obtained.

After each simulation, model-predicted potentials were compared to the initial interpreted potentials for layer 1 (Figure B.27). In addition, point comparisons were made by comparing the model-predicted potential values at wells to field-measured elevations as obtained for three different time periods discussed earlier. Based on these comparisons, transmissivities, interaquifer transfer coefficients, lake and river transfer coefficients, and seepage face transfer coefficients were adjusted within reasonable limits until a satisfactory level of agreement was obtained between predicted and observed (interpreted) potentials for layer 1 (Saddle Mountains-Wanapum).

The regional model was calibrated until the rms difference between the model-predicted potential surface and the well data was less than, or equal to,

the rms difference between the interpreted potential surface and the well data. For the initial model prediction, the transmissivity of the Grande Ronde Basalt was a uniform 60,000 gal/day/ft. The Saddle Mountain-Wanapum Basalt was represented by the transmissivity surface shown in Figure B.28. Interaquifer transfer between layer 1 and layer 2 was represented by a vertical permeability of 10^{-3} ft/day. Transfer between layer 1 and the alluvial systems was represented by a vertical permeability of 10^{-2} ft/day. Transfer to lakes and rivers was controlled by sediment permeabilities of 10^{-2} ft/day. Basalt seepage faces were assigned 10^{-2} ft/day permeabilities. Table 3.6 shows the comparisons between well data and model, as well as well data and interpreted potential for layer 1. The rms error comparison between the interpreted and predicted potential surface for the calibrated model was 214 ft.

TABLE 3.6. Average, rms, Maximum and Minimum Error Comparisons Between Well Data and Model Predictions and Well Data and the Interpreted Potentials for Layer 1 (all values in feet)

	1958		1968		1978	
	Model	Inter- preted	Model	Inter- preted	Model	Inter- preted
Average	74	79	96	116	105	108
rms	97	116	127	149	138	146
Maximum Positive Error	280	150	761	738	511	444
Maximum Negative Error	442	-649	-646	-471	-473	-519

For the calibrated model, the average vertical permeability controlling interaquifer transfer between layer 1 and layer 2 was 1.01×10^{-3} ft/day with a maximum value of 7.0×10^{-3} ft/day. The average absolute value of the vertical Darcy flux between layer 1 and layer 2 was 4.04×10^{-3} in./day. The average vertical permeability controlling movement between the alluvium and layer 1 was 6.9×10^{-3} ft/day with a maximum value of 0.36 ft/day. The average absolute Darcy flux between layer 1 and the alluvial systems was 1.6×10^{-2} in./day.

The interpreted transmissivity surface for layer 1 (Figure B.28) averaged approximately 25,000 gal/day/ft and layer 2 initial value was 60,000 gal/day/ft.

The average transmissivity values for layers 1 and 2 for the calibrated model are 85,000 gal/day/ft and 51,000 gal/day/ft, respectively. The increase in average transmissivity values for the calibrated model over those in the interpreted input of Figure B.28 is not uncommon. The transmissivity values used in the preparation of the interpreted surface generally are not a measure of the composite transmissive zones and therefore can generally be expected to be lower than the transmissivity of the calibrated model.

Regional Model Results

Figures 3.2 and 3.3 illustrate the model-predicted potentials for the transmissive zones of the Saddle Mountain-Wanapum Basalt and the Grande Ronde Basalt, respectively. The general shape of the model-predicted potential surface for layer 1 is in reasonable agreement with the interpreted surface. The calibrated regional flow model was used to predict the northern and eastern boundary conditions (recharge and discharge) for the local model of the Pasco Basin.

Total water transfer from layer 1 to layer 2 amounted to 0.64 million acre-ft/yr. Transfer from layer 2 to layer 1 amounted to 0.32 million acre-ft/yr for a net loss from layer 1 of 0.32 million acre-ft/yr. Total water transfer to the alluvium from layer 1 amounted to 0.71 million acre-ft/yr. Transfer from the alluvium to layer 1 amounted to 0.11 million acre-ft/yr for a net loss of 0.60 million acre-ft/yr from the layer 1 basalts to the alluvium.

Layer 1 losses to the modeled rivers not entrenched in alluvium amounted to 0.13 million acre-ft/yr, or approximately 8.0 cfs/river mile. Layer 1 losses to the 18 modeled lakes entrenched in layer 1 amounted to 0.035 million acre-ft/yr. Total losses to the seepage face along the northern boundary of layer 1 amounted to 0.011 million acre-ft/yr.

Layer 2 losses to modeled rivers amounted to 0.59 million acre-ft/yr. Columbia River losses along the western boundary of the model average 0.8 cfs/river mile. Snake River losses in the mid to eastern half of the modeled area averaged 5.5 cfs/river mile. Total losses to lakes entrenched in layer 2 amounted to 0.12 million acre-ft/yr. Seepage face losses along the northern boundary amounted to 0.015 million acre-ft/yr.

FIGURE 3.2. Regional Model-Predicted Potential for Layer 1 (Saddle Mountain-Wanapum Basalt Aquifer System). Potentials are in feet above mean sea level.

FIGURE 3.3. Regional Model-Predicted Potentials for Layer 2 (Grande Ronde Basalt Aquifer System). Potentials are in feet above mean sea level).

Predicted losses to lakes from the calibrated model is in the range of the 40-inch value measured for annual lake evaporation rates. Seepage face estimates along the northern boundary are on the order of 9.9×10^{-2} cfs/mile (10 gpm springs/mile). Overall the water balance and general flow directions of the regional model appear reasonable.

PASCO BASIN MODEL

Essentially three modeling technologies are involved in assessing the water pathways for a release consequence analysis--1) hydrologic models that define the ground-water flow field and provide water flow paths and travel times; 2) engineered barriers and leach rate models that predict the rate at which waste from a breached repository enters the flow system; and 3) transport models that describe the movement and concentration of radionuclides in the flow field. The hydrologic model used to simulate the local region is discussed in this section.

The local model simulates a subregion of the regional hydrologic model in greater detail. The subregion of interest is similar in areal extent to the Pasco Basin and includes the area surrounding the hypothetical site for a nuclear waste repository in basalt. Simulation of this smaller region allowed for greater resolution to be obtained around the repository and along the potential ground-water pathways from the repository to the point of discharge into the accessible environment and the biosphere. The Finite Element Three-Dimensional Ground-Water Model (FE3DGW) developed by Gupta et al. (1980a) was selected for modeling the local region. The FE3DGW model uses the Galerkin finite element method with deformable quadrilateral elements.

Finite elements provide a different method of approximation than the finite difference methodology. The finite difference method needs special formulas for describing boundaries. In many instances, the size of the grid is not changed as easily, and accounting for inhomogeneities and anisotropy can involve further complications. In finite element methodology, the whole domain can be divided into irregular subdivisions as dictated by the physical geometry of the problem. The advantage of irregular subdivisions is especially important when the spatial domain is complex. The size of each subdomain (element) can be

varied easily; small elements can be used in areas of rapid change and large elements where variations are less severe. Furthermore, inhomogeneities and anisotropy are quite easily accommodated.

Geohydrologic systems and surface-water bodies (e.g., lakes, rivers) usually have irregular boundaries. The finite element method provides a powerful tool for space and boundary definition. The spacing of the nodes near the repository, pumping wells, or surface-water bodies can be decreased, and the hydraulic conductivities can change abruptly from element to element so that fault zones and confining layers can be represented.

Some of the complex site-specific geologic configurations consist of multiaquifer systems separated by confining layers. These aquifers respond conjunctively to stresses imposed on either aquifer. Such coupling of aquifers requires simulation of several layers simultaneously. A three-dimensional model provides a realistic means of representing the kind of multilayered transmissive zones associated with the basalt demonstration.

Available Data and Interpretation

Because the model of Pasco Basin is a subregion of the regional hydrologic model, the sources and interpretation of hydrogeologic data are very similar. The data used in the local modeling effort are consistent with those of the regional model, but they were resolved in greater detail.

The input data structure of the FE3DGW code is based on hydrogeologic data normally compiled for ground-water systems. Because the accuracy of the results is a function of the quality of the input, the input data must be thoroughly understood and be verifiable by field geologists, hydrologists, and modelers for the simulation to be useful. The reader should have an understanding of the equivalent porous medium concept (Appendix D) as well as the effects of scale and the relationship between scale, isotropy, and heterogeneity to relate model input parameter values to field measurements.

Finite Element Grid and Boundary Conditions

The finite element grid for the local (Pasco Basin) model was constructed using the structural and potentiometric surface contours from each of four

layers. Local stratigraphy was grouped according to the major basalt formations (Saddle Mountains, Wanapum, and Grande Ronde) and an uppermost layer, which is a composite of surface water systems (rivers and lakes) and the alluvial/sedimentary ground-water system. The areal extent of the four layers is shown in Figure 3.4. Discontinuities, major breaks in slope or thickness, and faults in any of these surfaces were used to guide the development of the grid. Nodes necessary to define each surface individually, both at the saturated and geologic boundaries, were identified. All nodes were then combined into one surface grid. Additional surface nodes were placed along surface water bodies, at important recharge/discharge areas, and in areas of heavy pumping from wells. The resultant two-dimensional grid consists of 606 surface nodes and 555 surface elements, as shown in Figure B.48.

The northern and eastern boundary of the local model was defined as a held potential boundary with the values obtained from the regional model. The hydrogeologic properties of this boundary were defined from the regional model to account for the influx of water to the local model area from the regional system. In the finite difference regional model, the potential is defined at the nodes, and one vertically centered node represents each horizontal layer. In addition, more layers are defined in the local model than in the regional model. Therefore, an interpolation scheme was developed for obtaining the held boundary potentials for the local model from the regional model. Actual estimates of the flux into the local model area from the regional model will be presented later.

The southern and western boundary, which represents the rest of the local model boundary, was defined as a no-flow boundary based on evidence of ground-water divides related to elevation and structure. The local conceptual model covers approximately 1870 square miles in the southwestern corner of the regional model area (Figure B.31). The southern and western boundary of the local model region is identical to the regional model boundary. The geologic basis for this boundary selection was discussed earlier in Chapter 2.

Structural Surfaces

Surface elevations were constructed for the alluvium, the Saddle Mountains Basalt, the Wanapum Basalt, and the Grande Ronde Basalt.

FIGURE 3.4. Map of the Local Model Region Showing the Areal Extent of the Various Geologic Units Within the Local Model Boundary (Photo No. 81A086-11)

Alluvium. The areal extent of the alluvium within the Pasco Basin was determined from Hanford Project data (Kipp et al. 1972), and from USGS topographic contour maps. Figure B.33 illustrates the digitized topography in the local model area along with the local model boundary.

Saddle Mountains Basalt. The stratigraphic surface (top) of the Saddle Mountains Basalt was developed from a hybridization of Plates 4A (1 and 2) from Myers et al. 1979 and Plate 3 from Tanaka et al. 1979. Because of their completeness, these references were used almost exclusively. Figure B.34 illustrates the digitized top of the basalt stratigraphic surface used in the local modeling effort.

Wanapum Basalt. The final stratigraphic contour and unit boundary maps were constructed and digitized in a similar manner as for the Saddle Mountains Basalt, using Plates III 4B (1 and 2) from Myers et al. (1979) and Plate 4 of Tanaka et al. (1979). Figure B.35 shows the digitized stratigraphic surface for the top of the Wanapum that was used in the local hydrologic model.

Grande Ronde Basalt. The work required to obtain the Grande Ronde stratigraphic surface included: gathering published data from local sources (PNL and RH0), scrutinizing the data and sources to resolve conflicts in numerical values, determining the most reliable data values, and constructing maps of the upper and lower stratigraphic surface of the Grande Ronde Basalt and the Umtanum Flow within the Grande Ronde. Because only nine or fewer data points were available for constructing each of the upper three stratigraphic surfaces (i.e., top of the Grande Ronde, top of the Umtanum, and base of the Umtanum), the contour maps of the Wanapum Basalt, which are based on a considerably greater number of data points, were used to guide construction of the stratigraphic surfaces of the deeper units. This methodology is based on the assumption that the variation in the thickness of the Wanapum and Grande Ronde Basalt units is relatively small. By mimicking the proportions and configurations of the Wanapum contours while allowing for observed modest variations in the thickness of each unit, the upper stratigraphic surface of the Grande Ronde was completed. Figure B.36 shows the digitized top of the Grande Ronde structure map used in the local modeling effort.

The completed top of the Grande Ronde contour map was used to construct the upper surface of the Umtanum Flow and the bottom stratigraphic surfaces of the Grande Ronde Basalt and Umtanum Flow. The stratigraphic contour maps of the bottom of the Umtanum unit and the Grande Ronde Basalt were constructed using 8 and 1 data points, respectively, rather than the 9 available for the upper surfaces. Obviously, the accuracy of the bottom of the Grande Ronde Basalt is suspect. Using the single data point at RHS-1, which was the estimated depth to Grande Ronde Basalt [approximately 5000 ft (Raymond and Tillson 1968; Gephart et al. 1979b)], and the assumption of nearly accordant surfaces for the Grande Ronde top and base, the base structure map was constructed. This assumption may prove to be in error; however, without additional data points for preparing the contour map, this seems to be a reasonable approach.

After completion of the upper Grande Ronde structure surface, information regarding the depth and elevation of the top of the Grande Ronde Basalt at well DC-12 was received and checked against our predicted value. The elevation of the top of the Grande Ronde Basalt was estimated to be 1730 ft below mean sea level on the hand-contoured maps, which varied only one percent from the actual measured value of 1712 ft below mean sea level. Such close correlation between the predicted value and the actual field value suggests the "mimic" methodology is valid for at least one area of the Pasco Basin.

The different layers (alluvium, Saddle Mountain, Wanapum, and Grande Ronde) do not all extend to the boundaries of the primary finite element grid nor to the boundaries of the geologic extent of the layer. Therefore, nodal descriptions were prepared that define the hydrologic areal extent of each layer. Figure 3.4 depicts the geologic areal extent of the layers within the local model area. The relationship between the hydrologic (saturated) areal extent of the layers is shown in Figure B.46, as interpreted from geologic structure and potential interpretations.

Interpreted Potentiometric Surfaces

The potentiometric trend maps of the Saddle Mountains and Wanapum Basalts in Tanaka et al. 1979 and the composite aquifer potential maps in Gephart et al. 1979a were used to construct the potentiometric contour maps for the local

region. The Gephart report was the primary source of data. The Tanaka report was used primarily as a cross reference.

The alluvial potentiometric data was obtained from a 1975 Hanford Project water table map (RH0). The initial alluvial potential surface used in the local model is shown in Figure B.42.

The potentiometric map for the Saddle Mountains Basalt within the local model region, as shown in Figure B.43 was digitized from Plate III-7 of Gephart et al. 1979a.

The Wanapum potentiometric map, as shown in Figure B.44, for the local model region was digitized from the postirrigation contours on Plate II-8 of Gephart et al. 1979a.

The potentiometric contour maps of the Grande Ronde Basalt, as shown in Figure B.45, for the local model region was constructed entirely from data presented in Gephart et al. 1979). The four sites with suitable data, DC-1, DC-2, DC-6, and RSH-1, are shown in Figure B.40. It was assumed that the Grande Ronde geologic unit had a similar contour configuration to the Wanapum Basalt.

The areal extent of the saturated zone for each of the four layers was inferred from their interpreted structural and potential surfaces. A composite overlay map of the saturated zones for the four layers is shown in Figure B.46. The saturated thicknesses were tapered down to near zero along these boundaries where they were within the local model region.

Hydraulic Conductivity

Initially, transmissivity contour maps were prepared for the four layers of the local model. This data was later converted to equivalent porous media hydraulic conductivities by dividing by the saturated thickness of the layer as determined from potential and structural data (Appendix D). The transmissivity maps of the Saddle Mountains and Wanapum aquifers were copied from existing contour maps, whereas the Grande Ronde transmissivity map was constructed from values available from three data points within the basin.

The transmissivity maps of the Saddle Mountains and Wanapum represent transmissivity values obtained by a variety of test methods of varying duration, by different data collection procedures, by different parameter monitoring instrumentation, and often by the simplest methods of analysis. In addition to the wide variation in the reliability and accuracy of the results reported, the tests within the same geologic formation rarely represent the total transmissivity of all aquifers within that formation. Each of the transmissivity values within a portion of the local model area may represent different aquifers or combinations of aquifers. Some wells, despite the presence of casing (which should indicate isolation of overlying aquifers), obtain water from the overlying geologic formation as well as from the unit it is reported to represent. As a result, exaggerated values for transmissivity may be obtained.

More often the opposite is true: the transmissivity values represent only a portion of the total transmissivity of the composite of all the aquifers in a geohydrologic formation because the wells are not fully penetrating. (Drilling is terminated once adequate water supplies are obtained for the purpose intended by the well owner.) Nonetheless, a large number of wells that fully penetrate the upper geologic formations do exist; therefore, good reference points do exist.

Transmissivity data for the alluvial material was obtained from Hanford Project data (Kipp et al. 1972). A contour plot of the digitized transmissivity surface used in the modeling effort is shown in Figure B.37.

Except for minor peripheral modification of the transmissivity contours to facilitate use of the CIRMIS digitization program, this surface was taken from Plate II-11 of Gephart et al. (1979a). The digitized transmissivity surface used in the modeling effort is shown in Figure B.38.

The source for the Wanapum transmissivity contour surface was Plate II-12 of Gephart et al. (1979a). Some of the contours were extended to permit accurate digitization. The digitized Wanapum transmissivity surface used in the modeling effort is shown in Figure B.39.

The transmissivity contour map of the Grande Ronde Basalt was constructed entirely from data presented in Gephart et al. (1979a). Only four sites, DC-1, DC-2, DC-6, and RSH-1, exist that have suitable data, as shown in Figure B.40. For each site there are several values of transmissivity and hydraulic head reported. The criteria used to select representative values at each site were as follows:

1. Select the more or most accurate hydraulic head and conductivity (transmissivity) values. If practical, choose equivalent layers for parity of parameters.
2. Choose a representative transmissive zone based on the highest transmissivity and, therefore, the more likely flow path from a hypothetical breach of the repository.

Interpretive liberties were exercised in constructing the Grande Ronde transmissivity map because of the limited amount of data. The transmissivity contour map of the overlying Wanapum formation was used as a guide, based on the assumption that the two formations are similar. This seems to be a reasonable assumption, based on the similarities in the transmissivity and potential values at the few sites where data exists for both formations. The digitized transmissivity map for the Grande Ronde Formation is shown in Figure B.41.

An interpolation scheme was developed that assigned hydraulic conductivity (K) values to the nodes in the finite element model based on the saturated thickness at the node and the transmissivity. The K for each element was then computed by averaging the K values at the four nodes comprising the element. The K's varied from element to element over each surface, and from layer to layer vertically.

Porous-medium equivalent estimates of horizontal hydraulic conductivity for the modeled basalt layers (Saddle Mountains, Wanapum, and Grande Ronde) can be made from the published lithological data and hydraulic conductivity estimates and ranges (Gephart et al. 1979a; Staff BWIP 1980; Staff BWIP 1981). The equivalent porous medium hydraulic conductivity estimates made for the various layers are shown in Table 3.7. The ranges (maximum-minimum) and average values determined from the model input interpretations for saturated

TABLE 3.7. Equivalent Porous Medium Horizontal Hydraulic Conductivity Estimates for the Various Modeled Layers

<u>Description/ Source of Estimate</u>	<u>Published Sources^(a)</u>	<u>Published Sources^(b)</u>	<u>Model Input Interpretations</u>
Saddle Mountain (ft/day)			
Average	5.0	4.0	2.96
Minimum	0.046	---	---
Maximum	27.4	---	17.2
Wanapum (ft/day)			
Average	0.008	4.0	1.73
Minimum	0.008	---	0.28
Maximum	12.3	---	4.52
Grande Ronde			
Average	0.0027	0.104	0.75
Minimum	0.00015	---	0.10
Maximum	117.0	---	4.18

(a) Staff BWIP (1981)

(b) Staff BWIP (1980)

thickness and transmissivity are also shown in Table 3.7. Model input values agree with the estimated values based on lithology measurements and measurements for hydraulic conductivity.

Field data distinguishing vertical (K_v) from horizontal (K_h) hydraulic conductivity for the basalts are lacking. Therefore, the K_v distribution was determined in the model calibration process. Initially, the K_v to K_h ratio was set at 0.1 in the alluvium and 0.01 in all other layers over the model region. This distribution was adjusted in the model calibration process to better represent areas where the K_v to K_h ratio might be suspected to vary because of folding, fracturing, or other similar geologic features.

Field measurements of effective porosity were lacking. The porosity distribution was set as shown in Table 3.8 and maintained throughout the model calibration process.

TABLE 3.8. Equivalent Porous Medium Effective Porosity Estimates

<u>Modeled Hydrologic Unit</u>	<u>Equivalent Porous Medium Effective Porosity</u>		
	<u>Minimum</u>	<u>Average</u>	<u>Maximum</u>
Alluvium	--	0.10	--
Saddle Mountain	0.06	0.095	0.12
Wanapum	0.05	0.07	0.10
Grande Ronde	0.05	0.06	0.07

Recharge and Discharge

Recharge data were calculated for two different time periods, called "preman" and "current conditions." The preman time period accounted for recharges to the alluvium and basalts before any influence by man. The current condition scenario accounts for the recharge and discharge that is occurring today. The principal difference is that the current condition scenario accounts for stresses associated with agricultural, irrigation, and pumping practices.

In the preman scenario the total amount of precipitation estimated to fall on the modeled region is 772,000 AF/year (7.75 in./yr over the local model area). Of this total precipitation, the majority (717,000 AF/yr--7.20 in./yr), is lost back to the atmosphere as actual evapotranspiration. The remainder, 55,000 AF/yr (0.55 in./yr), was input to the model as the total recharge to the basalt and alluvial systems. The calculation of this recharge is discussed in more detail in the section on aquifer recharge. Figure B.49 shows the calculated areal distribution of the preman aquifer recharge.

In the current condition scenario, man-induced stresses (irrigation return flow and pumping, municipal, and domestic wells) were considered. Alfalfa and small grains are the two crop types considered as irrigated vegetation to bound the maximum and minimum ground-water recharge. The recharge from irrigating alfalfa is greater than that for small grains. Therefore, in the interest of taking the conservative approach (i.e., more recharge resulting in steeper gradients and shorter travel times), the recharge estimates associated with alfalfa were used in the local model.

The total precipitation in the current condition scenario was the same as in the preman scenario, 772,000 AF/yr (7.75 in./yr over the local model area). The amount of water used to irrigate alfalfa acreage provided an additional 859,000 AF/yr (42.0 in./yr) to the total water applied at the surface. Of this total input amount, 1,344,000 AF/yr (13.5 in./yr) was calculated as the amount lost to actual evapotranspiration, and 27,000 AF/yr was estimated for pumping from the basalts within the modeled area. The basalt pumping distribution used in the model is shown in Figure B.50, and the recharge distribution is shown in Figure B.51. No water was assumed lost to runoff within the Pasco Basin. A water balance calculation shows a net flux of 287,000 AF/yr (2.88 in./yr) recharging the ground-water system within the local model area. This amount of recharge was used in the local model for the current condition scenario. The detailed water balance estimates agree with the earlier estimates made by Gephart (1979a) for the Pasco Basin. Rockwell Hanford Operations estimates precipitation at 756,000 AF/yr, surface irrigation at 907,600 AF/yr, and recharge from artificial mechanisms at 250,000 AF/yr. The detailed estimates included in the basalt demonstration allow for areal distribution of recharge.

Model Calibration

Model calibration is accomplished by adjusting the model input parameters, boundaries, and the conceptual model within reasonable bounds. The bounds are obtained from uncertainty in measured quantities, and the input is adjusted until the model can accurately simulate what has been observed in the field. A model used in this manner during the early stages of a field study can help determine what data is most important, how much is needed, and where it should be collected. The computer model can also be used to improve the conceptual, site-specific model and primarily the understanding of the hydrologic system.

As in the regional modeling effort, a detailed estimate of the recharge distribution was used to bound the transmissivity values of the deeper basalt systems. In the calibration process, two steady state conditions or scenarios were used. The preman scenario simulated conditions that existed before man's influence. The second condition, called the current condition scenario, simulated present day conditions. Both scenarios used identical model input data with the exception of the recharge/discharge distribution.

The preman simulation was necessary to infer model-predicted water ages and the source for waters sampled from wells in the Mabton unit. Data on total dissolved solids, other geochemical and radioisotopic properties presented in Gephart (1979a) have been used to infer water ages and general water movement patterns. In the model calibration process, an effort was made to match model-predicted water movement and age with the inferred water movement patterns and water ages based on field data. The inherent dangers (Bentley and Davis 1980) associated with inferred radiocarbon water dates were considered, especially in light of bicarbonate ground waters and calcite precipitation (Gephart 1979a), which appear to be present within the Mabton unit. From the inferred water dates for the well samples (11,000 to 23,000 yr), the ground water traveled along most of its path to its current sample site before man began influencing the hydrologic system. This fact revealed the need for the preman scenario. The current conditions scenario was used to match model-predicted potential distributions with the potential distribution interpreted from the well data.

When performing a calibration-sensitivity study for a first cut analysis the best estimates for the most certain parameters are used and the range for parameter values for the least certain parameters are investigated to narrow the range. Model calibration involves making use of the available data and an understanding of hydrology to control the manner in which the uncertain parameter or parameter distribution maximizes the agreement between model predictions and observations.

Because of the limited data available to measure model calibration quantitatively, only two parameter distributions were varied to achieve model calibration. These were the vertical hydraulic conductivity distribution and the horizontal hydraulic conductivity distribution. After a best estimate was determined for the vertical hydraulic conductivity distribution, some final iterations were performed in which the horizontal hydraulic conductivity distribution was varied in conjunction with the vertical to obtain a better match with observed data.

Initial calibration runs assumed a constant K_v/K_h ratio for each model layer. Our calibration runs, made in the same way (i.e., by holding the K_v/K_h

ratio constant on a layer by layer basis), indicated that a ratio of 0.01 produced the best match of the interpreted potential distributions. Calibration experience showed that the smaller the K_v/K_h ratio, the higher the potential levels predicted for the deeper basalts in the mid or discharging sections of the Pasco Basin. In addition, in the recharge areas of the upper basalt zones, the model-predicted potentials were too high.

Comparison statistics for potential distributions are shown in Table 3.8. The comparison statistics relate how well the interpreted and predicted potential distributions compare for all modeled layers. Run 1 (Table 3.8) had the K_v/K_h ratio set at 0.1 in the alluvium and 0.01 in all basalt layers. Run 2 was the same in the alluvium, but the basalt ratios were 0.001. All the measures degenerate as the K_v/K_h ratio decreases.

Model-predicted potentials in the upper basalt zones were considerably higher than interpreted. Much higher K_v values were required to achieve a reasonable comparison between predicted and interpreted potential distributions than can be deduced by assuming a layered system with the lithology and permeabilities as measured in the field. The layers of dense basalt or interbeds, when undisturbed, act as effective aquitards. Disturbed, however, they can become more permeable to make this layered basalt system more hydraulically connected in the vertical direction. A 44-ft² area of 1-ft/day permeability rock in every acre of completely impervious rock transmits water in an equivalent manner to a uniform 0.001-ft/day porous medium. These zones need not significantly affect travel times because it is the effective porosity of the more porous interflow and interbed zones that appears to dominate total travel time (Appendix D).

Based on the hypothesis that vertical permeability should increase closer to an area of tight folding, the structural map of the top of the basalt and the top of the Grande Ronde was used to prepare the map shown in Figure B.52. The zones on this map were interpreted to represent zones of equal deformation, based on the changes in slope near the anticlines. Figure 3.5 represents zones of equal deformation interpreted for anticlines and synclines. The zones are rated on a scale of 0 to 1, with zero representing no deformation. These maps

TABLE 3.9. Summary of Comparison Statistics Between Model-Predicted Potential Distributions and the Potential Distributions Interpreted from Water Level Data for Four Illustrative Model Calibration Runs and the Base Case. (Comparisons shown for both the current condition scenario and the preman scenario. All comparisons are in feet.)

Run Description	Scenario Description	Number of Positive Differences	Maximum Positive Difference	Average Positive Difference	Number of Negative Differences	Maximum Negative Difference	Average Negative Difference	Average Absolute Difference	Root Mean Square Difference
Run 1	Current Conditions	742	1454	66	1124	-674	-125	101	142
	Preman	778	1144	60	1088	-685	-119	94	133
Run 2	Current Conditions	1014	2965	135	852	-809	-148	141	214
	Preman	1060	2341	137	806	-733	-143	140	203
Run 3	Current Conditions	895	1021	75	971	-688	-133	105	134
	Preman	933	795	72	933	-698	-125	98	124
Run 4 (Base Case)	Current Conditions	991	948	100	875	-658	-135	116	135
	Preman	1050	735	95	816	-666	-125	108	119
Run 5	Current Conditions	995	627	87	871	-576	-122	103	112
	Preman	1066	971	96	800	-583	-118	106	118

FIGURE 3.5. Inferred Zones of Equideformation Associated with Both Anticlinal and Synclinal Structures Within the Local Model Area. (Scale is from 0 to 1 with 1 representing areas of greatest inferred deformation)
(Photo No. 81B554-1)

only represent an interpretation based on structure maps and do not represent any field data on deformation or stresses. If the horizontal permeability decreases in deformation zones, then the K_v/K_h ratio should increase considerably.

The next series of model calibration runs were performed by assigning, on a layer by layer basis, a constant K_v/K_h ratio for each deformation class. In all these runs, the alluvium was held at a K_v/K_h ratio of 0.1. These runs indicated that somewhat better results were achieved when both anticlines and synclines were considered. Illustrative Run 3 represents the best run of this type. The statistics for the comparison between interpreted and predicted potential distributions is shown in Table 3.9 along with the other illustrative run statistics. Figure B.54 illustrates the distribution of the K_v/K_h ratio used in Run 3.

The calibration runs of this type did not produce the desired decrease in the average and rms error statistics. An examination of the K_v (equivalent porous medium) hydraulic conductivity distribution indicated that it was generally too high. A constant K_v/K_h relationship to establish K_v makes the assumption that K_v is correlated with K_h . One can convincingly argue that in a layered system, such as the basalts, this is not the case. In fact, the hypothesis above, related to a decreasing K_h and increasing K_v in deformation areas, is the complete opposite. In general, one would expect K_v to be controlled by discontinuities in the dense basalts and tight interbeds, because these layers act as aquitards. One would also expect these areas of discontinuity to be somewhat limited, and that K_h , the (equivalent porous medium) horizontal hydraulic conductivity, is controlled by the properties of the interflow zones and the more permeable interbed zones.

In the next set of model calibration runs the K_v/K_h ratio in the alluvium remained at a ratio of 0.1. The K_v distribution was established directly. The initial runs of this type used values of 0.0015 ft/day in the zero deformation zones of Saddle Mountains and Wanapum layers and 0.0012 ft/day in the Grande Ronde. The best run of this class is listed as Run 4 in Table 3.9, and the K_v distribution used is shown in Figure B.55. Whereas this class of calibration runs showed some improvements in the extremes, it was not markedly better in comparison of potentiometric statistics.

The very last set of calibration runs showed the most improvement in comparison of potentiometric statistics. In this set of calibration runs, the K_h and K_v distributions were adjusted according to an error map between predicted and interpreted potentials for each of the three basalt layers. In low recharge areas, K_h and K_v were decreased, and in high recharge areas, both were increased. The comparison of potentiometric statistics for Run 5 are shown in Table 3.9.

Whereas Run 5 showed a marked improvement in the comparisons of head potential, most of the increase was caused by improvement in areas away from good well control data. In the regional modeling, we exercised the same caution by first matching to the interpreted potentials and finally to the actual well data. The potentials predicted by the model represent a steady-state condition, and the interpreted potentials represent a transient state, which may not be in equilibrium with the current state of system recharge and pumping. Given the current data on both the K_v and K_h distributions, as well as the head distribution in the deep basalts, and the purpose of the AEGIS technology demonstration, the model was considered calibrated at this point. Further calibration runs would not reduce the uncertainties.

Run 4 (Table 3.9) was selected as the base case for the following reasons:

- The model predicted travel times from the repository to the biosphere and the predicted water dates for the well samples were similar.
- The transmissivity distribution was consistent with that used in the regional hydrologic model.
- The assignment of the K_v distribution was consistent with the hypothesis that K_v and K_h are not necessarily correlated in a layered system such as the basalts.
- The model was consistent with the hypothesis that near deformation zones, K_v increases and K_h decreases.

Model Results

Figures B.56 through B.60 illustrate the model-predicted potential distributions for the base case (Run 4) using the current conditions scenario for the potentials at the top of the alluvium, top of the Saddle Mountains, top

of the Wanapum, top of the Grande Ronde, and base of the Grande Ronde formations, respectively. Figures B.61 through B.64 illustrate the model-predicted base case potential distributions for the preman scenario. (Alluvium is excluded because it is held everywhere within the model area and is the same for both cases.) Figure B.65 illustrates the location of the four representative cross-sections for which plots of the base case vertical potential distributions have been prepared for both the current conditions scenario and the preman scenario.

Figure 3.6 shows a comparison of head values at 13 wells within the local model region to head values predicted by the local region flow model as reported by RHO (Gephart et al. 1979; Staff BWIP 1980). The head values shown are for the water table, Rattlesnake Ridge Flow within the Saddle Mountains Basalt, and the Mabton Flow, which is at the top of the Wanapum Basalt sequence.

The water table was held in the local flow model; therefore, the model water table levels are very similar to the RHO values. The model-predicted water levels are in close agreement with the observed values within the Mabton Flow. The average difference at 10 wells is 46 ft. The Rattlesnake Ridge Flow shows a better comparison, with the average difference for five wells being 30 ft.

A comparison of heads within the individual basalt layers at the 13 wells supports the model predictions. Twelve of the 13 wells show that head increases or stays the same with depth. Well DB-14, located close to Dry Creek, is the only site where the elevation of the unconfined water table is significantly greater than in the lower interbeds. The model predictions were similar, with DB-14 having the only declining head with depth. The amount of increase or decrease in head as predicted by the model was generally in agreement with the difference observed in the field (Figure B.74).

CONCLUSIONS ON HYDROLOGIC MODELING

This AEGIS technology demonstration has shown the usefulness of ground-water modeling as a tool to aid the hydrologist in understanding a complex hydrologic system. The results of this modeling effort, while not providing

FIGURE 3.6. Comparison Between Model-Predicted and Observed Heads

a precise simulation for final prediction purposes (data limited), allow for approximate predictions. More importantly, ground-water modeling provides a tool to assess various system conceptualizations and the sensitivity of approximate predictions to various field data. These model results should guide further data gathering and system characterization studies.

Table 3.10 indicates the areas of greatest uncertainty for the local model region. Most of these have been addressed in the model calibration section. As estimated in Table 3.10, the first three parameter distributions (vertical hydraulic conductivity, effective porosity, and storage coefficient) are of poor quality. However, the storage coefficient distribution is not used in this study (steady-state). Effective porosity, while extremely important to model-predicted travel times, has no influence on model-predicted head distributions and flow paths, which is the primary measure of model calibration. There are carbon-14 water dates, but "an error of 100% or more is likely" unless the flow system is understood and extensive corrections can be made (Bentley and Davis 1980). As a result, the carbon-14 water dates, along with inferred water flow directions from other geochemical and water quality data, were only used in a qualitative sense as a measure of model calibration. Effective porosity data were addressed in sensitivity analysis runs once the model was calibrated. These data were not adjusted in the calibration process because: carbon-14 water dates cannot be considered accurate to more than $\pm 100\%$; water flow directions are not influenced by porosity; the range of available porosity data is limited; and the equivalent porous medium effective porosity values calculated from the scanty data are reasonable.

The hydrologic simulations performed as part of the AEGIS technology demonstration in basalt indicate the following:

1. A better understanding of the nature of the vertical permeability within the basalt systems is needed. Vertical permeability data are needed on a large scale to assess potential vertical movement. Features (if any) that give rise to the relatively large vertical permeabilities (compared to estimates for dense basalt) that were required for model calibration should be evaluated. There is a need to measure and understand the nature of the permeability (if any) in the dense basalts because (as indicated

TABLE 3.10. Subjective Assessment of the Areas of Uncertainty with Respect to the Available Hydrologic Modeling Parameters and the Hydrologic Model Presented in this Report

Area of Uncertainty	Layer (a)	Subjective Assessment of:			Estimate of Reasonable Range for the Parameter or Area of Uncertainty
		Quality of Information (b)	General Uncertainty (c)	Degree of Importance to Model Purpose (d)	
Vertical Hydraulic Conductivity	Al	4	2	1.5	Range for $K_v/K_h = 1.0-0.01$ Range for $K_v/K_h = 1.0-10^{-5}$ Range for $K_v/K_h = 1.0-10^{-5}$
	SM-WP	4.5	3	3	
	GR	5	3	3	
Effective Porosity	Al	3.5	2	1.5	0.05 - 0.2
	SM-WP	4.5	2	3	0.01 - 0.1
	GR	4.5	2	3	0.01 - 0.1
Storage Coefficient	Al	3 - 3.5	2	1	0.05 - 0.2
	SM-WP	4 - 4.5	3	1.5 - 2	0.1 - 10^{-5}
	GR	5	3	1.5 - 2	0.1 - 10^{-5}
Horizontal Hydraulic Conductivity	Al	2.5	1.5	1.5	$0.1-2 \times 10^5$ ft/day
	SM-WP	3.5	2.5 - 3	3	$0.01 - 10^2$ ft/day
	GR	4.5	2.5 - 3	3	$10^{-4} - 10^2$ ft/day
Hydrogeologic Structure or Geologic	AL-SM	2.5 - 3	1.5 - 2	2	
	WP	3	2	3	
	GR	4	2.5 - 3	3	
Potential Distribution	AL	2.5 - 3	1.5	2.5 - 3	
	SM-WP	3 - 3.5	2	3	
	GR	4 - 5	2.5 - 3	3	
Recharge and Pumping	All	2.5 - 3	1.5	3	+20%
Northern-North-Eastern Boundary and Boundary Conditions	All	2.5 - 3	1.5 - 2	2.5	
Southern-South-Eastern Boundary and Boundary Conditions	All	3 - 3.5	2	2.5 - 3	
Overall Conceptual Model of Hydrologic System	All	2.5 - 3	1.5 - 2	3	

(a) Layer designations are AL = Alluvium, SM = Saddle Mountains, WP = Wanapum, and GR = Grande Ronde.

(b) Quality of information is a subjective assessment based on the amount of available data and its general quality. A few good data points might be, for example, ranked the same as many poor data points. The ranking is on a scale of 1 to 5. 1 = excellent, 2 = good, 3 = probably satisfactory, 4 = poor, 5 = estimated or nonexistent.

(c) Subjective assessment of uncertainty on a scale of 1 to 3 and relative to this problem, 3 = highest degree of uncertainty, 2 = medium degree of uncertainty, 1 = lowest degree of uncertainty.

(d) Subjective assessment of the degree of importance of the parameter or area of uncertainty to the purpose of this modeling effort on a scale of 1 to 3, 3 = major importance, 2 = medium importance, 1 = minor importance.

by Remson 1980) the appropriate pressure testing of emplacement holes in nearly impermeable hard rocks can greatly reduce the uncertainty associated with nuclear waste disposal.

2. Porosity measurements are required because little field data exist.

Field data are needed to support the concept that horizontally conducting

layers having high porosity act together with the low permeabilities of the low porosity dense basalt layers (these dense layers control vertical flux) to dominate travel time. The kind of field tracer tests required to verify this concept can also provide information on hydrodynamic dispersivity. The high storage coefficients estimated and observed in the basalts support the relatively high range in porosity deduced for this basalt demonstration.

3. Potential head measurements deep within the Grande Ronde are needed to verify the boundary conditions and regional flow effects deduced through this study.
4. A collection of historical records of potentials, pumping, and irrigation data is needed to use history matching techniques to model, adjust, and determine vertical and horizontal permeability distributions.
5. The measurement of recharge in the Rattlesnake Hills and Horse Heaven Hills area is needed to affirm or refute the character of these boundaries.
6. Further field evidence regarding the deformation-induced decreased horizontal and increased vertical permeability is necessary as the axis of an anticline (and any deformation zones associated with synclines) is approached.

In summary, the site characterization studies conducted by BWIP have provided AEGIS with more data than in the previous reference site initial assessments. This does not imply that all the data necessary for a complete licensing assessment are currently available. Further data gathering and further sensitivity studies are needed to investigate the effects of repository heating on the model-predicted flow paths and travel times and to investigate the effects of eliminating the no-flow boundary in the Horse Heaven Hills.

CHAPTER 4

GEOLOGIC SIMULATION

The geologic simulations used for the AEGIS technology demonstration in basalt are a continuation of the WISAP/AEGIS release scenario model development effort that began during FY-1976. Several geologic and hydrologic consultants helped identify and analyze the various natural phenomena that may degrade or disrupt a nuclear waste repository located deep underground. Although their work continues, many consultants' reports have been published, several of which are cited in appropriate sections of this document, and others are being prepared for publication. In addition to these detailed, topical reports, several reports that discuss the overall AEGIS approach to geologic simulation modeling have been prepared. Perspectives on the Geological and Hydrological Aspects of Long-Term Release Scenario Analysis by Stottlemire et al. (1980) discusses release scenario development for basalt and other lithologies. Experience gained in this earlier work showed that further progress was dependent on site-specific analyses, and much of the work after FY-1979 focused on geologic simulations for nuclear waste repositories in the Columbia River Basalt of the Pasco Basin. A Conceptual Simulation Model for Release Scenario Analysis of a Hypothetical Site in Columbia Plateau Basalts, Stottlemire et al. (1981), describes the geologic considerations and computerized abstractions that enabled development of the AEGIS Geologic Simulation Model (GSM) for basalts of the Columbia Plateau. Geologic Simulation Model for a Hypothetical Site in the Columbia Plateau by Petrie et al. (1981) describes how a computer is used to "model" the geologic and hydrologic systems containing a hypothetical repository in the Pasco Basin.

PERFORMANCE ANALYSIS

The geologic simulations conducted for the AEGIS technology demonstration in basalt are designed to be an integral part of a coordinated performance analysis. Such an analysis endeavors to describe the behavior of the system modeled (e.g., the patterns of ground-water and contaminant movement), the

possible changes of that behavior over the time period of interest, and the probabilities and uncertainties associated with both the inputs and outputs of the analysis. The complex phenomenological codes described in other chapters of this report are too expensive and unwieldy to be used to explore the consequences of every "scenario" of undesirable system changes devised in site characterization and qualification studies. The performance analysis of a system whose behavior must be studied over substantial periods of time must include a geologic simulation model to quantify potential system changes and their probabilities. This model must include simple versions of the more complex phenomenological codes so that it can act as a filter, allowing the complex codes to be applied to modeling those changed states of the system that have the greatest combination of probabilities and consequences.

Effects of Natural Processes

In developing the Geologic Simulation Model (GSM) for basalt, numerous potentially disruptive natural phenomena were identified and analyzed. These phenomena form two groups, based on their potential for affecting the repository (Table 4.1). The phenomena in Group I--rock deformation (e.g., folding and faulting), volcanism, and meteorite impact--could directly disrupt the repository without the interaction of other phenomena. Group II phenomena could probably cause significant degradation or disruption only in combination with other phenomena or under unusual circumstances. In general, Group II contains phenomena that would only affect the geologic and hydrologic system boundary conditions at the repository. However, such boundary condition changes may act synergistically with other phenomena and eventually lead to significant degradation, or may simply affect the initial conditions for radionuclide transport and consequence analysis.

Rock Deformation

A report by RHO (Myers et al. 1979) indicates that the deformation observed in the Columbia Plateau Basalt began 14 to 15 m.y.B.P., was maximum in the period 10 to 5 million years before present (m.y.B.P.), and has since decreased to the present low level. The tectonic history is summarized in the following excerpt from that report.

TABLE 4.1. Potentially Disruptive Phenomena

Group I

Rock Deformation Magmatic Activity Meteorite Impact	}	Could Directly Disrupt Repository
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Group II

Climatic Change Glaciation Sea-Level Fluctuations Geomorphic Processes Hydrology	}	1. Probably Cause Significant Degradation or Disruption 2. Probably affect Hydrologic and Geologic Boundary Conditions
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"Much geologic evidence from the regional and Pasco Basin studies suggests some tectonic deformation began as early as late Grande Ronde time (approximately 14 to 15 million years before present). This deformation was localized along Yakima Fold trends and northwest-trending structures. The rate of tectonic deformation (i.e., an increase in structural relief) increased locally along these same trends, but was generally subdued through Wanapum time (approximately 13.6 to 14.5 million years before present). The rate of deformation was greatest in the Pasco Basin after later Saddle Mountains time (approximately 8.5 to 10.5 million years to approximately 5 million years before present). The extent of involvement of Ringold sediments in deformation appears to decrease from lower to upper Ringold units, suggesting that deformation continued into Ringold time possibly at a reduced rate. Upper Ringold sediments (more than 3.5 million years old) along the White Bluffs appear to be only slightly tilted, but here they overlies relatively gently dipping basalt."

Although Quaternary deformation is not clearly evident in the Pasco Basin, the report cites several cases where it has or may have occurred in the Columbia Plateau region. Such cases include: faulting of the Throp Gravels in Kittitas Valley between 3.5 and 0.13 m.y.B.P., possible young fault scarps on Toppenish Ridge, a small reverse fault southeast of Walla Walla, apparent deformation of the Touchet Beds at the east end of Yakima Ridge and near

Finley Quarry, low magnitude earthquake swarms at Wooded Island and along the north flank of the Saddle Mountains, and historic earthquakes near Umatilla, Milton-Freewater (Oregon), and at other locations. This evidence indicates that the region is still tectonically active, although apparently at a relatively low level. Also, work is currently in progress to evaluate the significance of recently discovered offsets in unconsolidated sediments on the Gable Mountain--Gable Butte structure. The present activity may represent the waning stage of the Miocene to Pliocene development of the Yakima Fold Belt that is often attributed to north-south compression. This is also suggested by the Myers et al. (1979) conclusion that:

Fault plane solutions (mostly composited from low-magnitude events in shallow swarms) indicate that the central Columbia Plateau is under a general north-south compression today.

In developing the GSM, it was assumed that tectonic forces active during the Quaternary will remain active for the next 10^6 yr, and that transport of radionuclides released from the degraded or disrupted repository will be by ground-water flow.

Magmatic Activity

The magmatic activities addressed in this section are limited to those that could directly affect the repository. These include intersection of the repository by either lava or explosive events, the circulation of hydrothermal fluids through the repository, and fracturing of the repository rock by injection of molten rock or doming. Lava flows and pyroclastic deposits mantling the ground surface would probably have no deleterious effect on the repository and could improve repository performance.

During the Miocene Epoch, the Columbia Plateau was the site of extensive basalt eruptions, most of them occurring between 16 and 13 m.y.B.P. Although flows as young as 6 m.y. are recognized in the Columbia Plateau, the youngest basalts cropping out in the Pasco Basin are about 8.5 m.y. old (Myers et al. 1979). These flows probably represented the waning stages of a volcanic cycle. The lack of volcanic activity during the last several million years indicates

that the Columbia Plateau is no longer an active volcanic province, as defined by Crowe (1978). Additionally, there appear to be no data suggesting that a new cycle of activity is beginning. Even if a new cycle were beginning, the lag time between its beginning and possible effects to the repository would probably be extensive. Consequently, magmatic activity in the Columbia Plateau is unlikely to have any deleterious effect on a deep underground repository during the next 10^6 yr.

Reactivation of volcanism in the Cascade Range, as exemplified by the recent eruptions of Mt. St. Helens, is not expected to affect a nuclear waste repository location at the Hanford Site. This is because of the distance between the site and the eastern edge of the Cascade Province (about 100 km) and because of the type of eruptions that generally are associated with volcanoes in the province. Eruptions of these volcanoes tend to be explosive, but lava flows, pyroclastic flows, and lahars are generally limited to within kilometers to a few tens of kilometers of the volcano (Crowe 1978). At greater distances, deposition of pyroclastic ejecta, principally ash, generally has the greatest impact.

Thus, because of the distance of the Hanford Site from the Cascade Range volcanoes, the greatest impact at the site resulting from a major volcanic eruption in the Cascades will probably be the deposition of pyroclastic material, principally ash. As indicated by the Mt. St. Helen's eruption, the effects of this ash would be far more culturally and environmentally, rather than geologically, hazardous, and should have no deleterious effects on the repository.

Meteorite Impact

Data from Hartmann (1978) and Grieve and Robertson (1979) suggest an empirical relation between both fracture and excavation depth, and meteorite impact crater diameter. The diameters of the impact craters associated with fracturing and excavation to the assumed repository depth (1000 m) are 2 km and 4 km, respectively. Wallace et al. (1980) analyzed methods of determining the probabilities of meteorite impact craters of given diameters occurring at a given site, and calculated the probabilities that impact craters with diameters of 2 km and 4 km would intersect or totally overlap the projection of the

repository at the surface. Because of the many uncertainties involved in this sort of calculation, these probabilities are "order of magnitude" rather than exact values. Also, because the final design of the repository is not yet available, a repository area of 10 km^2 was assumed.

Using the method and data discussed by Wallace et al. (1980), the following probabilities were calculated:

- Probability of a 2-km-diameter or larger crater intersecting the surface projection of the repository is $6.0 \times 10^{-11} \text{ yr}^{-1}$.
- Probability of a 4-km-diameter or larger crater intersecting the surface projection of the repository is $4.3 \times 10^{-11} \text{ yr}^{-1}$.
- Probability of a 2-km-diameter or larger crater occurring totally within or completely covering the surface projection of the repository is $3.3 \times 10^{-11} \text{ yr}^{-1}$.
- Probability of a 4-km-diameter or larger crater occurring totally within or completely covering the surface projection of the repository is $2.7 \times 10^{-11} \text{ yr}^{-1}$.

A 2-km-diameter or larger crater either intersecting or completely covering the surface projection of the repository would probably cause some fracturing of the repository, although the degree of fracturing would be related to the proximity of the repository center to the crater center. Consequently, the probability that a 2-km-diameter or larger crater will cause fracturing of the repository is conservatively taken to be $6.0 \times 10^{-11} \text{ yr}^{-1}$. Similarly, the result of a 4-km-diameter or larger crater either intersecting or completely covering the surface projection of the repository could range from fracturing to complete exhumation of the repository. Therefore, the probability that a 4-km-diameter or larger crater will cause at least partial exhumation of the repository is conservatively taken to be $4.3 \times 10^{-11} \text{ yr}^{-1}$.

The probabilities given above suggest that meteorite fracturing of the repository may be expected to occur once in $1.7 \times 10^{10} \text{ yr}$ and at least partial exhumation to occur once in $2.3 \times 10^{11} \text{ yr}$. These time periods exceed the age of the earth given by Verhoogen et al. (1970) by factors of about 3.8 and 5,

respectively. Because of the very low probability of occurrence, and the low frequency of these events in comparison with the age of the earth, effects of meteorite impact are not modeled in the GSM. The Meteorite Impact Submodel (Petrie et al. 1981) uses the above probabilities to generate impacts, but limits treatment to a comment in the history files.

Although probabilities were calculated only for cases with minimum crater diameters of 2 km and 4 km, smaller and larger craters are possible. Larger craters could occur at greater distances from the repository and yet have equal or greater effects than a smaller crater occurring nearer to the repository. Events of this sort are addressed in greater detail in Wallace et al. (1980).

Climatic Change

Kukla, in a consulting report summarized in Scott et al. (1979), indicates that future climatic conditions will fluctuate as widely as they have in the Pleistocene. The expected climatic states and their total durations during the next 10^6 years are:

- Interglacial--global climates possibly slightly warmer but not significantly different from that at present, 100,000 yr.
- Temperature Interstadial--global climates cooler than that at present but generally mild, 160,000 yr.
- Interstadial--global climates significantly cooler than that at present, 80,000 yr.
- Stadial (full glacial)--global climates harsh and cold, 660,000 yr.

Climatic fluctuations by themselves cannot affect the repository. However, the effects of the fluctuations, such as glaciation or increased precipitation, can have major impacts, especially on the hydrologic systems.

Glaciation

During the Pleistocene Epoch, the Pacific Northwest experienced four glaciations with each consisting of several cycles of advance and retreat. Bull (1980) estimates that the probability of another glaciation during the next

10^6 yr is nearly 1.0. Although no continental ice sheet apparently ever reached the repository reference site, Bull indicates that the probability of this occurring during the next 10^6 yr may be between 0.1 and 0.5.

The presence of a continental ice sheet at or within 100 km of the repository could have a wide range of effects, the most notable being erosion, fracturing, and changes in the hydrologic system. Bull (1980) cites average erosion rates for continental glaciers of between 16 and 20 m during the last 3 m.y. He cautions, however, that these are probably minimum rates and that erosion may be much greater in areas where deep erosion has occurred previously. Even with considerably higher rates, it appears unlikely that a 1000-m-deep repository could be disrupted by glacial ice scouring. Bull also cites work by Brothie and Silvester (1969), Peltier and Andrews (1976), and Weertman (1978), suggesting that rock fracturing within about 200 km of the ice edge is probable because of glacial ice loading. However, no definitive data concerning this phenomenon are currently available.

With respect to the development of the GSM, the most important effect of continental glaciation appears to be alterations to the hydrologic system. Of prime concern are alterations that would result in an increased flux of ground water through the repository. This could result from the presence of a wet-based glacier or glacial outwash area located at or near the recharge area of the Grande Ronde Basalt.

Sea-Level Fluctuations

Sea-level fluctuations of several hundred meters are common in the geologic record. Future fluctuations could potentially affect a deep underground nuclear waste repository, but would probably have only a minor impact, if any, at the reference site.

Table 4.2, taken from Schwartz (1978), gives expected parameters for future sea-level fluctuations. The effects of sea-level fluctuations would depend on both the magnitude and type of fluctuation. Decreasing sea level would tend to increase stream gradients and erosion. Increasing sea level would tend to decrease stream gradients and erosion. Table 4.3 shows changes

TABLE 4.2. Maximum Eustatic Sea-Level Fluctuations

Type	Time (Years)	Positive (m)	Negative (m)	Range (m)
Tectono-Eustatic	10^6	250	250	500
Glacio-Eustatic	10^5	100	100	200
Concurrent Tectono- and Glacio-Eustatic	$10^5 - 10^6$	350	350	700

TABLE 4.3. Changes in Stream Gradient Because of Sea-Level Fluctuations

Sea Level Change (m)	Reference Site Surface Elevation Relative to Changed Sea Level (m)	Columbia River Gradient (m/km)
-350	575	$575/550^{(a)} = 1.05$
-250	475	$475/550^{(a)} = 0.86$
-100	325	$325/550^{(a)} = 0.59$
0	225	$225/550^{(a)} = 0.41$
+100	125	$105/120^{(b)} = 0.88$
+250	-25	Site Inundated
+350	-125	Site Inundated

(a) River distance (km) from Hanford townsite to Pacific Ocean

(b) River distance (km) from Hanford townsite to Umatilla, Oregon

in gradient of the Columbia River for various changes in sea level. Except where noted, the gradient was calculated for the reach between the abandoned Hanford townsite and the Pacific Ocean. No adjustment in reach length was made for decreasing sea level.

Although Table 4.3 indicates that the gradient of the Columbia River could increase by a factor of 2.6 because of sea-level lowering, very little change would be expected in the reach between Sentinel and Wallula Gaps because of the bedrock incision at Wallula Gap. Because of this incision, erosion in the reach upstream from Wallula Gap is probably largely decoupled from erosion downstream

of the gap. Consequently, even though the overall gradient of the river downstream of the Hanford Site may more than double because of sea-level lowering, the reach between Sentinel and Wallula Gaps would probably experience little, if any, significant change in gradient during the assessment period.

Sea-level lowering would probably be associated with glaciation, and accompanied by changes in discharge of the Columbia River. Increased discharge, in combination with increased gradient, would tend to cause increased erosion of the river channel. The bed of the river in the Hanford reach is locally in bedrock and apparently well-armored elsewhere by bed load transported by past large discharges, possibly related to Missoula-type flooding. In addition, it is decoupled from erosion downstream of Wallula Gap. The character and thickness of the bed material would probably prevent large-scale erosion of the river channel. Consequently, the combination of decoupling and erosion-resistant bed material will probably prevent any significant deepening of the Columbia River channel in the Hanford reach related to fluvial or pluvial outwash discharges. Future Missoula-type floods would be capable of major channel alterations, as will be discussed in a later section.

The effects of changing sea level on ground-water flow within the Pasco Basin are difficult to quantify based on current knowledge. Decreasing sea level probably would increase head gradients, and increasing sea level probably would decrease head gradients. These effects would probably be of limited magnitude and have no significant impact on the performance of the repository.

Geomorphic Processes

The geomorphic processes addressed by the GSM are surficial and near-surface phenomena such as stream flow, erosion, deposition, flooding, denudation, eolian erosion, and weathering. These processes are generally most effective in mechanically weak materials, especially in areas of high relief or high tectonic activity. The reference site chosen for this analysis is in a tectonically stable basin and valley terrain of the Columbia Plateau characterized by low relief, fluvial plains, and alluvial drainage channels. The stratigraphy of the site is typical of the central Pasco Basin and includes about 100 m of alluvial and glaciofluvial sediments underlain by the thick Columbia River Basalt Group.

Because the reference site is located in dense basalt flows at a depth of about 1000 m below the surface, it is unlikely that geomorphic processes acting alone could significantly affect the repository during the 10^6 -yr analysis period. Tubbs (1979) synthesized information from several sources concerning geomorphic processes in the Pasco Basin and Columbia Plateau. Much of the following data, unless otherwise cited, is taken from his report.

For geomorphic processes to directly disrupt the repository, erosion must extend to the depth of the repository. This would primarily be by regional denudation or local stream erosion, or a combination of these. Denudation rates in the Pasco Basin average about $0.5 \text{ cm}/10^2 \text{ yr}$. If this denudation rate remains constant over the 10^6 -yr assessment period, the regional land surface would be lowered by an average of only 50 m. This is insignificant in comparison with the 1000-m repository depth.

Locally, stream erosion rates can greatly exceed regional denudation rates. In areas such as Wallula Gap and Sentinel Gap, stream erosion is quite pronounced. At these locations, stream erosion has averaged about $3.35 \text{ cm}/10^2 \text{ yr}$ for the last 10^6 yr . For the 10^6 -yr assessment period, projected total erosion would be 335 m. Much of this erosion is attributed to the catastrophic Missoula floods resulting from the repeated failure of glacial ice dams in Montana, Idaho, and Washington. This flooding was described by Bretz (1969) and Baker (1973). These floods, with peak flows of perhaps $9.1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$, eroded channels in the fractured and folded rock of the Saddle Mountains and Horse Heaven Hills anticlines. Erosion rates would be much lower in the comparatively undeformed basalt at the reference site location. Even in the unlikely event that the repository was located within an anticline directly beneath the Columbia River, approximately 3 m.y. would be required for erosion to reach the repository. Erosion to the repository depth also would require that the repository be uplifted to sea level. Such uplift is highly unlikely during the 10^6 -yr assessment period, but is included as a probability distributed function (PDF) in the GSM analyses, and will be discussed in a later section.

Hydraulic damming at Wallula Gap constricted the Missoula flood waters (Bretz 1969). This damming caused temporary impoundment of the flood water

to elevations as high as 350 m, thus forming lakes 230 m or deeper in the Pasco Basin. The duration of these lakes was probably two weeks or less; a few days to a week may be more reasonable.

The effect of such a lake on the 1000-m deep repository is difficult to ascertain and should therefore be studied. Possible effects of such impoundment could be increased pore pressure, possibly leading to tectonic stress relief. Myers et al. (1979) indicate that irrigation is at least partly responsible for the shallow, low magnitude earthquake swarms at Wooded Island near the Hanford Site. Although of a shorter duration and transitory nature, impounded flood water could conceivably have the same effect.

Although geomorphic processes probably could not directly disrupt a 1000-m deep repository during 10^6 yr, they could possibly do so in conjunction with other phenomena such as glaciation and tectonic deformation. Additionally, the processes could bring about changes in the geologic or hydrologic systems. Such changes could alter the boundary conditions around the repository or possibly lead to eventual significant degradation of the repository. Results of GSM analyses of such changes are presented in a later section.

Effects of Man-Caused Changes

Results of the long-term performance analysis of nuclear waste disposal systems can often be summarized by use of a risk approach. Risk in this context is defined as the product of the probability of an event and the corresponding consequences of that event. For the consequence analyses, many of the pertinent parameters have a substantial degree of uncertainty associated with them, although this uncertainty is being reduced because consequence analyses are becoming more sophisticated and reliable as the many research programs in that area progress. The probabilistic aspects of geologic phenomena, too, are subject to uncertainties. However, these uncertainties can be accommodated by the GSM in Monte Carlo simulations to be discussed below, (Petrie et al. 1981), and the estimated future behavior of the geologic system compared with past behavior to establish reasonable bounds on the ensemble of uncertainties.

In contrast, the probabilistic aspects of human-related disturbances of the waste-containment system are not quantifiable. Human activities hundreds

or thousands of years in the future, the period of time for which a performance analysis must be performed, cannot be predicted. Thus, the probabilities associated with possibly disruptive aspects of those activities cannot be estimated. For this reason, man-caused changes to the waste containment system are not included in the AEGIS geologic simulations. The consequences of a specific human activity--borehole drilling--are, however, examined by Zellmer and Lindberg (1981) in the course of development of a threshold criterion for GSM results.

GEOLOGIC SIMULATION MODEL OF COLUMBIA PLATEAU

The GSM for the Columbia Plateau (Petrie et al. 1981) is a quasi-deterministic process-response model that simulates the development for a million years into the future of the geologic and hydrologic systems of the ground-water basin containing the Pasco Basin. Effects of the processes discussed in the previous section on the ground-water hydrologic system are modeled principally by rate equations. The combined effects and synergistic interactions of different processes are approximated by linear superposition of their effects during discrete time intervals in a stepwise-integration approach.

Input Data

Knowledge of natural processes and the modeling of consequences of those processes are subject to varying degrees of uncertainty. Uncertainties arise because of inhomogeneities of the geologic/hydrologic system which preclude accurate characterization at a reasonable level of data collection and model complexity, because of lack of knowledge of the underlying physics driving some phenomena, or because some phenomena are inherently stochastic. The GSM accommodates these uncertainties by treating many of the input data as probability density functions (PDFs). Data whose behavior is better known (e.g., scalar quantities or polynomial combinations of other variables), may carry additional PDF terms to express uncertainties in their values.

Input data used in GSM simulations in support of the AEGIS technology demonstration in basalt are contained in Geologic Simulation Model for a

Hypothetical Site in the Columbia Plateau: Volume II--Results by Foley et al. (1982). Of 288 input variables, 130 are PDFs (including uncertainty terms for other variables), 126 are scalar quantities, and 32 are polynomials. Additional variables are arrays containing geologic system geometric parameters, and a quantized version of Kukla's (see Scott et al. 1979) astronomical climate index ACLIN.

These data were assembled from consultant inputs and from internal sources during development of the GSM, and represent the best "first cut" information available during that period (CY-1980, 1981). However, they have not been completely documented, nor have they been subjected to a complete peer review. Such a review, which should include contributions from Rockwell Hanford Operations and experts in the scientific community other than the consultants who provided many of the data, was beyond the scope of the AEGIS GSM development work and the basalt demonstration.

Summary of Results

The completed AEGIS GSM was used to generate 500 Monte Carlo simulations of the behavior of the geologic/hydrologic system affecting a hypothetical repository in the Pasco Basin over the next million years. As was discussed above, these simulations used data that were not subjected to a review adequate to the needs of a real site performance assessment. However, the general care used in generating the data, and the overall behavior of the GSM (Foley et al. 1982), suggest that the results are plausible, if not defensible, at this time.

The 26 million output data generated in the simulations can be summarized by considering the three primary questions to be answered by any consequence analysis: "where", "how much", and "when". The "where" was determined through an input to the hydrologic analysis contained in the GSM: the shortest path (vertical) from the hypothetical repository to the unconfined aquifer (Figure 4.1) was selected for conservatism and to enable a one-dimensional groundwater flow model to represent the three-dimensional behavior of the confined

FIGURE 4.1. Simplified Geologic and Hydrologic Cross-Section Used in the GSM

ground-water system (Petrie et al. 1981). The "how much," and "when" can be determined, for the most part, by examining the estimated Darcy velocity through the repository and by examining instantaneous travel times for ground-water movement from the repository to the Columbia River as functions of time.

Darcy Velocity Through Repository

Figure 4.2 shows the sum of Darcy velocities through the repository from the northeast and southwest components of the Grande Ronde flow system (see Petrie et al. 1981). Shown are the average value (solid line), envelope of maximum and minimum values (dashed line), and standard deviation (long-dashed, short-dashed line) as functions of time for the first 20,000 years of simulated time (Figure 4.2a) and for the full million years (Figure 4.2b). General

FIGURE 4.2. Total Darcy Velocity Through the Repository a) for the First 20,000 Yr. and b) for the Entire 106 Yr. (solid line). Dashed lines are maximum and minimum values in 500 simulations; long-dashed/short-dashed lines show $\pm$ one standard deviation

behavior of the Darcy velocity is a gradual increase over the first half-million years of a factor of approximately 6, with superimposed increases of the order of the initial value lasting only a few thousand years.

The repository Darcy velocity (Foley et al. 1982) is a function of head gradients and average hydraulic conductivities in the Grande Ronde flow path. The long-period component of change in Darcy velocity reflects:

- the increase in average hydraulic conductivity of this system caused by increase of the assumed small hydraulic conductivity of the repository induced by seismic shaking
- the increase of head gradients of the system resulting from net fluvial erosion of the Pasco Basin, which follows glacial advance through the Wallula Gap in the period from 55,000 to 65,000 years of simulated time. This advance eliminates the hydraulic damming effect of Wallula Gap on future Missoula floods and changes the Pasco Basin regime from one of net deposition to one of net erosion.

The short-term fluctuations of repository Darcy velocity show the effect of climatically induced recharge enhancement, principally during periods of deglaciation.

Instantaneous Travel Time

The Hydrology Submodel of the GSM calculates 1) an instantaneous travel time from the repository to the Columbia River for each time (step using Darcy's Law), 2) the average hydraulic conductivity of the remaining flow path, and 3) the current potentiometric head gradient. This travel time is not a measure of how long it takes an individual particle of water to reach the Columbia River, but rather an indicator to alert the user to major or catastrophic changes in the flow system. Figure 4.3 shows that instantaneous travel times are large (unrealistically so, as will be discussed below), undergo an order-of-magnitude increase with time, and are subject to pronounced short-term fluctuations.

The instantaneous travel time in the GSM is assumed to be controlled by the flow path in the Wanapum-Saddle Mountain layer (Petrie et al. 1981). The increase in travel time is a function of the progressive decrease in hydraulic

(a)

(b)

FIGURE 4.3. Instantaneous Travel Time from the Repository to the Columbia River
 a) for the First 20,000 Yr, and b) for the Entire 10^6 Yr (solid line).
 Dashed lines are maximum and minimum values in 500 simulations,
 long-dashed/short-dashed lines show $\pm$ one standard deviation.

conductivity induced by the formation of gouge on minor faults cutting the flow path, and tempered by the effects of fluvial erosion which shorten the path length as the simulations proceed (Foley et al. 1982). Short-term fluctuations appear to be in concert with climatically induced changes in recharge. The factor-of-16 increase in instantaneous travel time that occurs at 850 years of simulated time is probably the result of a subtle bug in the model; it has no basis in the time histories of hydraulic conductivity, head gradient, or effective porosity (constant).

As was mentioned above, the actual values of instantaneous travel time are unrealistic (initially of the order of 4 million years compared with 15,000 yr found elsewhere in this report). This difference is a result of incomplete calibration of the GSM Hydrology Submodel against the more detailed ground-water models. Also, the initial GSM value is for an undisturbed repository, compared with the faulted one used in the more detailed analyses. The spread of maximum and minimum values of instantaneous travel times (initially about three orders of magnitude) is also probably unrealistic, being the result of uncertainties contained in the PDFs used by the Undetected Features Submodel to establish the starting values of system parameters (Petrie et al. 1981). More detailed and effective calibration was beyond the scope of the GSM development and basalt demonstration work. However, the instantaneous travel time is linearly dependent hydraulic conductivity, head gradient, and effective porosity, so the behavior with time of a calibrated version will be proportional to the results shown in Figure 4.3.

The minimum value of instantaneous travel time undergoes a maximum decrease of about a factor of two, induced by a very slight long-term decline, with superimposed climatically induced perturbations. If a linear factor is introduced to make these results compatible with the results of the more detailed hydrologic analyses, and a more reasonable uncertainty is introduced for the initial value of travel time, then the shortest travel time experienced during any of the 500 simulations would be between 5000 and 10,000 years. This results in spite of the combinations of faulting, erosion, and climatically enhanced ground-water flow rates that occurred in individual simulations.

Discussion

The results of the GSM simulations are not yet defensible. They are promising, and the general behavior of the GSM over the near-term (20,000 years) and long-term (million years) is plausible. Thus, in terms of a demonstration of the GSM technology alone, the results indicate that the development effort was a success, and Foley et al. (1982) have indicated what additional effort is required to make the GSM defensible. However, the GSM is a part of a coordinated performance analysis which involves other models as well, and is intended as a primary guide to analyses to be performed in addition to that of the present system. The usefulness of the reported GSM results to the demonstration of a coordinated performance analysis technology must be determined by considering the validity of the results and how they may be applied realistically (unmodified) to guiding more detailed analyses.

Validity of Results

Evolution of the GSM hydrologic system resulted primarily from the effects of climatic changes and of movement on local faults (Foley et al. 1982). Thus, the time histories of Darcy velocity and travel time shown in Figures 4.2 and 4.3 depend on the accuracy of the Milankovitch climate driver (see Petrie et al. 1981) and an ancillary data and subroutines (e.g., rainfall rates, glacial advances, Missoula floods, and river erosion). In addition, these time histories rely on the data and code of the Deformation Submodel that resulted in insignificant folding, major fault offset, or relative elevation changes between the Pasco Basin and the ground-water recharge areas. Review of input data will be necessary before these results can be relied on for the full million-year simulations.

However, the first 20,000 years of the simulations probably will not change much even if the input data are revised substantially, because the major uncertainties discussed above are related primarily to slow-acting processes not important in the early stages of the simulations. Significant tectonic warping or major fault displacement in the Columbia Plateau in the next 20,000 years are improbable. Similarly, based on the late Quaternary, it is reasonable to expect another stage of continental glaciation and at least one

Missoula flood in the next 20,000 years. The first advance of ice estimated by the GSM is similar to advances of the Pinedale stages. Thus, uniformitarianism is as much of a guide to validity of the results as would be an exhaustive peer review of the GSM and its data.

Thus, with the exception of Hydrology Submodel calibrations discussed previously, the GSM results for the first 20,000 years of simulated time have sufficient validity to provide input for the more detailed analyses of the demonstration of coordinated performance analysis technology. Results for the full million years are plausible, but cannot be relied on yet as an accurate guide to more detailed performance analysis.

APPLICATION OF RESULTS TO HANFORD PERFORMANCE ANALYSIS

Figures 4.2 and 4.3 show that none of the 500 simulations produced substantial changes to either Darcy velocity or travel time in the first 20,000 years of simulated time--a maximum factor of 4 increase in Darcy velocity and, as discussed above, a decrease of a factor of about 2 to 3 in travel time. These results do not provide a compelling alternative to the present hydrologic system for application of the detailed AEGIS model. A threshold value of Darcy velocity of an order of magnitude greater than the starting value was used in the GSM analyses to detect significantly increased flow rates. (See Appendix C for the derivation of this criterion.). Figures 4.2 and 4.4 show that this threshold was not exceeded until about a quarter of a million years of simulated time had passed. Figure 4.2 shows that even then a combination of gradual deterioration of the repository and glacially enhanced recharge was necessary to exceed the threshold in the simulations that had maximum Darcy velocity.

This is an encouraging situation in that nothing happened, within the validity of the data, in the first 20,000 years of simulated time to cause disruption of the hypothetical repository, and that degradation of repository performance was not substantial. However, a demonstration of the AEGIS technology would have been incomplete without consideration of some undesirable

FIGURE 4.4. Relative Frequency of Threshold Exceedance Assuming Exceedance Occurs in 1,000,000 Years

altered state of the geologic/hydrologic system. Such a state was not generated in 10^5 time steps (10^7 years), however, so a separate analysis was necessary to select a lower-probability altered state for more detailed treatment.

Probabilities for disruption of a generic repository in basalt have been derived by the Environmental Protection Agency (Arthur D. Little, Inc. 1980). Selected values (Table 4.4) show that probabilities of natural processes directly disrupting a generic basalt repository are $5 \times 10^{-7} \text{ yr}^{-1}$ or smaller. This is in reasonable agreement with the finding of the GSM that nothing disrupts the repository directly in 500 simulations of the first 20,000 years, especially considering that the EPA probabilities for a generic repository are larger (perhaps by an order of magnitude or more) than those for an actual site such as the Pasco Basin. (Five hundred simulations of the first 20,000 years amounts to a total of 10^7 yrs; probabilities in GSM input data for such an occurrence are on the order of 10^{-8} yr^{-1}).

TABLE 4.4. Probabilities of Direct Disruption

<u>Process</u>	<u>Probability (yr^{-1})</u>
Meteorite	4×10^{-11}
Volcano	6×10^{-10}
Faulting	5×10^{-7}
(Drilling)	(10^{-2})

As has been discussed previously, man-related activities such as drilling cannot be assigned reliable probabilities and have not been used in this technology demonstration; the probability for borehole penetration has been included in Table 4.4 for illustrative purposes only. A borehole calculation was included in Zellmer and Lindberg (1981) in the derivation of a threshold Darcy velocity, but the probability itself (calculated from the number of boreholes drilled in the United States in 1977, assumed to be distributed uniformly over the U.S.) is meaningless.

Faulting, then, appears to be the most probable of the unlikely mechanisms by which the hypothetical repository could be disrupted in the first 20,000 years (beginning 100 years after closure). Foley et al. (1982) has suggested that

high-angle faults (NW-SE, N-S, NE-SW trends) may have an average spacing of about 4-km beneath the sediments of the Pasco Basin. However, this hypothesis has not been confirmed by independent mapping or interpretation. In contrast, thrust faults are known to be associated with the anticlinal structures near and in the Pasco Basin. Thus, a thrust fault with the geometry shown in the fault intersection calculation in Zellmer and Lindberg (1981) was chosen for the disruptive mechanism to provide the altered repository state for further analysis.

CHAPTER 5

GEOCHEMICAL SIMULATION

Geochemical modeling was used in conjunction with available ground-water analyses to interpret major ion solubility controls in transmissive zones of the Columbia Plateau Basalt. Previous geochemical modeling studies of these basalts have been concerned with simulating the mass transfer of basaltic components to the ground water to describe the chemical evolution of the hydrogeologic system (Benson et al. 1978, 1979). Preliminary results have shown that mass transfer modeling, under constrained initial conditions, produced an assemblage of minerals and ground-water compositions qualitatively similar to those found in the transmissive zones of the basalt formations. From a different approach, the basalt demonstration employs solubility modeling, whereby the analytical ground-water chemical data are used to identify the solid phases that may be influencing the ground-water composition. The following analyses summarize a more detailed document prepared by Deutsch et al. (1982) for the Waste/Rock Interaction Technology (WRIT) program at PNL.

The geochemical aspects of each potential repository location play an important role in site characterization and subsequent performance assessment. The importance of geochemical effects arises from the expected chemical interactions between ground water and barrier materials surrounding the nuclear waste and the possible leaching of the waste form (source term). In addition, radionuclides dissolved in ground water may be removed by processes of precipitation, sorption, and ion exchange with the aquifer material (contaminant transport). Geochemical site characterization begins with descriptions of the pertinent physical and chemical parameters for each ground-water and rock type, and progresses through geochemical modeling, to an understanding of the chemical processes active in the hydrogeologic system.

GROUND WATER AND MINERAL CHEMISTRY

Ground-water analyses consisted of 118 sets of chemical data published by Washington State (Van Denburgh and Santos 1965), the U.S. Geological Survey

(La Sala and Doty 1971; La Sala et al. 1973), and Hanford area reports (Apps et al. 1979). The analyses selected were from wells described by the preceding authors as being completed in basalt aquifers. However, a given well may draw from multiple water-bearing (transmissive) zones. In cases where tritium concentrations, carbon-14 ages or stable isotopic analyses are reported, it was possible to eliminate water samples having components of very recent meteoric water.

The analytical data reported from the well-sampling programs include temperature, pH, and major element concentrations; several analyses also list concentrations for Al, Mn, Sr, Li, F, and B. The cation/anion imbalance of the unspiciated data exceeded 5% in only six of the samples. The imbalance never exceeded 12%. Unfortunately, E^H measurements are available for only four of the water samples used in this study. The tritium content of one of these four samples was relatively high, suggesting that it has a component of recent meteoric water. The ground-water analyses used in the geochemical simulation are given in Appendix E.

The continental basalts of the Columbia Plateau have been extensively characterized with respect to their mineralogy, as well as to the chemistries of their major and minor elements. Subtle differences in the mineralogy and bulk compositions are utilized to differentiate between the various basalt units. These data are summarized by Smith et al. (1980) for the basalt flows that comprise the geology of the Hanford Reservation. The mineralogy and chemistry of the primary minerals for basalts in this region has been studied and summarized by Ames (1980). The primary minerals consist principally of plagioclase feldspar, with compositions that range between those of laradorite and andesine; pyroxenes, generally with augite and pigeonite compositions; and andesine; pyroxenes, generally with augite and pigeonite compositions; and minor iron oxides, with compositions in the ilmenite-magnetite solid solution. The accessory minerals identified by Ames (1980) include apatite; sometimes olivine a minor Fe-Co-Ni sulfide; and an unidentified Fe-rich mineraloid. The primary and secondary minerals are contained within a groundmass of SiO_2 -rich basaltic glass.

Fractures and vesicles in the basalts (Figure 5.1) contain a complex series of alteration products. Because these fractures and vesicles can be conduits for ground-water flow in the basalt aquifers, the mineralogy of these alteration products is important in determining the solubility controls for the composition of the ground water. Mineralogical and chemical analyses by Ames (1980), Benson et al. (1978), Benson and Teague (1979), BWIP and Colorado School of Mines staff (1979), and Teague (1980), are summarized in Table 5.1. Of the minerals listed, iron-rich smectite and clinoptilolite are the predominant secondary minerals, followed in relative abundance by silica minerals (quartz, cristobalite, and tridymite), with the remaining minerals present only in minor amounts. In addition to the mineralogical characterization, Benson and Teague (1979) performed an extraction of easily dissolvable Fe and Al from "clay" scraped from four fractures of a basalt core. Although there was no significant change in the Al content of the material upon extraction processing, an appreciable amount of extractable Fe was observed in all cases, which suggests the presence of an amorphous iron component in the "clay" material.

A distinction has been noted between the secondary minerals found in the vesicles and along fractures. As Benson and Teague (1979) state, "Vesicles exhibit a more complex mineralogical assemblage than fractures. Other than clinoptilolite, smectite, and silica, the only minerals found in fractures are illite (an iron-rich variety) and pyrite. Vesicles, on the other hand, were found to contain minor amounts of a variety of secondary phases such as erionite, chabazite, analcime, vermiculite, phillipsite, gypsum, and calcite."

GEOCHEMICAL MODELING

The ion-speciation solubility model, WATEQ2 (Ball et al. 1979), was used to determine the solubility constraints for the published water analyses. The WATEQ2 geochemical model was selected because: 1) its data base contains thermodynamic data for trace elements and metastable solids, as well as the stable minerals, 2) it is the best documented of the available models, and 3) it may have the most thoroughly evaluated thermodynamic data base (Truesdell and Jones 1973; Plummer et al. 1976; Ball et al. 1979, 1980, 1981). Analytical data required as input to the computerized model include the concentrations of

FIGURE 5.1. Typical Structure of a Columbia River Basalt Flow

dissolved elements, temperature, pH and E^H . An iterative aqueous speciation is computed by WATEQ2 using equilibrium constants based on the Gibbs free energy of reaction, an extended Debye-Huckel equation for activity coefficients, and either analytical expressions or Van't Hoff relations to adjust the equilibrium constants to the temperature of the water sample.

TABLE 5.1. Secondary Minerals Calculated to be in Equilibrium with the Ground Waters or Identified on Fractures and Vesicles in the Columbia Plateau Basalt

	Calculated Equilibrium Phases (a)				BWIP and CSM	
Solid Phases	Deutsch et al. (1982)	Ames (1980)	Benson et al. (1978)	Benson and Teague (1979)	Staff (1979)	Teague (1980)
<u>Minerals</u>						
Analcime			X	X		X
Calcite	X	X		X		
Chabazite		X		X		
Chlorite		X				
Clinoptilolite		X	X	X	X	X
Cristobalite		X	X	X	X	X
Dolomite	X					
Erionite		X	X	X		
Fluorite	X					
Gmelinite		X				
Gypsum		X		X		
Halloysite	X					
Harmotome		X				
Heulandite		X			X	
Illite (celadonite)			X	X		X
Laumontite		X				
Mordenite		X	X	X	X	X
Opal ^(b)		X	X	X		X
Phillipsite		X		X		
Pyrite		X	X	X	X	X
Quartz		X		X	X	X
Sepiolite	X					
Smectite Clay	X	X	X	X	X	X
Tridymite			X	X		X
Vermiculite		X	X	X		
Wairakite	X		X	X		
<u>Other Solids</u>						
Allophane	X					
Ferric Hydroxide	X					
Iron oxides		X				
MnHPO ₄	X					
SiO ₂ (amorphous)	X					

(a) Rhodocrosite calculated to be at equilibrium solubility in one sample.

(b) Opal: poorly ordered cristobalite and tridymite.

Solubility-equilibrium hypotheses are then tested by first computing ion activity products (AP) from the activities of the uncomplexed ions based on the stoichiometries of the minerals and amorphous solids in the WATEQ2 data base. These activity products are then compared to the solubility products (K) for the same solid phases to test the assumption that certain of the dissolved constituents in the ground water are in equilibrium with particular minerals and amorphous solids. Disequilibrium indices ($\log AP/K$) are calculated to determine if the water is at equilibrium ($\log AP/K \approx 0$), oversaturated ($\log AP/K > 0$), or undersaturated ($\log AP/K < 0$) with respect to a certain phase.

Aqueous speciation, hence the testing of solubility hypotheses, is only reliable if the quality of the chemical analyses is adequate. As an operating constraint, the WATEQ2 geochemical model does not attempt to model a water analysis with a cation/anion imbalance greater than 30%. The cation/anion balances computed for the modeled analyses are included in the tabulation of the analytical data in Appendix E. In general, the electrochemical balance falls well within a 5% range.

MODEL RESULTS

The disequilibrium indices for calcite calculated from the ground-water analyses indicate that calcite is a principal solubility control for dissolved calcium and a pH buffer. This is in agreement with site studies that show calcite as a common secondary mineral in the basalt (Table 5.1). Several ground-water analyses show undersaturation with respect to calcite, but there is no obvious geographic pattern to these water samples. Moreover, depth correlations for these same samples are not possible due to the sparsity and unreliability of the depth data reported for the samples.

Based on the calculated disequilibrium indices, nearly all of the ground-water analyses for the basalt aquifers are in equilibrium with an amorphous silica phase. The computed equilibrium of these waters with amorphous SiO_2 also suggests that the dissolution of the glassy groundmass in the Columbia Plateau basalts is proceeding at a faster rate than the formation of secondary clay minerals. If clay minerals were limiting the silica concentrations in the ground water, then the concentration of dissolved silica would not attain values

necessary for equilibrium with amorphous SiO_2 . The zedite wairskite and the amorphous clay allophane are in apparent equilibrium with the basalt ground waters. This implies that the omnipresent crystalline clays (smectites) identified in the basalts (Benson and Teague 1979) are not in equilibrium with the ground water. In general, the clay minerals, except halloysite, are oversaturated with respect to the ground water. Three of the samples are at near equilibrium with the smectites montmorillonite, but these are analyses of waters from the bottom of a deep (≈ 1000 m) borehole which has an ambient temperature $>40^\circ\text{C}$. These elevated temperatures may be responsible for equilibrium of the water with crystalline clays. In the majority of cases, however, it does not appear that clays are effective solubility-limiting phases.

The geochemistry of iron in the ground water of basalt aquifers is particularly important because: 1) iron is a major constituent of the clay minerals in the altered basalts (Ames 1980), 2) fresh precipitates of iron oxyhydroxides are known to be strong sorbers for ions in solution (Jenne 1977; Koons et al. 1980), and 3) the $\text{Fe}^{3+}/\text{Fe}^{2+}$ redox couple is important in ground water under reduced oxygen fugacities because it may control the E^H of the waters. Because iron is so sensitive to redox conditions, the concentrations of Fe(II) and Fe(III) must be determined analytically or the redox potential must be accurately measured to model the two valence states and hence the various complexes of iron. Usually, ferrous [Fe(II)] iron dominates over ferric [Fe(III)] iron in basalt (Carmichael et al. 1974). Dissolution of the basalt releases both species, but, due to complexation and the relatively high solubility of ferrous iron with the major anions, no solubility-limiting solids were identified.

Ferric iron, on the other hand, forms very insoluble oxides and hydroxides and as is found elsewhere, the crystalline iron oxides generally show supersaturation. The iron phase calculated to be closest to saturation is the amorphous compound ferric hydroxide, $\text{Fe}(\text{OH})_3(\text{A})$.

A question arises concerning the occurrence of secondary minerals that have been identified in samples of altered basalt but were not computed to be at equilibrium with samples of present-day ground water. The majority of these identified, secondary minerals are layer silicates, zeolites, and various

polymorphs of crystalline SiO_2 (Table 5.1). The disequilibrium indices for these minerals show that these water samples are all generally supersaturated with these minerals. If these minerals are forming under the present chemical conditions in the basalt aquifers, there are two possible modes for their formation. These secondary minerals might be the result of the transformation of the initially precipitated amorphous compounds (SiO_2 , allophane, and ferric hydroxide) into a more stable sequence of crystalline minerals. Alternatively, these phases may be precipitating directly from the ground water at such a slow rate that they do not limit the concentration of their constituent elements in the aqueous phase. In either case, these minerals would not be expected to be at equilibrium with the present-day ground water.

Discussion

The geochemical model must be able to describe the response of the geochemical system to any anticipated perturbations that might arise from natural and man-induced causes. The WATEQ2 model as used in this investigation appears to do a moderately good job of describing the chemical equilibria between the ground water and the aquifer material, based on previous modeling studies (Jenne et al. 1980; Jenne and Truesdell 1973; Jones et al. 1974, 1977; Nordstrom et al. 1979). Other geochemical models such as EQ6 (Wolery 1979) and PHREEQE (Parkhurst et al. 1980) can simulate mass transfers between the solid and liquid phases. However, amorphous and other metastable solids are generally absent from the thermodynamic data bases of these two models. This, in turn, affects the accuracy of the modeling results.

Temperature competency above 100°C has not previously been considered a necessity for most existing geochemical models, with the exception of the PATHCALC family of reaction-path models which includes EQ6. Consequently, the thermodynamic data in most models must be supplemented with high-temperature data to adequately characterize the near-field environment during the superambient thermal period of the repository. Thermodynamic data for elements that compose the waste package (e.g., the actinides, rare earths, Tc, I, Zr, etc.) will also need to be added to the data base of existing models.

With respect to the far-field environment, the existing geochemical models are currently useful for this application, but they require additional thermodynamic data for other solid phases and radioactive elements contained in the waste package. The model results have demonstrated the necessity for acquiring accurate and comprehensive data for the chemistry of the waters. The lack of analyses for Al, Mn, PO_4 and the trace metals hampered the calculation of potential phases that could be equilibrium-solubility controls for dissolved constituents. Although estimates of E_{Pt}^{H} and $E_{\text{Fe}^{+2}/\text{Fe}^{+3}}^{\text{H}}$ are valuable, limited measurements of the redox potential of the water samples similarly hindered the determination of solubility controls for redox-sensitive solids.

CHAPTER 6

SOURCE TERM MODEL

The source term (i.e., the rate of release of radionuclides from the repository) provides the required boundary condition for geotransport modeling. A simple source term for spent fuel based on uranium solubility constraints and congruent leaching was used in this technology demonstration. The model was unusual; it applied to waste packages that were hypothetically sheared in half by geologic faulting. Because the assumed fault intersected only 0.5% of the waste packages, the radionuclide release rate was found to be less than 10^{-5} /yr of the total repository inventory. The following analyses summarize a more detailed document prepared by Kuhn (1982) for the Waste/Rock Interaction Technology (WRIT) program at PNL. The analytical development can be used to define additional experimental and theoretical work in the areas of waste-package and repository design.

WASTE PACKAGE BREACH SCENARIO

The assumed breach scenario is that of a new thrust fault intercepting the repository. These characteristics were interpreted from fault data given in Chapter III of a draft copy of Geologic Studies of the Columbia Plateau, Myers et al. (1979). These data indicate that: 1) the major folds and faults in the Pasco Basin are oriented northwest-southeast to east-west, 2) Umtanum Ridge, Gable Mountain, Yakima Ridge, the Rattlesnake Hills, and the Saddle Mountains are associated with reverse/thrust faults or possible reverse/thrust faults, 3) the reverse/thrust faults associated with Umtanum Ridge, Gable Mountain, and the Rattlesnake Hills dip to the south, 4) reverse/thrust fault dips generally range from near horizontal to near vertical, 5) at and near Gable Mountain-Gable Butte the faults dip between 10° and 45° , and 6) tectonic breccia zones range up to about 100 m wide, but as we assume that a "new" fault will disrupt the repository, a narrow (e.g., 2-m-wide) fault zone was selected.

In the repository, spent fuel waste packages are assumed to sit in a 12-ft by 120-ft grid of holes in the floor, with each hole 4 ft in diameter by 19.5 ft deep. The 12-ft centers lie north-south. The fault strike is assumed to lie north 60° west, and the dip is assumed to be 30°, as shown in the plan and section views of Figure 6.1. It is also assumed that the interception of a hole anywhere along its 19.5-ft depth will breach a waste package. (Actually, the waste packages are shorter than the hole depth.) Water flows along the fault plane from an aquifer below the repository, through the repository, and to an upper aquifer. Shear at the fault plane is assumed to cut spent fuel waste packages in two, leaving two remnants, each open on one end, into which water can flow, as shown in Figure 6.2 and Figure 6.3. Therefore, the fault can breach waste packages over this 19.5-ft range of elevations, which corresponds to a width in the horizontal direction of:

$$W = 19.5 \text{ ctn } 30^\circ = 33.8 \text{ ft}$$

The repository is assumed to extend 10,400 ft east-west and 7650 ft north-south, such that the maximum length of the fault intercepting the repository is:

$$L = 10,400 \text{ sec } 30^\circ = 12,000 \text{ ft}$$

Then the fractional repository area over which waste packages can be breached is:

$$\frac{LW}{(7,600)(10,400)} = 0.005$$

Therefore, we assume 0.5% of the waste packages are available for radionuclide release by the faulting scenario.

The repository dimensions assumed are based on a preliminary BWIP design for a repository at Hanford, but these have been used only as a guide. This source term should not be interpreted as an assessment of the performance of an actual BWIP repository or its waste packages. In this analysis, no credit has been taken for engineered barriers included in backfill, overpack, or waste package design other than geometry.

FIGURE 6.1. Thrust Fault Scenario

ELEVATION VIEW

FIGURE 6.2. Ground-Water Flow from a Fault into the Open End of a Sheared Waste Package

PLAN VIEW

FIGURE 6.3. Flow Pattern in the Fault Plane as Ground Water Enters the Open End of a Waste Package

In a vertical plane oriented north-south along the waste packages, the fault could intercept waste package holes over a horizontal distance of:

$$19.5 \left(\frac{\text{ctn } 30^\circ}{\cos 30^\circ} \right) = 19.5(2) = 39 \text{ ft}$$

A minimum of three and a maximum of four waste package holes could be cut over this length. We assume four waste packages are breached: two at one end, and two one-third from one end. Therefore, for every four waste packages breached, we assume the remnants consist of two with the entire waste package spent fuel inventory, two with a third of the inventory, and two with two-thirds of the inventory.

RELEASE MECHANISM

An upper bound can be put on the release of radionuclides from the waste if solubilities of the various radionuclides are known and if the volumetric flow rate of ground water leaching each waste package remnant is known. Because spent fuel is predominantly UO_2 , as a first approximation one can assume that radionuclides release as the UO_2 matrix dissolves, so that each radionuclide releases in proportion to its concentration in the spent fuel ("congruent" leaching) and that spent fuel dissolves according to the solubility of uranium.

The solubility of uranium depends on its oxidation state, temperature, and the pH and concentration of complexing ligands in solution. The temperature and solution chemistry are discussed below. The oxygen fugacity of deep basalt ground water will be very low, on the order of 10^{-50} atm or less (Smith et al. 1980), which is too low to oxidize UO_2 . However, radiolysis caused by alpha irradiation and initial gamma irradiation will create oxidants, perhaps as free radicals, at an unknown rate. For this study, we do not assume that redox buffers (e.g., H_2 , Fe^{++}) enter a waste package remnant with the ground water at a rate sufficient to defeat radiolytic oxidation of the spent fuel. Therefore, we assume the spent fuel oxidizes as though by

Then the solubility of uranium of interest is that of the phase $\text{UO}_2(\text{OH})_2$.

Experiments show that the assumption of congruent leaching of spent fuel in an oxidizing environment is accurate only within an order of magnitude in terms of relative release rates (Katayama et al. 1980). Departures from congruent leaching are not considered here, but might occur as follows:

1. While the release of uranium as $\text{UO}_2(\text{OH})_2$ is constrained by its solubility, the oxidation/hydrolysis of UO_2 would proceed, creating a layer of $\text{UO}_2(\text{OH})_2$ in which other radionuclides might be mobile.
2. Relatively soluble radionuclides, such as ^{129}I , ^{137}Cs , ^{134}Cs , ^{90}Sr , or ^{99}Tc (anionic), would release at a rate corresponding to the conversion of UO_2 to $\text{UO}_2(\text{OH})_2$.
3. Relatively insoluble radionuclides, such as the actinides, might be subject to important solubility constraints, as for $\text{UO}_2(\text{OH})_2$, and hence would release accordingly.

REPOSITORY TEMPERATURE

Because the solubility of uranium is a function of temperature, the temperature of the ground water in waste package remnants must be estimated. This is done by considering:

$$T = \Delta T_{\text{wp}} + \Delta T_{\text{h}} + \Delta T_{\text{r}} + T_0$$

where T is the desired temperature, ΔT_{wp} is the temperature difference from the waste package centerline to the basalt hole, ΔT_{h} is the temperature rise at the surface of the hole caused by the waste package in the hole, ΔT_{r} is the temperature rise at the same point but is caused by all other waste packages in the repository, and T_0 is the initial basalt temperature at the repository depth. We assume $T_0 = 57^\circ\text{C}$.

The temperature differences are calculated according to steady-state conductive heat transfer inside the holes (ΔT_{wp}), and unsteady-state conductive heat transfer outside the holes (ΔT_{h} and ΔT_{r}) where waste packages are treated as line and volume sources of heat. Inside the holes, the thermal conductivity is taken to be $1 \text{ W/m}^\circ\text{C}$, a value intermediate between water ($0.6 \text{ W/m}^\circ\text{C}$) and basalt ($1.5 \text{ W/m}^\circ\text{C}$).

Each waste package is assumed for temperature calculations to contain the spent fuel from three PWR fuel assemblies. The assemblies are assumed to be 10 yr old at interment, and to have a burnup of 33,000 MW-day/MTU at

30 MW/MTU. The thermal power at repository closure is 1.74 kW/waste package, and the resulting repository heat load is 53 kW/acre.

The calculated temperature can be presented as:

$$T, ^\circ\text{C} = 57 + 244 (t, \text{ years})^{-0.2037}, t > 100$$

where t is the time elapsed after repository closure. It is assumed for convenience that all waste packages are deposited simultaneously. The estimated temperature decreases from 152°C at 100 yr to 84°C at 50,000 yr.

URANIUM SOLUBILITY

Given the oxidation state and temperature, the solubility of uranium depends further on the pH and concentration of complexing ligands in solution. Hanford basalt ground water has been found to include CO_3^{-2} , F^- , SO_4^{-2} , and Cl^- , which can complex with the uranyl (UO_2^{+2}) ion in solution. Consequently, the dissolution of uranium as solid $\text{UO}_2(\text{OH})_2$ is assumed to occur through the following reactions:

These are the reactions for which data are found in Lemire and Tremaine (1980).

All but one of the reactions are both sensitive to pH and influence the pH. As the reactions proceed, H^+ is added to or removed from solution; the resulting pH depends on the concentration of pH buffers in solution. We assume that the ground water remains saturated with respect to silica; this is expected because of vitreous siliceous inclusions in the basalt. Consequently, there is a silicate/silicic acid pH buffer, as well as a carbonate pH buffer, present in the ground water entering waste package remnants.

To estimate the composition of ground water entering remnants, we assume the following:

- The pH is taken to be an empirically determined function of temperature:
 $\text{pH} = 1.64 + 2640/(\text{T}, ^\circ\text{K})$ (Smith et al., 1980)
- The ground water is saturated with respect to silica.
- Both calcite and fluoroite are present. (Ground water composition reported at 45°C is oversaturated with respect to fluorite; calcite is also expected.) Assuming Ca^{+2} is not influenced by other minerals, this fixes the F^- and total carbonate concentrations.
- Sulfate and chloride concentration remain those reported for 45°C ground water.

To find the equilibrium uranium concentration (solubility) inside the waste package as a function of temperature, the procedure is as follows:

1. Assume a temperature.
2. Assume a pH.
3. Calculate the resulting concentrations of all ions, including silicate, subject for the entering ions to a mass balance.
4. Vary the assumed pH until a charge balance is obtained.

Activity coefficients have been all taken to be unity; the resulting inaccuracy is felt to be unimportant to this study. The calculations were done for 60°, 100°, and 150°C, using the thermodynamic data of Lemire and Tremaine (1980). The results are:

Temperature, °C	60	100	150
Inlet pH	9.6	8.7	7.9
Equilibrium pH	9.5	8.6	7.4
Solubility, ppm U	280	370	460

This can be presented as:

$$\text{ppm U} = 141 + 2.28 (T, ^\circ\text{C})$$

or

$$\text{U, kg/m}^3 = 0.141 + 0.00228 (T, ^\circ\text{C})$$

The most important contributions to the solubility are illustrated by considering the results at 150°C:

Species	M
$(\text{UO}_2)_3(\text{OH})_7^-$	6.8×10^{-4}
UO_2CO_2^0	6.6×10^{-7}
$\text{UO}_2(\text{OH})_2^0$	6.3×10^{-7}
$\text{UO}_2(\text{CO}_3)_2^{-2}$	5.0×10^{-7}
Others	$< 10^{-7}$

The solubility is dominated by the anion $(\text{UO}_2)_3(\text{OH})_7^-$, and the pH buffering capacity of the entering ground water is dominated by H_3SiO_4^- , such that the dissolution of uranium is effectively controlled by:

for this scenario.

GROUND-WATER FLOW

The rate at which ground water can flow into the end of a waste package remnant can be estimated in terms of the volumetric flow rate per unit width in the fault plane, using potential flow theory. Assuming that at the interception of a hole in the basalt by the fault there is effectively a circular region of infinite permeability in the fault plane, the maximum flow that can pass through this region is that flowing in the fault plane across a width equal to twice the hole diameter (Kuhn 1982, Appendix B).

Because it is difficult to determine the extent of thermal convection that might occur within a waste package remnant, ground water in a remnant is assumed to be well mixed. The radionuclide release rate is then found directly from:

$$\text{Release rate} = \frac{\text{Inventory in remnant}}{\text{Time to release U in remnant}}$$

and

$$\text{Time to release U} = \frac{\text{U inventory in remnant}}{(\text{U solubility})(\text{ground-water flow rate})}$$

In the absence of significant thermal convection, either diffusive mass transfer resistance or flow stratification might increase the release time dramatically.

From the fault scenario analysis, the ground-water flow rate in the fault is on the order of 0.1 to 1.0 m³/yr per meter width of fault (Appendix C). Because the hole diameter is 4 ft = 1.22 m, the flow rate per waste package remnant is from 0.24 to 2.4 m³/yr.

RESULTS

The uranium inventory per waste package is estimated to be 1320 kg. The time t to release the uranium is found from:

$$\int_{t_0}^{\dagger} C_s \, dt = \frac{\phi I}{Q}, \quad C_s = C_s(T), \quad T = T(t)$$

where C_s is the temperature-dependent solubility of uranium, t_0 is the time after closure at which the breach occurs, I is the uranium inventory, and Q is the volumetric flow rate of ground water into a remnant, and ϕ is 1, 2/3, or 1/3, depending on the kind of remnant.

For breaches occurring at 100, 1000, and 10,000 yrs after closure, the release times for $\phi = 1$ vary as follows:

Q	$t_0 = 100$ Years	$t_0 = 1,000$ Years	$t_0 = 10,000$ Years
$2.4 \text{ m}^3/\text{yr}$	1,300 yr	1,400 yr	1,600 yr
$0.24 \text{ m}^3/\text{yr}$	14,000 yr	15,000 yr	16,000 yr

For any given combination of Q and t_0 , the fraction of the remnants remaining is:

$$0 < t < \frac{1}{3} t_1$$

$$f = 1 - \frac{3t}{2t_1}$$

$$\frac{1}{3} t_1 < t < \frac{2}{3} t_1$$

$$f = \frac{5}{6} - \frac{t}{t_1}$$

$$\frac{2}{3} t_1 < t < t_1$$

$$f = \frac{1}{2} - \frac{t}{2t_1}$$

where t_1 is the release time for $\phi = 1$. We have further assumed that the release time is proportional to ϕ , since the effect of t_0 , and hence of declining temperature, is seen to be small. The undisturbed waste packages in the repository have been excluded from further consideration in the source term.

DISCUSSION AND SIGNIFICANCE

The source term applies to waste packages that have been sheared open on one end, thereby completely compromising a collection of engineered barriers.

The approach illustrates how mass balance and equilibrium constraints can be used to construct a source term model to support performance assessment. Radionuclide release by other mechanisms can be incorporated once they become understood.

Numerous assumptions are made to provide this simple source term model. The significance of some of the important ones is reviewed as follows:

1. Assumption: Hexavalent uranium prevails inside the waste package.

The alternative assumption, that tetravalent uranium prevails, would result in a source term several orders of magnitude smaller due to the smaller solubility. However, this would imply an assumption that the rate of net radiolytic oxidation in the waste package is orders of magnitude less than that implied in the current source term, because the rate of oxidation of uranium would have to be small compared to the release of tetravalent uranium. This is of course possible (e.g., because of ingress of reducing agents), but it is difficult to defend quantitatively. If there is any net radiolytic oxidation, its effect would probably be to directly control the rate of oxidation of uranium dioxide through a mass balance over oxidizing agents. Whether this would permit the formation of a $\text{UO}_2(\text{OH})_2$ layer would depend on the available flow (i.e., on whether the rate of release of hexavalent uranium could exceed the rate of production of hexavalent uranium by oxidation).

2. Assumption: The theoretical maximum ground-water flow into the package occurs.

The theoretical maximum flow (Kuhn 1982, Appendix B) was chosen simply because no less arbitrary, and especially no other definitive, assumption was available. The assumed flow can be made arbitrarily small by postulating an arbitrarily small permeability in the fault plane within its intersection with the emplacement hole. Possibly, swelled clay from a backfill could infiltrate the intersection and substantially decrease the permeability. The degree of conservatism introduced by the assumption used is difficult to estimate, but is potentially large.

3. Assumption: Congruent leaching occurs.

This is one of the few nonconservative assumptions made. The release of "soluble" species, such as ^{129}I or ^{14}C could be limited by the (unknown) rate of oxidation of uranium dioxide, rather than the rate of release of uranium.

4. Assumption: Precipitation outside waste packages is omitted.

Although an oxidizing environment inside a waste package is conceivable, the basalt environment outside is reducing. This will reestablish tetravalent uranium and cause uranium to precipitate from the ground water as it exits a waste package. Due to a lack of time, this additional solubility constraint was not invoked for uranium release, but could be easily introduced into the model. For other species sensitive to redox changes, such as other actinides or technetium, the potential effect of reduced solubilities outside packages is not so obvious. These other species could exit packages at concentrations below the exterior solubility as a result of their dilution in the spent fuel.

5. Assumption: Effects of fuel cladding are omitted.

So long as fuel cladding surrounds the spent fuel it will resist mass transfer, even if cracked or porous. The effect is to reintroduce a " Q_b " term into the mass transfer constraint equation, even for a sheared package. Also, zirconium metal could promote a reducing environment adjacent to the spent fuel interface. These two effects should be complementary in reducing the source term; if the cladding corrodes slowly, a mass transfer barrier would be sustained; if it corrodes quickly, and while it still remains, oxidizing agents near the spent fuel would be consumed.

6. Assumption: Mineralization is omitted.

No attempt has been made to include solubility constraints that are a result of reactions with basalt external to waste packages. One possibility would be the precipitation of cesium as pollucite.

The assumptions and omissions weigh heavily on the side of conservatism. Although the maximum release rate is found to fall under 10^{-5} /yr only because 99.5% of the waste packages are assumed to not contribute to the source term, the conservatism in this calculation is probably so great that the release rates from the individual contributing waste packages would in fact also be less than 10^{-5} /yr.

Among the uncertainties in the calculation are those attached to the equilibrium constant for the reactions involving $\text{UO}_2(\text{OH})_2$. Lemire and Tremaine (1980) report an uncertainty of three orders of magnitude for the equilibrium constant for the species $(\text{UO}_2)_3(\text{OH})_7^-$, which dominates the uranium concentration calculated in this study. An increase of three orders of magnitude would have a modest effect on the equilibrium uranium concentration, because it is limited by the entering H_3SiO_4^- concentration. However, a decrease of three orders of magnitude proportionally reduces the calculated equilibrium uranium concentration and elevates the importance of accurately estimating CO_3^{2-} concentrations, because UO_2CO_3^0 becomes as important as $(\text{UO}_2)_3(\text{OH})_7^-$. Again, the uncertainty weighs on the side of conservatism.

Because of the importance of the entering H_3SiO_4^- concentration and its dependence on the basalt ground water pH, the uncertainty in the correlations of pH versus temperature is important. Unfortunately, a critical review of the experimentation supporting the published correlation is not available, and so the uncertainty is unknown (Kuhn 1982).

CHAPTER 7

TRANSPORT MODELING

Radionuclide transport modeling is one of the last steps in the AEGIS performance assessment technology. It is preceded by a geologic simulation of processes and events that have the potential to affect the integrity of:

- the host rock
- the engineered barrier systems of the repository and of the waste package
- the surrounding geohydrologic system leading to the biosphere

Each of these time-history sequences is evaluated in terms of its probability and potential consequences to identify particular events or processes (or classes of events or processes) that need more detailed analysis. These events or processes or combinations of events and processes are then analyzed to determine the impact they would have on the repository host rock, the engineered barrier systems, and the surrounding hydrologic system.

The output of these more detailed analyses for the engineered barrier systems and the near-field hydrology takes the form of a repository release-rate characterization (far-field source term), which serves as one of the inputs to the transport model. The more detailed results from the hydrologic simulation take the form of predicted ground-water flow patterns and velocities, which ultimately determine the contaminant dispersal and influence the arrival times of dissolved radioisotopes that have leached from the geologic repository. This hydrologic simulation output also serves as an input to the transport modeling effort.

In addition to convection, which is described by the hydrologic simulation, mechanisms such as dispersion, retention, and radioactive decay govern the migration and fate of radionuclides that might be leached from the buried nuclear waste. The following definitions describe the convention applied to the basalt demonstration:

Convection is the movement of dissolved radionuclides with the average velocity of water, as determined from the hydrologic simulation.

Dispersion is the combination of molecular diffusion, which occurs under condition of no flow, and of hydrodynamic dispersion, which represents the effect of the variation of the velocity of water in the medium with respect to its average value described by the convection. This variation of velocity exists at any scale, from microscopic (in the pore) to macroscopic (heterogeneity of the medium) and even megascopic (large-scale variation in the rock properties). Dispersion causes mixing and spreading (longitudinally and transversally with respect to the flow direction) of the transported elements.

Under conditions of no flow, molecular diffusion is the only mechanism generating movement of elements through the rock mass. However, if temperature gradients exist, thermal diffusion (Soret effect) can increase this migration.

Retention is a general term covering all kinds of interaction that can take place between the transported elements and the rock matrix. A non-exhaustive list might include:

- filtration
- molecular diffusion of elements into immobile water (e.g., dead-end fracture, and matrix porosity adjacent to the fracture)
- ion exchange
- chemical reactions between radionuclides, other elements transported in the water, and the rock matrix; these processes are time dependent (kinetics of the chemical reaction)
- precipitation/dissolution
- flocculation.

Radionuclide decay, an easily characterized phenomenon, needs to be superimposed onto the other mechanisms because it causes radionuclides to disappear (thus reducing their concentration in the medium), and causes

nuclides to be generated along the flow path. Migration of the decay products will take place according to their own retention properties and needs to be considered in the transport models.

The basic retentive phenomena are often not specifically distinguished in models, their total effects being empirically represented by a constant ratio between the amount of radionuclides retained on rocks and the amount in solution. Effective distribution coefficients (K_d , K_a) are defined either per unit mass of the rock or by unit area of fractures. They can be supported by tracer tests in situ or from batch experiments in the laboratory. The use of distribution coefficients implies that each element migrates independently of the others, under a unique chemical form (e.g., ion of a given valence, or complex molecule electrically neutral) and that retention is instantaneous and reversible. Recent improvements have introduced a kinetic factor in the modeling of distribution coefficients. Consequently, it must be pointed out that chemical exchange phenomena are not the only phenomena involved in the retention factor.

Uncertainty is associated with the use of the distribution coefficient (K_d) approach for modeling retention. On the other hand, if each potential retention mechanism is identified and modeled precisely, the data and computational requirements can be tremendous, especially for chemical speciation, and chemical reactions, including precipitation and selective ion-exchange capacity. If this approach is used, the Eh, pH, and the natural geochemical equilibrium of the water in the medium are needed, as well as a complete mineralogic description of the rock and a large number of chemical reaction constants, along with the spatial variation of these parameters. Because of the complexity and interaction among the various retentive mechanisms, a great deal of caution must be exercised in the selection of K_d values when the distribution coefficient approach is used in a simulation. When selecting the K_d values used in a transport modeling effort, a conscious effort has to be made to factor in the changes in the geochemical properties that occur along the predicted path of the contaminant migration and to account for possible interaction between migrating nuclides, as well as any other unmodeled mechanisms or effects. Recent theoretical developments, as well as field experiments, have shown that the dispersion

equation only roughly approximates the transport (Gelhar et al. 1979; Matheron and DeMarsily 1980; Simmons 1981). The variations of velocity that are represented by dispersion appear to vary with the average travel distance of each element, which cannot be done in the usual formulation. Thus, it appears that a new type of equation, where the velocity variations are treated in a stochastic framework, should be developed.

In principle, the classical convective-diffusion equation based on the ground-water velocity at each aquifer location and each geological stratum can be solved for the concentration of transported radionuclides over time. Such a calculation requires a thorough knowledge of the release rate from the breached repository, the hydrodynamic dispersivity defined over the entire region, and a complete characterization of the chemical phenomena of contaminant interaction with various geologic media. Currently, acquisition of all such data on a regional scale is not achievable. When predicting contaminant transport through a ground-water system, the inherent spatial variability of media properties is an additional obstacle. This stochastic aspect affects the practical validity of the classical transport equation when applied to large regions and to predictions over thousands of years.

In view of these limitations and uncertainties in the site characterization data, a one-dimensional transport model was used for the far-field transport simulations of this technology demonstration.

MODEL SELECTION

The one-dimensional Multicomponent Mass Transport (MMT1D) model (Washburn et al. 1980), based on the method of discrete parcel random walk, was used to simulate the movement and to predict the concentrations of radioisotopes released by the waste repository. The basic operational concepts incorporated in the model are:

- convective transport with dispersion
- retention as an adsorption equilibrium process
- radioactive decay of contaminants
- repository release rates.

DATA REQUIREMENTS

The data required by the MMT code include the following:

- Repository Release Characterization
 - Time of repository release after closure
 - Release Source Term (or Leach Rate) description
 - Initial inventory and fraction exposed
 - Radioactive decay constants (half-lives) for all nuclides in the inventory
 - Mapping of the parent-daughter relationships for chains
- Flow Tube Characterization
 - Description of the path to the biosphere release point
 - Flow-tube length
 - Flow dimensions, width, height
 - Flow-tube porosity
 - Ground-water velocity
 - Actual or effective dispersivity in the longitudinal direction, lateral and hydrodynamic dispersivity in the transverse directions
- Nuclide Retardation Data
 - Distribution Coefficient (K_d , K_a)
 - Beta-ratio of the bulk mass density to porosity for unconsolidated granular deposits, or a surface area to void-space (volume) ratio for fractured media.

The MMT model uses a random walk form of the method of characteristics to numerically solve the transport equation. In this method, the convection and dispersion are simulated separately through the movement of a large number of parcels. Each of these parcels represents a small fraction of the total mass to be leached into the ground-water system. The amount of mass to be

released is determined from the repository release rate characterization that was dependent on the geologic simulation. The release source term curve reflects the details of the release scenario and is the primary factor establishing the initial radioisotope concentrations during transport simulation. Without the effects of sorption and dispersion, released concentration levels propagate along the flow tube with the ground-water flow velocity, altered only by radioactive decay. Sorption differences among nuclides and dispersion cause separation in the concentration distributions. The release source term of each nuclide is a function of exposed surface area, leach rate, solubility, the water flow rate exiting from the repository, and an analysis of the functioning of the engineered barrier systems. Another factor determining the initial radioisotope concentrations is the distribution of the source in the flow field. MMT allows this source distribution to be accounted for by specifying a release center and release length. Parcels of mass released are then released uniformly over the extent of this source area.

Parcels of nuclides not interacting with the porous media are transported away with a velocity equal to the average velocity of the ground water along the streamlines defined from the hydrologic model. Nuclides that are absorbed move with a retarded velocity equal to the average velocity divided by a retardation factor K , given by:

$$K = 1 + \beta K_d$$

where K_d is the effective distribution coefficient (L^3/M) for the particular nuclide, and β is the ratio of geomedial bulk density to geomedial porosity when the medium is porous and subtends flow. In the case of flow in fractured media, the retardation factor K is defined by:

$$K = 1 + A K_a$$

where K_a is the effective distribution coefficient (L) for the particular nuclide, and A is the surface area to void-space ratio ($1/L$) for the fracture opening.

The K_d distribution coefficient is defined by:

$$K_d = \frac{\text{mass of solute on the solid phase per unit mass of solid phase}}{\text{concentration of solute in solution}}$$

The K_A distribution coefficient is defined by:

$$K_a = \frac{\text{mass of solute on the solid phase per unit area of solid phase}}{\text{concentration of solute in solution}}$$

Immobilization is primarily viewed as an adsorption process but can occur by other chemical mechanisms. The water velocity is assumed to be low enough that the ground-water system is in constant equilibrium.

The radioisotopes contained in both the repository and the flow tubes undergo radioactive decay. Released parcels of fission or activation products have their mass reduced according to a simple first-order exponential decay as they transit the flow tube. Transuranic nuclides are involved in four decay chains: the actinide series, the uranium series, the neptunium series, and the thorium series. Mass balance is maintained in the MMT model by creating daughter parcels with total activity equal to that derived from chain decay. Only parent and daughter nuclides with relatively long half-lives are considered for transport simulations. Daughter nuclides with relatively short half-lives that are in secular equilibrium have the location and spatial distribution of their parents.

Dispersion, defined most simply as the phenomena associated with the mixing between different regions, is a consequence of actual movement deviating from the mean flow velocity. The extent of dispersion for a particular system is quantified by the dispersion length or dispersivity. A random walk process is used by the model to simulate the dispersion of radioisotopes. During transit with a retarded average flow velocity, parcels are given random displacements as a function of the dispersion length. Such a random process

generates the concentration solution to the partial differential equations for convective dispersive transport.

Concentrations of radioisotopes are calculated by a summation of parcel weights over time or space intervals as the parcels exit the flow tube, or for each of the space intervals along the flow tube. The parcel flux obtained from that summation is divided by the total Darcy flow through the tube, or the total volume of water in the spatial interval, to obtain concentration. Because the summation of parcel weights constitutes sampling a random walk transport process, the primary concentration versus time or space curves display statistical fluctuations. The expected concentration curve versus time or space is obtained by averaging the primary curve or histogram with a moving average filter to remove most of these statistical fluctuations. As a result of this methodology, the concentration graphs can include small statistical variations.

APPROXIMATION OF MULTIDIMENSIONAL MODELING WITH A ONE-DIMENSIONAL MODEL

The one-dimensional model can be made to more realistically represent a real system's three-dimensional flow by associating a width and height with the lines of travel (the streamlines obtained from the hydrologic model of the ground-water flow). A collection of streamlines beginning at the repository and ending at a release region at the biosphere is called a macroscopic flow tube. The flow tube's width and height are represented by the initial width and height required to carry the Darcy flux from the repository. An additional component of width and height representing the extent of transverse hydrodynamic dispersion of radionuclides expected during transit along the flow tube may also be added. Furthermore, flow tubes are dimensioned to be mass conservative by requiring all material released from the repository to remain within this macroscopic flow tube until exiting.

The hydrodynamic dispersion coefficient D , required as a parameter for the transport model, must be empirically evaluated using the specific geological media involved. Commonly its value is not available. In a three-dimensional flow, the transverse dispersion coefficient establishes the transfer

rate of radioisotopes between streamlines of varying flow velocity. In a macroscopic flow tube, the dispersion caused by velocity variation between streamlines usually dominates the porous media longitudinal dispersion, which is a microscopic scale phenomenon. Thus, from the perspective of a one-dimensional flow-tube representation of a real three-dimensional flow, dispersion is mainly a consequence of the macroscopic variation in convective transport of nuclides. Radioisotopes entering a specified flow tube are assumed to follow with equal likelihood along any streamline within. On the other hand, concentrations of discharged nuclides having variable transit times are determined by the flow tube's entire discharge volume. This is because exiting parcels of radioisotopes cannot be localized with any greater accuracy than the tube's cross-sectional area.

In view of the above considerations, an effective macroscopic dispersion parameter can be constructed. Let p denote the p th streamline comprising a macroscopic flow tube characterized by p streamlines. Streamline length is L , and travel time is t . An estimate of an effective dispersion parameter, D^* , is obtained by equating the random walk variance in parcel locations and that derived from convective velocity variation:

Let

$$t = \frac{1}{p} \sum_{p=1}^p t_p$$

$$L = \frac{1}{p} \sum_{p=1}^p L_p$$

denote average values. Travel time variance is:

$$\sigma_t^2 = \frac{1}{p-1} \sum_{p=1}^p (t-t_p)^2$$

Average flow-tube velocity is:

$$v = L/t$$

The estimate of variance in location is:

$$(v \sigma_t)^2 = 2D^* t$$

Then, the estimated effective dispersion length d is:

$$d = v \sigma_t^2 / 2t$$

Observe that, unlike the true hydrodynamic dispersion length, the effective macroscopic dispersion value depends on travel time. As the complete location variance equals the sum of variances because of hydrodynamic dispersion and travel time, the complete dispersion coefficient equals $D + D^*$.

Required means and variances for streamline lengths and travel times are obtained from hydrologic modeling and effective dispersion is assumed to dominate the transport.

HYPOTHETICAL REPOSITORY LOCATION AND CHARACTERISTICS

The hypothetical repository was assumed to be located beneath the Hanford Meteorological Station (latitude 46° 33' 47", longitude 119° 35' 54") in the center of the Umtanum flow at about 3700 ft below ground surface (Staff BWIP 1981). This places the repository at approximately 3100 ft below mean sea level (Staff BWIP 1981). The repository is 7650 ft by 10,400 ft with emplacement tunnels 20 ft high. The coordinates of the four corners of the repository (A, B, C, and D) measured in feet from the lower-left-hand corner of the local model region are as follows:

	<u>x (ft)</u>	<u>y (ft)</u>
A	150,932.7	209,911.5
B	161,332.7	209,911.5
C	161,332.7	217,561.5
D	150,932.7	217,561.5

The repository is located within elements 3395 and 3386 of the finite element grid. These elements are in the Grande Ronde and are the third layer of elements below surface elements 395 and 386 (see Figure B.48).

MODEL PREDICTIVE TRANSPORT RUNS FOR THE BASE CASE

The transport analysis for the base case (i.e., the 100-yr initiation, 14,000-yr leach duration, and the fault intersection event) was divided into two cases, long- and short-term predictions. The long-term analysis was used to predict which nuclides, if any, would escape to the biosphere in the two million years after the fault intersection event. This analysis was used to determine the maximum rate of arrival (Ci/yr), time of maximum arrival rate, and the total amount of activity released to the environment during this two-million-year period. The short-term analysis predicted the distances traveled and radionuclide ground-water concentration distribution after 1000 yr and 10,000 yr, because these appear to be emerging as the times of particular interest to the proposed criteria for geologic disposal by the Nuclear Regulatory Commission (1981) and the proposed draft standards by the Environmental Protection Agency.^(a)

DISCUSSION OF TRANSPORT MODEL INPUT DATA FOR THIS ANALYSIS

This section discusses the actual input data used in this transport modeling assessment, along with the sources of the data and selection rationale. Most of the MMT model input parameters are identical for the two transport cases that were analyzed. These common input parameters will be discussed along with the model input parameters, which must be defined differently because of the differences in time frame between the long-term and short-term transport cases being analyzed.

Repository Release Characterization Data

The repository release source term and the rationale behind its calculation has been described in an earlier section. For the base case analysis presented here, which involves an assumed intersecting fault, the total leach time was 14,000 yr. The event initiation was 100 yr post-closure, and no

(a) Environmental Protection Agency. 1981. Environmental Standards and Federal Radiation Protection Guidance for Management and Disposal of Spent Fuel, High-Level and Transuranic Radioactive Wastes, 40 CFR 191, Draft 19, unpublished.

remedial action was assumed in order to be consistent with the Nuclear Regulatory Commission (1981) assumption of loss of institutional control after 100 yr. The total inventory available for leach was estimated at 0.005 of the 46,800 MT of heavy metal radioactive waste in the form of 103,250 boiling water reactor (BWR) and 60,500 pressurized water reactor (PWR) spent fuel assemblies (Staff BWIP 1981). The far-field model was run assuming the source location to be the 12,000-ft line source along the fracture at the top of the Umtanum flow. Table 7.1 illustrates the initial inventory and half-lives for the isotopes considered in this analysis.

Nuclide Retardation Data

As was stated earlier, caution needs to be used when selecting the distribution coefficients for use in transport modeling. The predicted path of flow needs to be considered, so that changes in the geochemical factors along the flow path can be considered.

Retardation is calculated, as indicated earlier, from:

$$\text{Retardation} = 1.0 + (\text{Bulk Density/Porosity}) K_d$$

To be conservative, the average of the porosity for fractured basalts and the interbeds was used to calculate β . The porosity estimates for fractured basalt and interbeds from Gephart et al. (1979a, Table II-13) are 0.16 and 0.2, respectively. This yields an average of 0.18, which was used in this study for the estimation of β .

Bulk densities for the various rock layers, existing along the predicted flow path, were taken from values reported in Gephart et al. (1979a Table IV-7). These values are shown in Table 7.2. A value of 120 pounds per cubic foot (1.92 g/cc) was chosen for use in this study because the majority of the total travel time, as indicated earlier, will be in the more porous zones, which are represented by the fractured basalt and interbed. From these two values β can be estimated as follows:

$$\beta = \text{Bulk Density/Porosity}$$

$$\beta = 1.92/0.18 = 10.6 \text{ g/cc}$$

TABLE 7.1. Isotopes Considered in this Transport Analysis
Along with Their Inventories and Half-Lives

Isotope	Half-Life (yr)	Inventory ^(a) (curies) Time = 10 yr
<u>Fission and Activation Products</u>		
³ H	1.2×10^1	1.2×10^7
¹⁴ C	5.8×10^3	3.5×10^4
⁷⁹ Se	7.0×10^4	1.6×10^4
⁹⁰ Sr	2.9×10^1	2.4×10^9
⁹⁹ Tc	2.1×10^5	6.1×10^5
¹⁰⁷ Pd	7.0×10^6	4.6×10^3
¹²⁶ Sn	1.0×10^5	2.2×10^4
¹²⁹ I	1.6×10^6	1.5×10^3
¹³⁵ Cs	2.0×10^6	1.3×10^4
¹³⁷ Cs	3.0×10^1	3.5×10^9
¹⁵¹ Sm	9.3×10^1	5.2×10^7
^{166m} Ho	3.0×10^1	2.5×10^1
<u>Chain 1 Thorium Series</u>		
²⁴⁴ Cm	1.8×10^1	4.2×10^7
²⁴⁰ Pu	6.5×10^3	2.1×10^7
²³⁶ U	2.3×10^7	1.0×10^4
²³² Th	1.4×10^{10}	-----
<u>Chain 2 Neptunium Series</u>		
²⁴⁵ Cm	8.5×10^3	8.4×10^3
²⁴¹ Pu	1.4×10^1	3.2×10^9

Table 7.1 (contd)

<u>Isotope</u>	<u>Half-Life (yr)</u>	<u>Inventory^(a) (curies) Time = 10 yr</u>
<u>Chain 2 Neptunium Series (continued)</u>		
²⁴¹ Am	4.3×10^2	7.5×10^7
²³⁷ Np	2.1×10^6	1.5×10^4
²³³ U	1.6×10^5	1.8×10^0
²²⁹ Th	7.3×10^3	1.3×10^{-3}
<u>Chain 3 Uranium Series</u>		
²⁴⁶ Cm	4.7×10^3	1.6×10^3
²⁴² Am	1.5×10^2	4.7×10^5
²⁴² Pu	3.9×10^5	7.5×10^4
²³⁸ Pu	8.8×10^1	9.4×10^7
²³⁸ U	4.5×10^9	1.5×10^4
²³⁴ U	2.4×10^5	3.5×10^3
²³⁰ Th	7.7×10^4	1.9×10^{-1}
²²⁶ Ra	1.6×10^3	3.5×10^{-4}
<u>Chain 4 Actinium Series</u>		
²⁴³ Cm	2.9×10^1	1.5×10^5
²⁴³ Am	7.4×10^3	6.6×10^5
²³⁹ Pu	2.4×10^4	1.4×10^7
²³⁵ U	7.1×10^8	1.5×10^2
²³¹ Pa	3.3×10^4	2.5×10^{-1}

(a) Inventory was taken from Staff BWIP 1981, Table 2, page 24.

TABLE 7.2. Bulk Densities of Rock Layers Along the Predicted Flow Path to the Location of Biosphere Discharge

Rock Layer	Bulk Density	
	(lb/ft ³)	(g/cc)
Sediments	112	1.79
Basalt	181	2.90
Fractured		
Basalt	120	1.92
Sandstone	120	1.92

Estimates for the distribution coefficients were obtained from a variety of sources. In selecting the coefficients we attempted to account for the path the nuclides would follow and the amount of time in each segment of the path. We also accounted for the geochemistry of waters and the properties of the rocks along this path to the location of biosphere discharge. Table 7.3 contains a summary of the K_d values obtained from a variety of sources, along with our best estimate value for the distribution coefficients and the conservative estimates. These estimates were based on the following assumptions about the flow path:

- With the exception of the movement through the fracture from the repository to the top of the dense portion of the Umtanum unit, the majority of the movement would be through, and the major of the total travel time would be spent in, the more permeable and porous fractured basalt and interbed zones (see Appendix D).
- As a result, the nuclides would be in contact with little freshly fractured basalt, but instead would be moving along pathways where the basalt had been altered and secondary minerals had been deposited on the rock surfaces.
- The majority of the total nuclide travel would be spent in the Grande Ronde and Wanapum Basalt units, as the majority of the total water travel time would be spent within these units. Analysis of streamline data indicated that even after 10,000 yr the average streamline elevation was -1611 ft referenced to MSL.

TABLE 7.3. Summary of the Distribution Coefficient Values Used in the Selection of the Best and Conservative Values for Use in this Study

Serne and Relyea (1982)				Representative K _d Ranges			Altered Basalt	Interbed Tuff	Barney and Wood (1980)	Conser-vative	Best	
Nuclide	Red. (a)	No Redox	Ox. (b)		Basalt	Interbed						Secondary
Pu	500		40		10	100	500	100	100	100	40	300
U	10		3	Range	2-1000	100-1000	100>1000	50	50	10	3	5
				Gr(c)	5(0-70)		1(0-7)					
				L Ph(d)	10(0-70)		3(0-7)					
Th		500			-----100-----					100	100	500
Ra		50			50(48-150)		25(15>3000)	50	100	50	25	50
Am		50		Gr	6	100	500	100	100	100	50	100
				Range	4-1000	70-1000	100-1000					
				L Ph	50(30-1000)							
Np	150		10		-----			500	250	5	5	50
Pa		100			-----100-----					100	100	100
C		0			-----						0	0
Cs		300		Gr	200	300	1000	1000	500	100	100	300
				Range	180-1000	30-1000	500>10E4					
				L Ph	100	300						
				Range	70-1000	50-1000						
I		0			-----0 Oxidizing-----			0	0	0	0	0
Se	20		5		0	20		2	0	0	5	10
Sr		100		Gr	150	200	250	500	500	100	50	100
				Range	40-200	40-1000	100-1000					
				L Ph	100	50	100					
				Range	40-150	10-300	30-1000					
Tc	20		40		-----0 (0-1000)-----			200	50	0	0	5
Pd		50			-----					10	50	50
Pb		25			-----					10	25	25
Sn	50		500		-----					10	50	50
Nb		100			-----10-----						10	10
Cm		50			-----			100	100	100	50	100
Rb					-----			100	500	100	100	300
Sm		50			100	200(200>1000)				100	50	100
Ho					-----					100	10	10
H		0			-----					10	0	0

(a) Reducing conditions. (b) Oxidizing conditions. (c) Grande Ronde conditions. (d) Low Ph.

- As most of the total nuclide travel time is spent within the Wanapum and Grande Ronde, reducing-to-highly-reducing conditions could be assumed, because water quality data (Deutch 1980; Apps et al. 1979) indicate the chemistry in the Grande Ronde and Wanapum units to be moderate to highly reducing.

Only the best estimate values have been used in the calculations contained in the basalt demonstration. Table 7.4 shows the best estimate distribution coefficients, K_d 's, chosen for use in this study, along with the retardation factors and estimated migration distances after 1000 and 10,000 yr.

TABLE 7.4. Distribution Coefficients, K_d 's, Used in this Study, Along With the Retardation Factors and Estimated for the 1000-yr and 10,000-yr Migration Distance

<u>Nuclide</u>	<u>K_d (cc/g)</u>	<u>Retardation Factor(a)</u>	<u>Estimated 1000-yr Migration Distance (ft)(b)</u>	<u>Estimated 10000-yr Migration Distance (ft)(b)</u>
Am, Cm, Pa, Sm, Sr	100	1061	6.8×10^{-1}	6.8×10^0
Rb Pu, Cs	300	3181	2.3×10^{-1}	2.3×10^0
U, Tc	5	54	1.3×10^1	1.1×10^2
Np, Ra Pd, Sn	50	531	1.4×10^0	1.4×10^1
Th	500	5301	1.4×10^{-1}	1.4×10^0
H, I, C	0	1	7.2×10^2	7.2×10^3

(a) Retardation factor = $1. + 10.6 \text{ (g/cc)} \times K_d \text{ (cc/g)}$

(b) Migration distance calculations based on a water velocity of 0.72 ft/yr.

Flow-Tube Characterization Data

In this section the macroscopic flow-tube parameters used in both the long-term and short-term analyses are defined.

Flow Path, Biosphere Discharge Point, Travel Time, and Velocities

An auxiliary subroutine of the FE3DGW code was used to determine the streamlines and the associated travel times from the repository to the biosphere and to identify the location of the predicted biosphere discharge. These streamlines and travel times were calculated according to the hydraulic conductivity and porosity input values and the model-predicted gradients along the flow path to the biosphere discharge location. Eleven streamlines, equally spaced along the postulated fault, were started at the top of the Umtanum Flow above the repository. Figures 7.1 to 7.3 show the predicted flow paths and biosphere discharge locations for these streamlines. Figure 7.1 shows the X-Y map view; Figures 7.2 and 7.3 show the X-Z (west-east) view and the Y-Z (south-north) vertical cross-section, respectively. Table 7.5 summarizes the minimum, maximum, and average values for the flow-tube length, travel time, and velocity predicted for these streamlines to move from the top of the Umtanum to the biosphere discharge location. The average values presented in Table 7.5 can be used to represent the flow-tube length, travel time, and velocity for our macroscopic flow tube used to simulate the long-term case.

More detailed information regarding these streamlines was used because of shorter distances of travel for the short-term simulations. In the long-term case we are interested in characterizing what enters the biosphere (the Columbia River in this case). For the 10,000-yr and 1000-yr time frames, even the conservative or nonretarded nuclides will never leave the basalts because the average velocity of the waters transporting the nuclides is smaller. The estimation of the average velocities was broken into two parts to address the 1000- and 10,000-yr time frames for the short-term case. The first dealt with nuclides that were not retarded. This case was analyzed by determining how far the water alone would move in 10,000 yr along each of these eleven streamlines. Even after 10,000 yr the water had not moved out of the deeper basalts. Table 7.6 summarizes the averages and ranges for the distance traveled, velocities, and depth after 10,000 yr of travel.

The second part of the analysis for the short-term case dealt with retarded nuclides. This analysis proceeded by taking the retarded nuclide with the

FIGURE 7.1. Predicted Flow Paths and Biosphere Discharge Locations for Hypothetical Repository Release (plan view)

FIGURE 7.2. Predicted Flow Paths in Cross-Section for Hypothetical Repository Release (east-west)

FIGURE 7.3. Predicted Flow Paths in Cross-Section for Hypothetical Repository Release (north-south)

TABLE 7.5. Summary of the Minimum, Maximum, and Average Values for the Streamline Length, Travel Time, and Velocity for the Eleven Streamlines Shown in Figures 7.1 Through 7.3

<u>Description</u>	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
Length (ft)	40,000	51,000	45,000
Time (yr)	13,000	17,000	15,000
Velocity (ft/yr)	2.82	3.29	3.03

TABLE 7.6. Summary of the Minimum, Maximum, and Average Values for the Distance Traveled, Depth, and Velocity for the Eleven Streamlines Shown in Figures 7.1 Through 7.3 after 10,000 yr of Travel

<u>Description</u>	<u>Minimum</u>	<u>Maximum</u>	<u>Average</u>
Length (ft)	4,100	7,400	5,800
Depth (ft) (referenced to MSL)	-1,200	-2,100	-1,600
Velocity (ft/yr)	0.41	0.74	0.58

smallest retardation factor (uranium in this case, $K_d = 5$, retardation factor = 54) and calculating the maximum distance that it would migrate in 20,000 yr (twice the 10,000 yr of interest) if it were moving at the higher 3.03 ft/yr velocity of Table 7.5. This distance calculation is as follows:

$$\text{Distance} = \text{velocity} \times \text{time} / (1 + \text{beta} \times K_d)$$

$$\text{Distance} = (3.03 \times 20000.) / (1 + 10.6 \times 5) = 1122 \text{ ft}$$

Given this indicated maximum movement of 1122 ft, the data generated on the movement of the eleven streamlines was again investigated to determine the average velocity for each of the eleven streamlines. The minimum was 0.35 ft/yr, the maximum was 0.72 ft/yr, and the average was 0.53 ft/yr. The similarity of the ranges and average values for the water velocities over the longer path of the nonretarded isotopes and the shorter path of the retarded isotopes allowed

the same velocity to be used for each. The more conservative water velocity (0.72 ft/yr) was chosen for the macroscopic flow tube used to simulate our short-term case.

Dispersivity--Longitudinal, Lateral, and Effective

For the long-term case an effective longitudinal dispersivity value for our macroscopic flow tube is required to account for the variation in arrival time at the biosphere discharge location. An estimate of the transverse hydrodynamic dispersivity is also required to make a more realistic estimate for the width and height for our macroscopic flow tube. For the short-term case, an estimate of longitudinal hydrodynamic dispersivity is needed because of the interest in estimating the concentration in the ground waters versus distance from the top of the Umtanum flow above the repository. An estimate of a transverse dispersivity as above could be used for a more realistic estimate for the width and height of our macroscopic flow tube.

Table 7.7 (Staff BWIP 1981, page 54, Table 13) shows the estimated ranges for porosity, longitudinal hydrodynamic dispersivity, and the transverse to longitudinal ratio for hydrodynamic dispersivity. For the purposes of this study, a value of 32.8 ft was chosen for the base case estimate of longitudinal hydrodynamic dispersivity. A value of 10.0 was assumed for the transverse to longitudinal dispersivity ratio, yielding an estimate of 3.28 ft for the transverse hydrodynamic dispersivity.

As mentioned in earlier discussions, the spread in arrival time for nuclides arriving at a location of biosphere discharge is dominated by the variation in velocity or arrival time between the various streamlines (or flow paths), and not by hydrodynamic dispersion. As a result, an effective longitudinal dispersivity must be calculated to use a single macroscopic flow tube to represent multidimensional flow and to predict rate of arrival of nuclides at this location of biosphere discharge. This effective dispersivity, as discussed earlier, is calculated from the arrival-time statistics for a set of streamlines that represents the movement from the source to the discharge. The data on the eleven streamlines discussed above were used to estimate the effective dispersivity. The variation, σ , in arrival time was estimated as

TABLE 7.7. Estimates for Porosity, Longitudinal Dispersivity, and the Ratio of Lateral to Longitudinal Dispersivity (Taken from Staff BWIP 1981, page 54, Table 13)

<u>Property</u>	<u>Colonnade/ Entablature Basalt Zones</u>	<u>Interflow Zones</u>	<u>Interbed Zones</u>	<u>Source of Data</u>
Porosity	0.001 - 0.06	0.06 - 0.12	0.10 - 0.15	LaSala and Doty 1971
Longitudinal dispersivity α_L m (ft)	1.0 - 10.0 (3.28 - 32.8)	1.0 - 20.0 (3.28 - 65.6)	1.0 - 20.0 (3.28 - 65.6)	Grove and Beetem 1971
Dispersivity ratio (α_L/α_T)	10.0 - 50.0	1.0 - 10.0	1.0 - 10.0	Assumed

1715.0 yr from the average arrival time and the arrival time distribution. The effective dispersivity of 303 ft was then calculated from this variance, the average velocity, and the average arrival time for the eleven streamlines as follows:

$$d = v \sigma^2 / 2t$$

$$d = (3.03 \times (1715 \times 1715)) / (2 \times 14706)$$

$$d = 303 \text{ ft}$$

Flow-Tube Dimensions--Cross-Sectional Area and Porosity

To estimate ground-water concentrations at the location of biosphere discharge or in the ground waters at any other points, a cross-sectional area and a porosity must be assigned to the macroscopic flow tube. The conservative approach (adopted in this study) is to assign the cross-sectional area according to the porosity estimate, the average velocity, and the flux of contaminated fluid exiting the fracture or initially dissolving the waste. If, as is the case for the long-term analysis, we are only interested in the arrival rate versus time information, then the assignments of flow-tube cross-sectional area (width and height) and porosity are not used.

The repository is capable of holding 20 yr of waste estimated at 1750 packages per year (Staff BWIP 1981) for a total of 35,000 packages. A total of

175 packages (0.5% of the packages) are exposed for leaching. As indicated earlier in the description of the source term, each exposed waste package has $8.47 \text{ ft}^3/\text{yr}$ ($0.24 \text{ m}^3/\text{yr}$) flowing past it. As a result, the total flow that must be supported by our macroscopic flow tube is given by $175 \times 8.47 = 1483 \text{ ft}^3/\text{yr}$ ($0.02/\text{gpm}$). Assuming the flow-tube porosity for the short-term analysis to be 0.06 (see Table 8.7) the required cross-sectional area is calculated as:

$$\text{Cross-sectional Area} = \text{Flow Rate}/(\text{Porosity} \times \text{Velocity})$$

$$\text{Cross-sectional Area} = 1483/(0.06 \times 0.72) \text{ ft}^2$$

$$\text{Cross-sectional Area} = 34,329 \text{ ft}^2$$

If the length of the fracture (12,000 ft) is assumed as one dimension for the macroscopic flow tube then the width can be calculated as 2.86 ft.

A somewhat more realistic approach for estimating concentration versus distance requires an estimate of transverse dispersivity. The width and height of the macroscopic flow tube then increase with distance from the repository source according to the predicted transverse spreading. This spread is a function of distance and not time, and is given as:

$$\text{spread} = 2 \sqrt{2 \alpha_t d_r}$$

$$\text{where: } \alpha_t = \text{transverse dispersivity}$$

$$d_r = \text{distance from the repository or source}$$

If we let C_c be the conservative concentration estimate based only on the width, w_c , and height, h_c , of the flow tube required to carry the leaching fluid through the medium of porosity, θ , with average velocity, v , then the more realistic concentration estimate, C_r , at distance d_r is given by:

$$C_r = C_c [w_c h_c] / ((h_c + 2\sqrt{2 \alpha_t d_r})(w_c + 2\sqrt{2 \alpha_t d_r}))]$$

Summary of Flow-Tube Characterization Data

Two macroscopic flow-tube descriptions were required to deal with the two different time frames required in this analysis. For the analysis of the 1000-yr and 10,000-yr transport, our macroscopic flow tube was assumed, or has been shown, to have the following properties:

Average Velocity	= 0.72 ft/yr
Flow-Tube Width (conservative)	= 12,000 ft
Flow-Tube Height (conservative)	= 2.86 ft
Porosity	= 0.06
Longitudinal Dispersivity	= 32.8 ft
Transverse Dispersivity	= 3.28 ft
Flow Rate	= 1,483 ft ³ /yr
Flow Tube or Path Length	= 44,250 ft

For the long-term analysis of biosphere discharge versus time, our macroscopic flow tube was assigned, or has been shown, to have the following properties:

Average Velocity	= 3.03 ft/yr
Effective Longitudinal Dispersivity	= 303 ft
Flow Tube or Path Length	= 44,250 ft

For the 1000- and 10,000-yr short-term analysis, the conservative ground-water concentration estimate at any distance, d_r , from the repository (source) may be converted to a more realistic ground-water concentration estimate, C_r , by:

$$C_r = C_c [3.432E4 / ((12,000 + 5.12 \sqrt{d_r})(2.86 + 5.12 \sqrt{d_r}))]$$

TRANSPORT ANALYSIS RESULTS

The transport analysis results will be presented in two parts. The short-term analysis results deal with the 1000- and 10,000-yr time frames. First, ground-water concentration and migration distance results will be summarized, along with results on cumulative release to the accessible environment. For the purposes of this study the "accessible environment" includes the basalt and alluvial aquifer system at a one-mile distance from the repository boundary in the X-Y or plan dimension.

The long-term analysis will deal with release rates and cumulative releases to the natural ground-water discharge location in the biosphere (the Columbia River).

The analysis results presented for both the short- and long-term are for the base case, which has been previously described as:

- a fault intersection event
- a 100-yr initiation
- a 14,000-yr leach duration
- having 0.005 of the total fraction of the repository inventory exposed (175 canisters)
- a repository containing 46,800 MTHM
- the best estimate for distribution coefficients (see Table 8.3) and $\beta = 10.6 \text{ g/cc}$.

Short-Term Transport Analysis Results

The transport analysis for the first 1000 yr following initiation indicated zero release to the accessible environment as defined above. In this first 1000 yr, the maximum distance any contaminated waters migrated from the repository was 1300 ft. This maximum migration was for the leading dispersive edge of the contaminant plumes for the nonretarded isotopes ^{14}C and ^{129}I . The actual peak concentrations and their relationships to MPC values at 1000 and 10,000 yr for these and all the rest of the isotopes are shown in Table 7.8. The peak concentrations for the nonretarded isotopes (^{14}C , ^{129}I) were located approximately 200 ft from the repository. The maximum migration distance for the rest of the isotopes, all of which are retarded, was on the order of 100 ft and the peak concentrations locations were well within the 13-ft maximum migration distance estimated for U and Tc over a 1000-yr period (see Table 7.4). In all, 16 isotopes had concentration peaks in excess of MPC, but this contaminant plume represents only 0.021 gpm and is located approximately 3000 ft below ground surface and within the 1-mile buffer zone around the repository. Assuming a 100-gpm well as a practical minimum for a well drilled to this depth, the dilution factor of 4700 would reduce all withdrawn waters below MPC values.

Table 7.8 shows the predicted peak ground-water concentrations at 10,000 yr for all the isotopes modeled. Peak ground-water concentrations for ^{14}C and ^{129}I (the nonretarded radioisotopes) were located 5000 ft from the repository. The peak ground-water concentrations for all the other isotopes were less than 100 ft from the repository. Leading dispersive edges for some of the retarded isotopes were just beginning to reach 300 ft at 10,000 yr. In all, 16 isotopes had peak ground-water concentrations in excess of MPC, as shown in Table 7.8. As indicated for the 1000-yr scenario, the dilution factor of 4700 provided by a 100-gpm well would reduce all withdrawn ground-water concentrations from this 2.86-ft-wide, 12,000-ft-long plume well below MPC. In addition, with the exception of ^{129}I , all ground-water concentrations above MPC after 10,000 yr are located within 300 ft of the top of the Umtanum unit above the repository.

For the 10,000-yr analysis it is not clear whether any of the nuclides would actually leave the 1-mile buffer zone around the repository and enter the accessible environment (see the streamlines shown in Figures 7.1, 7.2, and 7.3). For the sake of conservatism we assumed that the accessible environment was reached at a macroscopic flow-tube length of $5375 \text{ ft} = \sqrt{(5280)^2 + (1000)^2}$. The 1000 ft in the formula accounts for the minimum vertical movement during the first 10,000 yr (see Table 7.6). The results of this analysis indicated that only ^{14}C and ^{129}I (the nonretarded isotopes) reached the accessible environment in 10,000 yr. Table 7.9 shows the total curies and maximum arrival rates for ^{14}C and ^{129}I during the first 10,000 yr.

Long-Term Transport Analysis Results

The long-term simulations predict the rates that radionuclides would enter the biosphere following the fault intersection event. Most of the fission and activation products are too short-lived or are so greatly retarded that they will never enter the biosphere. These nuclides were not included in the long-term simulations (up to two million years). Many of the nuclides involved in decay chains were not included because either they were in secular equilibrium with parents or their fully decayed inventory did not significantly

TABLE 7.8. Summary of Transport Model Results at 1000 and 10,000 Years Showing Predicted Peak Ground-Water Concentration and the Ratio of the Peak Concentration to MPC(a)

Isotope	MPC ^(a) ($\mu\text{Ci}/\text{m}\ell$)	At 1000 yr		At 10,000 yr	
		Peak Con- centration ($\mu\text{Ci}/\text{m}\ell$)	Ratio of Peak Concentration to MPC	Peak Con- centration ($\mu\text{Ci}/\text{m}\ell$)	Ratio of Peak Concentration to MPC
Fission and Activation Products					
^{14}C	8.0×10^{-4}	3.5×10^{-4}	4.8×10^{-1}	1.3×10^{-4}	1.7×10^{-1}
^{79}Se	3.0×10^{-6}	3.1×10^{-5}	1.0×10^1	7.9×10^{-5}	2.6×10^1
^{90}Sr	3.0×10^{-7}	---	---	---	---
^{99}Tc	3.0×10^{-4}	2.0×10^{-3}	6.6×10^0	4.1×10^{-3}	1.4×10^1
^{107}Pd	3.0×10^{-6}	2.8×10^{-6}	9.4×10^{-1}	1.1×10^{-5}	3.8×10^0
^{126}Sn	3.0×10^{-6}	1.3×10^{-5}	4.3×10^0	5.0×10^{-5}	1.7×10^1
^{129}I	6.0×10^{-8}	1.8×10^{-5}	3.1×10^2	1.9×10^{-5}	3.1×10^2
^{135}Cs	1.0×10^{-4}	1.3×10^{-6}	1.3×10^{-2}	8.9×10^{-6}	8.9×10^{-2}
^{137}Cs	2.0×10^{-5}	---	---	---	---
^{151}Sm	4.0×10^{-4}	4.2×10^{-6}	1.0×10^{-2}	---	---
$^{166\text{m}}\text{Ho}$	3.0×10^{-5}	---	---	---	---
Chain 1 Thorium Series					
^{244}Cm	7.0×10^{-6}	---	---	---	---
^{240}Pu	5.0×10^{-6}	2.0×10^{-3}	4.0×10^2	5.1×10^{-3}	1.0×10^3
^{236}U	3.0×10^{-5}	3.3×10^{-5}	1.1×10^0	1.1×10^{-4}	3.6×10^0
^{232}Th	2.0×10^{-6}	N/A ^(b)		N/A ^(b)	
Chain 2 Neptunium Series					
^{245}Cm	2.0×10^{-6}	2.3×10^{-6}	1.2×10^0	6.1×10^{-6}	3.0×10^0
^{241}Pu	2.0×10^{-4}	8.2×10^{-7}	4.1×10^{-3}	2.1×10^{-6}	1.1×10^{-2}

Table 7.8 (contd)

Isotope	MPC ^(a) (μCi/ml)	At 1000 yr		At 10,000 yr	
		Peak Con- centration (μCi/ml)	Ratio of Peak Concentration to MPC	Peak Con- centration (μCi/ml)	Ratio of Peak Concentration to MPC
Chain 2 Neptunium Series (contd)					
²⁴¹ Am	4.0 x 10 ⁻⁶	9.7 x 10 ⁻³	2.4 x 10 ³	5.9 x 10 ⁻⁶	1.5 x 10 ⁰
²³⁷ Np	3.0 x 10 ⁻⁶	2.6 x 10 ⁻⁵	8.5 x 10 ⁰	1.1 x 10 ⁻⁴	3.7 x 10 ¹
²³³ U	3.0 x 10 ⁻⁵	5.7 x 10 ⁻⁷	1.9 x 10 ⁻²	2.1 x 10 ⁻⁵	7.0 x 10 ⁻¹
²²⁹ Th	3.0 x 10 ⁻⁶	3.5 x 10 ⁻¹⁰	1.1 x 10 ⁻⁴	1.5 x 10 ⁻⁷	5.0 x 10 ⁻²
Chain 3 Uranium Series					
²⁴⁶ Cm	4.0 x 10 ⁻⁶	4.3 x 10 ⁻⁷	1.1 x 10 ⁻¹	5.6 x 10 ⁻⁷	1.4 x 10 ⁻¹
²⁴² Am	1.0 x 10 ⁻⁴	---	---	---	---
²⁴² Pu	5.0 x 10 ⁻⁶	7.7 x 10 ⁻⁶	1.5 x 10 ⁰	4.9 x 10 ⁻⁵	9.8 x 10 ⁰
²³⁸ Pu	5.0 x 10 ⁻⁶	1.1 x 10 ⁻⁴	2.3 x 10 ¹	N/A ^(b)	---
²³⁸ U	4.0 x 10 ⁻⁵	4.8 x 10 ⁻⁵	1.2 x 10 ⁰	9.9 x 10 ⁻⁵	2.5 x 10 ⁰
²³⁴ U	3.0 x 10 ⁻⁵	1.1 x 10 ⁻⁴	3.8 x 10 ⁰	2.5 x 10 ⁻⁴	8.3 x 10 ⁰
²³⁰ Th	2.0 x 10 ⁻⁶	1.6 x 10 ⁻⁸	8.0 x 10 ⁻³	8.2 x 10 ⁻⁷	4.1 x 10 ⁻¹
²²⁶ Ra	3.0 x 10 ⁻⁸	3.2 x 10 ⁻⁸	1.1 x 10 ⁰	4.9 x 10 ⁻⁶	1.6 x 10 ²
Chain 4 Actinium Series					
²⁴³ Cm	5.0 x 10 ⁻⁶	---	---	---	---
²⁴² Am	4.0 x 10 ⁻⁶	19 x 10 ⁻⁴	4.8 x 10 ¹	4.4 x 10 ⁻⁴	1.1 x 10 ²
²³⁹ Pu	5.0 x 10 ⁻⁶	1.5 x 10 ⁻³	2.9 x 10 ²	7.0 x 10 ⁻³	1.4 x 10 ³
²³⁵ U	3.0 x 10 ⁻⁵	2.3 x 10 ⁻⁶	7.8 x 10 ⁻²	6.2 x 10 ⁻⁶	2.0 x 10 ⁻¹
²³¹ Pa	9.0 x 10 ⁻⁷	4.2 x 10 ⁻⁹	4.6 x 10 ⁻³	1.7 x 10 ⁻⁷	2.0 x 10 ⁻¹

--- Isotope decayed away before time period.

(a) Maximum permissible concentration (MPC) for uncontrolled soluble species, International Commission on Radiation Protection (1959, 1962).

(b) Values less than 1.0×10^{-11} .

TABLE 7.9. Summary of Cumulative Arrival Quantities and Maximum Arrival Rates for All Isotopes Reaching the Accessible Environment in the First 10,000 yr for the Base Case

Isotope	Maximum Arrival Rate (fract/yr) ^(a)	Maximum Arrival Rate (curies/yr)	Cumulative Arrival Over First 10,000 yr (curies)	EPA Proposed Standards ^(b,c) (curies)
¹⁴ C	1.7×10^{-7}	5.9×10^{-3}	1.6×10^1	2.0×10^2
¹²⁹ I	5.5×10^{-7}	8.2×10^{-4}	2.0×10^0	9.0×10^2

(a) Fraction of the total repository inventory (for that isotope) per year. The rate in curies per year divided by the initial repository inventory (for that isotope) at t = 10 yr.

(b) Per 1000 metric ton of heavy metal (MTHM).

(c) Environmental Protection Agency, 40 CFR 191, Draft 19, unpublished.

contribute to the daughters' inventory and the were short-lived. The inventory of these isotopes has been accounted for by forward decay and inclusion in the daughters' initial inventory.

The nuclides considered in this analysis appear in Table 7.10. This table also includes half-lives, initial total and released inventory, maximum discharge rate (Ci/yr), time of maximum rate (yr), and the total amount (Ci) of the nuclide exiting to the biosphere in the two million years after the fault intersection event. The inventory shown in Table 7.10 is for 10-yr-old waste, and represents the part of the total repository inventory affected by the fault intersection event (i.e., 0.005 of the total).

As can be seen from Table 7.10, some nuclides have more total curies exiting than were present in the original inventory. This is due to the effect of chain decay. For those nuclides that are not involved in chain decay, the exiting inventory is less than the initial inventory in the repository. Depending on the radioactive half-life, some of the fission or activation products have decayed more than others. For example, ¹²⁹I decays very little during its transit from repository to biosphere entry point, whereas in the case of ¹⁴C and ⁹⁹Tc, over 90 percent of the original inventory has decayed before it exits into the biosphere.

TABLE 7.10. Long-Term Transport Analysis Results

Isotope	Total Inventory (Ci)	Released Inventory (Ci)	Half-Life (yr)	Peak Rate (Ci/yr)	Time of Peak (yr)	Total Curies Exiting
<u>Activation and Fission Products</u>						
^{129}I	1.5×10^3	7.5×10^0	1.6×10^7	7.3×10^{-4}	1.8×10^4	7.5×10^0
^{14}C	3.5×10^4	1.8×10^2	5.8×10^3	2.1×10^{-3}	1.7×10^4	1.7×10^1
^{99}Tc	6.1×10^5	3.1×10^3	2.1×10^5	8.8×10^{-4}	7.7×10^5	2.0×10^2
<u>Chain 1 Thorium Series</u> <u>3-Member Linear Decay Chain</u>						
^{236}U	1.0×10^4	5.0×10^1	2.3×10^7	2.1×10^{-4}	7.9×10^5	4.9×10^1
^{232}Th	0.0	0.0	1.4×10^{10}	3.2×10^{-11}	9.4×10^5	3.4×10^{-5}
<u>Chain 2 Neptunium Series</u> <u>4-Member Linear Decay Chain</u>						
^{237}Np	5.2×10^4	2.6×10^2	2.1×10^6	---(a)	---(a)	0.0
^{233}U	1.8×10^0	9.0×10^{-3}	1.6×10^5	5.0×10^{-5}	2.0×10^6	5.6×10^1
^{229}Th	1.3×10^{-3}	6.5×10^{-6}	7.3×10^3	2.2×10^{-6}	1.4×10^6	2.3×10^0
<u>Chain 3 Uranium Series</u> <u>4-Member Linear Decay Chain</u>						
^{238}U	1.5×10^4	7.5×10^1	4.8×10^9	3.1×10^{-4}	7.9×10^5	7.5×10^1
^{234}U	3.8×10^4	1.9×10^2	2.4×10^5	3.5×10^{-4}	7.9×10^5	8.7×10^1
^{230}Th	1.9×10^{-1}	9.5×10^{-4}	7.7×10^4	4.8×10^{-6}	8.6×10^5	1.6×10^0
^{226}Ra	3.5×10^{-4}	1.8×10^{-6}	1.6×10^3	2.7×10^{-5}	7.9×10^5	8.0×10^0
<u>Chain 4 Actinium Series</u> <u>4-Member Linear Decay Chain</u>						
^{239}Pu	1.4×10^7	7.0×10^4	2.4×10^4	---(a)	---(a)	0.0
^{235}U	7.5×10^2	3.8×10^0	7.1×10^8	2.5×10^{-5}	7.9×10^5	6.1×10^0
^{231}Pa	2.5×10^{-1}	1.3×10^{-3}	3.2×10^4	1.3×10^{-6}	8.0×10^5	3.4×10^{-1}

(a) Isotope never enters the biosphere but instead remains in the flow tube.

The biosphere entry point for nuclides released from the repository is the Columbia River (see Figure 7.1).

Summary of Transport Results

The results of this basalt demonstration indicate that the geohydrologic systems separating the nuclear waste from the natural biosphere discharge site mitigate the consequences of the postulated fault intersection event. This analysis also indicates that the basalt system, with the exception of some limited release of ^{129}I and ^{14}C , satisfies the 1000- and 10,000-yr proposed standards for no release to the accessible environment. The reader should be cautioned, however, that the results presented in this analysis are valid only for one particular set of parameters and one postulated release scenario. A complete sensitivity analysis must be performed to evaluate the range of effects that might be observed under different release conditions and for the different ranges in parameters.

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APPENDIX A

BATTELLE-ROCKWELL AGREEMENT

BATTELLE-ROCKWELL AGREEMENT

The following is a copy of the agreement signed by A. M. Platt and R. A. Deju in late January 1980.

Pursuant to discussions held between staff of the Pacific Northwest Laboratory (PNL) and Rockwell Hanford Operations on 19 October 1979, a coordinated effort will be implemented between the Basalt Reference Site Initial Assessment (RSIA) being performed by the PNL Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) Program and the Site Characterization Report (SCR) being prepared by the Rockwell Basalt Waste Isolation Program (BWIP). This coordination will include the exchange and interpretation of relevant data, the development of an analysis (and modeling) plan, the formulation of a conceptual model of the geology and subsurface hydrology of the Pasco Basin, the development of disruptive event scenarios, and the consequence analysis based on selected scenarios.

An initial version of the repository simulation model being developed by AEGIS will be used to assist the AEGIS and BWIP team of geoscientists in the release scenario analysis. Current site-specific data obtained by BWIP will be used to assist the AEGIS and BWIP team to perform hydrologic and radionuclide transport modeling as part of the release consequence analysis. Radiological dose modeling will be performed if warranted by the results of the scenario, hydrologic and radionuclide transport analyses, or by the emerging federal performance criteria for nuclear waste repositories. These cooperative working arrangements between AEGIS and BWIP personnel will facilitate technology transfer and enhance acceptability of the analytical results.

The AEGIS basalt RSIA will be performed according to the following schedule, which includes analytical participation and review by BWIP staff at key points during and following the analyses:

5 Feb 1980	AEGIS Receive BWIP Final Reports (Hydrology and Geology)
3 Mar 1980	Working Paper to ONWI/Rockwell
	Title: Basalt Conceptual Model and Mathematical Modeling Plan

1 Apr 1980	Comments to PNL from ONWI/Rockwell on Conceptual Model and Modeling Plan
1 May 1980	Working Paper to ONWI/Rockwell Title: Basalt Scenarios
2 June 1980	Comments to PNL from ONWI/Rockwell on Scenarios
2 June 1980	Working Paper to ONWI/Rockwell Title: Basalt Hydrologic Modeling
1 July 1980	Comments to PNL from ONWI/Rockwell on Hydrologic Modeling
1 Sept 1980	Working Paper to ONWI/Rockwell Title: Basalt Transport Modeling
1 Oct 1980	Comments to PNL from ONWI/Rockwell on Transport Modeling
1 Dec 1980	Draft Report to ONWI/Rockwell Title: Basalt RSIA
15 Jan 1981	Comments to PNL from ONWI/Rockwell on RSIA Report
1 Apr 1981	Draft Report to DOE Clearance Title: Basalt RSIA

This schedule incorporates suggestions made at the meeting on 29 October. AEGIS staff have discussed scheduling with ONWI, and it appears to meet ONWI's approval. Final approval is subject to review of the FY-1980 AEGIS Technology Program Plan by ONWI and DOE. This agreement will be revised if ONWI or DOE should require changes in the above schedule.

The BWIP SCR will be prepared according to the following schedule, which includes analytical participation and review by AEGIS staff at key points during and following its preparation:

31 Aug 1980	Complete Draft of Site Characterization Report (SCR)
31 Mar 1981	Submit SCR to DOE-R1 for review and clearance.

Mutual review of both AEGIS and BWIP analyses is considered essential to assure coordinated and comparable results.

Effective coordination of the AEGIS and BWIP studies requires a clear understanding of the responsibilities of respective staff with respect to specific management and technical functions. Accordingly, the following Rockwell and PNL staff are designated to provide specific interfaces:

<u>Function</u>	<u>Rockwell</u>	<u>Battelle</u>
Programmatic Aspects	R. A. Deju G. S. Hunt	A. M. Platt M. R. Kreiter
AEGIS/SCR Project Aspects	L. R. Fitch	A. Brandstetter
Basalt RSIA and SCR Planning	L. R. Fitch	F. H. Dove
Data	R. L. Bielefeld	F. H. Dove
Scenario Analysis	D. J. Carrol	J. T. Zellmer
Hydrologic and Transport Analysis	R. G. Baca	C. R. Cole
Dose Analysis	---	J. K. Soldat

In anticipation of the future analytical needs of the Department of Energy (DOE) for other than salt or basalt sites, the analyses to be performed by AEGIS are expected to demonstrate the capabilities of AEGIS methodology for a non-salt geology. Coordination of this effort with the basalt site evaluations by BWIP will assure that DOE will have defensible methodology available when needed for site evaluations and licensing in other parts of the country. In addition, the AEGIS basalt RSIA will assist Rockwell in meeting both the DOE's and the public's expectations with respect to scientifically sound evaluations of the Pasco Basin as a potential repository location.

Signed _____
A. M. Platt
Manager
Nuclear Waste Technology
Program Office, PNL

Date _____

Signed _____
R. A. Deju
Director
Basalt Waste Isolation
Project, Rockwell

Date _____

APPENDIX B

DETAILED HYDROLOGIC ANALYSIS

DETAILED HYDROLOGIC ANALYSIS

With the increasing importance of ground-water modeling for assessment of contaminant transport, estimating ground-water recharge for the regional hydrologic simulation of the Columbia River Basalt was considered essential. The calculation of recharge rates provided an additional means to verify that the ground-water modeling results were reasonable. (Quantitative data on the transmissive properties of the deeper basalts are limited.) An estimate of the amount of water that must be transmitted through the basalt aquifer systems was required to bound the transmissivity values and to estimate the transmissivity distributions in the deeper basalts. Along with the actual data available on the aquifer properties of the system, the use of aquifer recharge values that were independently determined at each grid point provided a means to predict ground-water potentials as a function of estimated flow. When these recharge rates were used in conjunction with observed data on transmissivity to predict ground potential distributions, the confidence in the accuracy of the ground-water model was enhanced, and the model-predicted potentials were in agreement with the measured potential distributions (agreeing in actual shapes and elevations). The transmissivity values play an important role in consequence analysis. Definition of the flow volumes in and out of the hydrologic system, in conjunction with observed potential distributions, provides a tool that can be used to bound the transmissive properties of the ground-water system.

AQUIFER RECHARGE CALCULATIONS

Recharge from precipitation and irrigation constitutes the major source of water for the ground-water system of any given basin. In ground-water modeling, this input is either ignored or implied through the held potential boundaries. The held boundary condition for ground-water potential serves as an infinite source or sink. Surrounding areas near held boundary conditions give a nonunique system response of the rates of discharge/recharge with varying transmissivities, although the predicted potentials match with the observed potentials.

The net recharge reaching ground water from precipitation and irrigation depends on many parameters. Some of the important factors are as follows:

1. Precipitation and Irrigation--If the rate of water reaching the ground surface is in excess of the infiltration rates for the given antecedent moisture content of the soil, then surface runoff of the exceeded amount takes place. If the amount is in excess of the water-holding capacity of soil in the root zone, deep seepage occurs, which may affect the ground-water system. The time of occurrence of precipitation or irrigation is also important because two quick water applications exceeding the soil water-holding capacity will result in higher recharge rates than the same amounts spaced widely apart.
2. Soil--Infiltration rates, water-holding capacity, and depth of soils are some of the important parameters affecting recharge rates. Soil transmits and retains water for plant use.
3. Climate--Temperature, relative humidity, net solar radiation reaching ground surface, and wind velocity are some of the other important climatic factors affecting net withdrawal of water from soil. This, in turn, affects net ground-water recharge rates. All these factors are usually combined into one parameter, called potential evapotranspiration.
4. Vegetation--The important properties of vegetative cover that affect rates of recharge are the root zone and consumptive use rates. The consumptive use rate depends on many factors such as crop growth coefficients, moisture status in the root zone, and climatic parameters defining the potential evapotranspiration (ET_p). Using ET_p rates, crop coefficients, and moisture status, the actual evapotranspiration can be estimated.
5. Topography--Precipitation data for a given basin is available for a few discrete locations and these are interpolated for each subregion (node) of the ground-water system. For rolling and undulating regions, the topography influences the net precipitation at a given location. Appropriate interpolation is used to estimate precipitation for a given subregion at a specific elevation from nearby measurements of precipitation at different elevations and varying distances.

The following section includes a brief literature review of methods used for estimation of some of the above parameters, the source of input data used for the Columbia River Basalt, the procedure adopted for estimation of recharge, and discussions of the results.

Potential Evapotranspiration

A general definition of potential evapotranspiration (ET_p) is given by Dunne and Leopold (1978) as "when a vegetated surface is losing water to the atmosphere at a rate unlimited by deficiencies of water supply." Other definitions specify or imply the use of a reference crop. Penman (1956) defined potential evapotranspiration as the "amount of water transpired in a unit time by a short green crop, completely shading the ground, of uniform height and never short of water." The short green crop is normally assumed to be grass. Jensen (1973), in defining potential evapotranspiration, used alfalfa as a reference crop. Instead of potential evapotranspiration, Doorenbos and Pruitt (1975, 1977) used reference evapotranspiration (ET_o), which they defined as "the rate of evapotranspiration from an extended surface of an 8- to 15-cm-tall grass cover of uniform height actively growing, completely shading the ground, and not short of water."

Numerous methods are available for calculating potential evapotranspiration, some more detailed than others. The approach used depends on the type and extent of available climatic data, as well as on the refinement of the required estimate. The methods discussed below include some of the methods outlined by the Food and Agricultural Organization (FAO) of the United Nations methods (Doorenbos and Pruitt 1975, 1977) and the Thornthwaite Method (Palmer and Havens 1958).

Radiation Method

Doorenbos and Pruitt (1977) developed the following regression relationship for climatic data.

$$ET_o = C(W \cdot R_s)$$

where

ET_0 = reference evapotranspiration (L)

R_s = measured or calculated solar radiation expressed in equivalent evaporation per day (L)

W = temperature-related proportionality factor

c = adjustment factor dependent on mean relative humidity and daytime wind conditions.

Graphical solutions of ET_0 for the radiation equation are shown in Figure B.1.

Modified Penman

The original Penman (1948) equation consisted of two terms: the energy (radiation) term and the aerodynamic (wind and humidity) term. Doorenbos and Pruitt (1977) modified this slightly, using a revised wind function term. The form of the equation is

$$ET^*_0 = W \cdot R_n + (1 - W) f(u)(e_a - e_d)$$

radiation term aerodynamic term

where

ET^*_0 = unadjusted reference crop evapotranspiration (L)

W = temperature-related weight factor

R_n = net radiation in equivalent evaporation per day (L)

$f(u)$ = wind function term, $0.27 (1 + U_2/100)$, where U_2 is the mean daily wind run (km/day) measured at a 2 m height

$(e_a - e_d)$ = difference between saturated vapor pressure (e_a) at mean air temperature and the mean actual vapor pressure (e_d) of the air, both in mbar

The Penman equation is based on the "most common" conditions where R_n is medium to high, mean relative humidity is medium to high, and moderate daytime wind is double the nighttime wind. When conditions are other than those specified above, an adjustment factor (c) is applied to the equation to compensate for climatic differences. Table B.1 gives the FAO guidelines for the adjustment factor, which depends on mean relative humidity, wind, and radiation data.

FIGURE B.1. Graphical Relationships for Determination of ET_0 from Calculated Values of $W \cdot R_s$, Accounting for Mean Relative Humidity (RH menu) and Daytime Wind Conditions (after Doorenbos and Pruitt 1977)

TABLE B.1. Adjustment Factor c for the Modified Penman Method (from Doorenbos and Pruitt 1977)

Uday m/sec	RH _{max} · 30%				RH _{max} · 60				RH _{max} · 90			
	3	6	9	12	3	6	9	12	3	6	9	12
	Uday/Unight · 2.0											
0	0.86	0.90	1.00	1.00	0.96	0.98	1.05	1.05	1.02	1.06	1.10	1.10
3	0.79	0.82	0.92	0.97	0.92	1.00	1.11	1.19	0.99	1.10	1.27	1.32
6	0.68	0.77	0.87	0.93	0.85	0.96	1.11	1.19	0.94	1.10	1.26	1.33
9	0.55	0.65	0.78	0.90	0.76	0.83	1.02	1.14	0.88	1.01	1.16	1.27
	Uday/Unight · 3.0											
0	0.86	0.90	1.00	1.00	0.95	0.98	1.05	1.05	1.02	1.06	1.10	1.10
3	0.76	0.81	0.88	0.94	0.87	0.96	1.06	1.12	0.94	1.04	1.18	1.28
6	0.61	0.68	0.81	0.83	0.77	0.88	1.02	1.10	0.86	1.01	1.15	1.22
9	0.26	0.56	0.72	0.62	0.67	0.79	0.88	1.05	0.78	0.92	1.06	1.18
	Uday/Unight · 2.0											
0	0.86	0.90	1.00	1.00	0.96	0.98	1.05	1.05	1.02	1.06	1.10	1.10
3	0.69	0.76	0.85	0.92	0.83	0.91	0.99	1.05	0.89	0.98	1.10	1.14
6	0.53	0.61	0.74	0.84	0.70	0.80	0.94	1.02	0.79	0.92	1.05	1.12
9	0.37	0.28	0.65	0.76	0.59	0.70	0.84	0.95	0.71	0.81	0.96	1.06
	Uday/Unight · 3.0											
0	0.86	0.90	1.00	1.00	0.96	0.98	1.04	1.04	1.02	1.06	1.10	1.10
3	0.64	0.71	0.82	0.89	0.78	0.86	0.94	0.99	0.85	0.92	1.01	1.05
6	0.23	0.53	0.68	0.79	0.62	0.70	0.84	0.93	0.72	0.82	0.95	1.00
9	0.27	0.21	0.59	0.70	0.50	0.60	0.75	0.87	0.62	0.72	0.87	0.96

Evaporation Pans

Where evaporation pan data is available, estimates of ET_o are obtained from the relationship in which E_{pan} is the measured pan evaporation (L), either Class A or Sunken Colorado type, and K_p is the pan coefficient suggested in the FAO guidelines:

$$ET_o = K_p E_{pan}$$

Table B.2 give K_p for different ranges of humidity and wind. The K_p values are a function of upwind fetch (Figure B.2).

TABLE B.2. Pan Coefficient K_p for Class A and Sunken Colorado Pans for Different Ground Cover. Levels of mean relative humidity and 24-hours wind (from Doorenbos and Pruitt 1977)

Class A Pan RH mean %	Case A: Pan Placed in Short Cropped Area				Case B(a): Pan Placed in Dry Fallow Area			
Wind km/day	Windward Side Distance of Green Crop m	Low <20	Medium 10-70	High >70	Windward Side Distance of Dry Fallow m	Low <40	Medium 40-70	High >70
Light < 175	1	0.55	0.65	0.75	1	0.7	0.8	0.85
	10	0.65	0.75	0.85	10	0.55	0.65	0.75
	100	0.7	0.8	0.85	100	0.55	0.65	0.75
	1,000	0.75	0.85	0.85	1,000	0.5	0.6	0.7
Moderate 175 - 425	1	0.5	0.6	0.65	1	0.65	0.75	0.8
	10	0.6	0.7	0.75	10	0.55	0.65	0.7
	100	0.65	0.75	0.8	100	0.5	0.6	0.65
	1,000	0.7	0.8	0.8	1,000	0.45	0.55	0.6
Strong 425 - 700	1	0.45	0.5	0.6	1	0.6	0.65	0.7
	10	0.45	0.6	0.65	10	0.5	0.55	0.65
	100	0.6	0.65	0.7	100	0.45	0.5	0.6
	1,000	0.65	0.7	0.75	1,000	0.4	0.45	0.55
Very Strong > 700	1	0.4	0.45	0.5	1	0.5	0.6	0.65
	10	0.45	0.55	0.6	10	0.45	0.5	0.55
	100	0.5	0.6	0.65	100	0.4	0.45	0.5
	1,000	0.55	0.6	0.65	1,000	0.35	0.4	0.45

Sunken Colorado RH mean%	Case A: Pan Placed in Short Cropped Area				Case B(a): Pan Placed in Dry Fallow Area			
Wind km/day	Windward Side Distance of Green Crop m	Low <20	Medium 10-70	High >70	Windward Side Distance of Dry Fallow m	Low <40	Medium 40-70	High >70
Light < 175	1	0.75	0.75	0.8	1	1.1	1.1	1.1
	10	1.0	1.0	1.0	10	0.85	0.85	0.85
	≥100	1.1	1.1	1.1	100	0.75	0.75	0.8
					1,000	0.7	0.7	0.75
Moderate 175 - 425	1	0.65	0.7	0.7	1	0.95	0.95	0.95
	10	0.85	0.85	0.9	10	0.75	0.75	0.75
	≥100	0.95	0.95	0.95	100	0.65	0.65	0.7
					1,000	0.6	0.6	0.65
Strong 425 - 700	1	0.55	0.6	0.65	1	0.8	0.8	0.8
	10	0.75	0.75	0.75	10	0.65	0.65	0.65
	≥100	0.8	0.8	0.8	100	0.55	0.6	0.65
					1,000	0.5	0.55	0.6
Very Strong > 700	1	0.5	0.55	0.6	1	0.7	0.75	0.75
	10	0.65	0.7	0.7	10	0.55	0.6	0.65
	≥100	0.7	0.75	0.75	100	0.5	0.55	0.6
					1,000	0.45	0.5	0.55

(a) For extensive areas of bare-fallow soils and no agricultural development, reduce K_{pan} by 20% under hot, windy conditions; by 5 to 10% for moderate wind, temperature and humidity conditions.

FIGURE B.2. Classification of Pan Evaporation as Per Fetch Conditions (after Doorenbos and Pruitt 1977)

Blaney-Criddle Method

For areas where air temperature is the most reliable climatic data available, the Blaney-Criddle method can be applied. The equation has been presented in several different forms; the one below is given by the U.S.D.A., SCS (1970) as

$$ET_p = (0.142 T_a + 1.095)(T_a + 17.8) \cdot k_c \cdot d$$

where

ET_p = potential evapotranspiration per month (L)

T_a = mean monthly air temperature ($^{\circ}\text{C}$). When T_a is less than 3°C , the first term in parentheses is set equal to 1.38

K_c = empirical crop factor that varies with crop type and stage of growth (Table B.3)

d = monthly fraction of annual hours of daylight (Table B.4).

Doorenbos and Pruitt (1977) attempted to refine these predictions by using correction factors based on relative humidity and general wind velocity (Figure B.3).

Thornthwaite Method

An alternative method for estimating potential evapotranspiration where reliable climatic data is limited to air temperature is the Thornthwaite method. The Palmer-Havens technique (Palmer and Havens 1958) presents graphical solutions to the Thornthwaite equation. The empirical relationship is

TABLE B.3. Empirical Crop Factors (K_c) for the Blaney-Criddle Formula (from USDA, SCS 1970)

Crop	Beginning Mean Temp. (°C)	End Mean Temp. (°C)	Maximum Length (days)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Perennials															
Pasture Grass	7	7	Variable	0.49	0.57	0.73	0.85	0.90	0.92	0.92	0.91	0.87	0.79	0.67	0.55
Alfalfa	10	-2 (frost)	Variable	0.63	0.73	0.86	0.99	1.08	1.13	1.11	1.06	0.99	0.91	0.78	0.64
Grapes	13	10	Variable	0.20	0.24	0.33	0.50	0.71	0.80	0.80	0.76	0.61	0.50	0.35	0.23
Deciduous Orchard	10	7	Variable	0.17	0.25	0.40	0.63	0.88	0.96	0.95	0.82	0.54	0.30	0.19	0.15
Annuals															
				0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100		
Small Vegetables	16	0	100	0.33	0.47	0.64	0.74	0.80	0.82	0.82	0.76	0.66	0.48		
Peas			100	0.54	0.65	0.80	0.97	1.08	1.12	1.11	1.08	1.04	0.98		
Potatoes	16	0 (frost)	130	0.36	0.45	0.59	0.85	1.09	1.26	1.35	1.37	1.34	1.27		
Sugar Beet	-2 (frost)	-2 (frost)	180	0.46	0.54	0.69	0.87	1.03	1.16	1.24	1.24	1.18	1.10		
Grain Corn (maize)	13	0 (frost)	140	0.46	0.54	0.64	0.82	1.00	1.08	1.08	1.03	0.97	0.89		
Silage Corn (maize)	13	0 (frost)	140	0.45	0.50	0.59	0.71	0.90	1.03	1.07	1.07	1.04	1.00		
Sweet Corn (maize)	13	0 (frost)	140	0.43	0.52	0.62	0.81	1.00	1.07	1.08	1.07	1.04	1.02		
Spring Grain	7	0 (frost)	130	0.36	0.58	0.82	1.04	1.25	1.31	1.18	0.87	0.49	0.13		
Grain Sorghum	16	0 (frost)	130	0.32	0.47	0.72	0.93	1.07	1.04	0.94	0.82	0.70	0.60		
Soybeans			140	0.22	0.30	0.37	0.48	0.63	0.84	0.98	1.02	0.83	0.72		
Cotton	17	0 (frost)	240	0.22	0.28	0.40	0.64	0.90	1.01	1.00	0.88	0.73	0.57		

TABLE B.4. Monthly Fraction of Annual Hours of Daylight (from Dunne and Leopold 1978)

Latitude	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
60°N	0.047	0.057	0.081	0.096	0.117	0.124	0.123	0.107	0.086	0.070	0.050	0.042
50°N	0.060	0.063	0.082	0.092	0.107	0.109	0.110	0.100	0.085	0.075	0.061	0.056
40°N	0.067	0.066	0.082	0.089	0.099	0.100	0.101	0.094	0.083	0.077	0.067	0.075
20°N	0.073	0.070	0.084	0.087	0.095	0.095	0.097	0.092	0.083	0.080	0.072	0.072
10°N	0.081	0.075	0.085	0.084	0.088	0.086	0.089	0.087	0.082	0.083	0.079	0.081
0	0.085	0.077	0.085	0.082	0.085	0.082	0.085	0.085	0.082	0.085	0.082	0.085
10°S	0.098	0.079	0.095	0.081	0.082	0.079	0.081	0.083	0.082	0.086	0.084	0.088
20°S	0.092	0.081	0.086	0.079	0.079	0.074	0.078	0.080	0.081	0.088	0.089	0.093
30°S	0.097	0.083	0.086	0.077	0.074	0.070	0.073	0.078	0.081	0.090	0.092	0.099
40°S	0.102	0.086	0.087	0.075	0.070	0.064	0.068	0.074	0.080	0.092	0.097	0.105

FIGURE B.3. Prediction of ET_0 from Blaney-Criddle F Factor for Different Conditions of Minimum Relative Humidity, Daily Sunshine Hours, and Daytime Wind (Doorenbos and Pruitt 1977)

$$ET = 1.6 (10 T_a / I)^a$$

where

ET = potential evapotranspiration (L) per month

T_a = mean monthly air temperature ($^{\circ}\text{C}$)

I = annual heat index computed by $\sum_{i=1}^{12} (I_{ai}/5)^{1.5}$

$$a = 0.49 + 0.0179I - 0.0000771 I^2 + 0.000000675 I^3$$

The annual heat index can be determined graphically using the mean annual air temperature and Figure B.4. Figure B.5 shows graphical solutions to the Thornthwaite equation as a function of mean monthly air temperature and the annual heat index I. This standard potential evapotranspiration value is multiplied by the proper correction factor from Table B.5 to adjust for month and latitude.

FIGURE B.4. Annual Heat Index I of the Thornthwaite Equation as a Function of Mean Annual Temperature (from Palmer and Havens 1958)

FIGURE B.5. Graphical Solutions to the Thornthwaite Equation for ET_p as a Function of Mean Monthly Air Temperature for Various Values of Annual Heat Index I (from Palmer and Havens 1958)

Along with the Blaney-Criddle method, the Thornthwaite approach assumes that net radiation and other controls of evapotranspiration are correlated with air temperature. The Thornthwaite method also assumes that available energy is shared in fixed proportion between heating the atmosphere and evapotranspiration. No correction factor is offered for changes in vegetation.

TABLE B.5. Correction Factor for Monthly Sunshine Duration for Multiplication of the Standard Potential Evapotranspiration from Figure B.5 (from Palmer and Havens 1958)

<u>Latitude</u>	<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>Apr.</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug.</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>
60°N	0.54	0.67	0.97	1.19	1.33	1.56	1.55	1.33	1.07	0.84	0.58	0.48
50°N	0.71	0.84	0.98	1.14	1.28	1.36	1.33	1.21	1.06	0.90	0.76	0.68
40°N	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
30°N	0.87	0.93	1.00	1.07	1.14	1.17	1.16	1.11	1.03	0.96	0.89	0.85
20°N	0.92	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.02	0.98	0.93	0.91
10°N	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10°S	1.05	1.04	1.02	0.99	0.97	0.96	0.97	0.98	1.00	1.03	1.05	1.06
20°S	1.10	1.07	1.02	0.98	0.93	0.91	0.92	0.96	1.00	1.05	1.09	1.11
30°S	1.16	1.11	1.03	0.96	0.89	0.85	0.87	0.93	1.00	1.07	1.14	1.17
40°S	1.23	1.15	1.04	0.93	0.83	0.78	0.80	0.89	0.99	1.10	1.20	1.25
50°S	1.33	1.19	1.05	0.89	0.75	0.68	0.70	0.82	0.97	1.13	1.27	1.36

Comparison of Methods

All five empirical methods presented for estimating potential evapotranspiration are useful for different situations and types of available input data. The Evaporation Pan method is a measurement of evaporation that integrates the effects of the prevailing climatic conditions. The net evaporation measured from these pans are highly influenced by the surrounding environment. Under the same given climatic conditions, an evaporation pan in a surrounding dry area may register evaporation higher than the pan with the green crops. As stated earlier, some empirical adjustment coefficients are proposed (Table B.2), depending on the conditions surrounding the pan. The Radiation and Modified Penman methods can only be used where detailed climatic data are available, and where approximations of potential evapotranspiration on a daily basis are required. The Blaney-Criddle and Thornthwaite methods are based on the single index for air temperature and are suitable for areas where detailed climatic data are lacking or the estimate of potential evapotranspiration is not needed on a daily basis. Dagg and Blackie (1970) compare results of some of the methods (Figure B.6). The study area was from the Southern Hemisphere, which reverses the time of greatest and least evapotranspiration. Their findings reveal that the Penman method (developed for humid climates) has close prediction to measured pan data. Doorenbos and Pruitt (1975) observed that average

FIGURE B.6. Measured Pan Evaporation and Calculated Potential Evapotranspiration at Muguga, Kenya, for 1963. The curve marked "pan" is measured evaporation (after Dagg and Blackie 1970)

ET_p by Penman method was 20 to 30% under prediction in some locations, while 10 to 15% higher in other locations. They suggested a correction factor based on wind velocity for the Penman method.

As stated earlier, the Penman and Blaney-Criddle methods are estimations of potential evapotranspiration to be adjusted for actual evapotranspiration using crop coefficient and moisture status in the root zone, while the Thornthwaite method is an empirical relationship without the use of vegetation correction factor.

Actual Evapotranspiration (ET) Estimation Methods

Potential evapotranspiration estimates are based on the assumption that water is not a limiting factor and that the crop is uniform and of a given

height. Soil moisture content and the type of vegetation vary significantly in a given region, from no cover to agricultural crop, rangeland, or forest. The estimation of the actual evapotranspiration from potential evapotranspiration is generally described by use of empirical crop coefficients and soil moisture status.

Crop Coefficients (k_c)

To account for the effects of crop characteristics on crop water requirements, the crop coefficient (k_c) is generally used to convert ET_p or ET_o for the given crop. Main factors affecting the value of crop coefficients are the crop characteristics, crop planting or sowing date, rate of crop development, length of growing season, climatic conditions, and frequency of irrigation (particularly during the early growth stage). Crop characteristics include differences in plant mechanisms for resisting transpiration (stomatal behavior), crop height, crop roughness, reflection, and the ground cover produced (Doorenbos and Pruitt 1975; Jensen 1973). Table B.3 describes the empirical crop coefficients (k_c) suggested by the Soil Conservation Service for this region.

Estimation Based on Moisture Status in the Crop Root Zone

Transpiration relationships to soil-water status are vital to the model. Following are some of the relationships frequently quoted in the literature for estimation of actual evapotranspiration from potential evapotranspiration:

"ON-OFF" Relationship

$$\begin{array}{ll} ET = ET_p & \theta_{wilt} < \theta \leq \theta_{field\ capacity} \\ ET = 0 & \theta < \theta_{wilt} \end{array}$$

where θ is the average soil moisture status (L^3/L^3) in the crop root zone and θ_{wilt} is the permanent wilting point, generally considered to be the moisture content against a suction of 15 atmosphere.

This method is based on the assumption that evapotranspiration occurs at the potential rate until soil moisture is depleted to the permanent wilting point. Plants then wilt and evapotranspiration rates fall sharply to near zero (Veihmeyer 1964).

Logarithmic Decrease. Jensen et al. (1971) proposed the following logarithmic decrease:

$$ET = ET_p \ln[(SWS/AW) 100 + 1] / \ln(101)$$

where

SWS = actual soil water storage at any given time in the crop root zone

AW = so-called amount of water available between θ_{wilt} and θ_{field} capacity.

Linear Decrease. Thornthwaite and Mather (1955) proposed the following relationship:

$$ET = ET_p (SWS/AW)$$

In this relationship, the amount of evapotranspiration decreases linearly with the amount of water in the root zone of the plant.

Combination of "ON-OFF" and Linear Decrease. Marlatt et al. (1961) and Hanks (1974) proposed:

$$ET = ET_p (SWS/AW)^b$$

$$ET = ET_p (SWS/AW)^{-b}$$

Figure B.7 is a graphical comparison of the Veihmeyer (1964) and Thornthwaite and Mather (1955) approach of estimating ET from ET_p based on soil moisture status. In this study these two methods are considered.

Input Parameters

The following input parameters are used in the recharge calculations for the basalt demonstration: precipitation, potential evapotranspiration, irrigation topography, stream runoff, soil, and vegetation types. A brief discussion of each and the sources of the information used follows.

FIGURE B.7. Actual Evapotranspiration as a Ratio to Potential Plotted Against the Ratio of Available Soil Moisture to Available Water Capacity. The ratio of soil moisture to water capacity varies from zero to wilt to 1.0 at field capacity (after Holmes 1961).

Precipitation

Precipitation data were taken from a series of Washington Climate Circulars prepared for groups of counties by Washington State University in cooperation with the U.S.D.A. (Donaldson 1979; Donaldson and Ruscha 1975; Phillips 1965, 1970). These circulars list monthly and annual data in inches for each station, along with locations (latitude and longitude) and elevations. A total of 115 weather stations were used in this effort. Figure B.8 shows the location of these stations.

Potential Evapotranspiration

Potential evapotranspiration values are given for a more limited number of stations in the Washington Climate Circulars. The monthly and annual potential evapotranspiration values are estimates calculated using the Thornthwaite equation, based on climatic and weather data. Data from 37 weather stations were used. Figure B.9 shows the location of these stations.

FIGURE B.8. Map Showing the Location of the 115 Weather Stations Used for Precipitation Data

FIGURE B.9. Map Showing the Location of the 37 Weather Stations Used for PET Data

Irrigation

Irrigation water requirements for various crops were taken from the U.S.D.A. SCS Irrigation Guide for the Columbia Basin (1973). Annual requirements were determined by subtracting the 50% chance effective rainfall from the consumptive use for the crops. Effective rainfall is the "precipitation falling during the growing period of the crop that is available to meet the consumptive water requirements of the crop" (U.S.D.A. 1973). Monthly percentages

of application during the growing season were taken from a study performed for the U.S. Army Corps of Engineers (1978).

Topography

The topography for the modeled area was acquired from Digital Terrain Tapes, obtained from the U.S. Department of the Interior, Geologic Survey (USGS), National Cartographic Information Center. Figure B.10 is the topographic output produced by PNL.

FIGURE B.10. Topography from the USGS Digital Terrain Tapes

Stream Runoff

Annual runoff was obtained from a map of "Distribution of Mean Annual Runoff in Inches within the Washington State Portion of the Columbia Plateau" (prepared by the U.S.D.A. 1972). Figure B.11 shows the digitized version of this map used in this study.

FIGURE B.11. Distribution of Annual Runoff Used in this Study (digitized from U.S.D.A. 1972 map)

Soil Type

The soil type distribution was obtained from a "General Soil Map for the State of Washington" (prepared for the U.S.D.A. by Ray W. Chapin 1968). For use in this study, the soil types have been organized into the categories listed in Table B.6. The general soil descriptions were condensed from the State map (U.S.D.A. 1968), and the resulting soil distributions are shown in Figure B.12.

TABLE B.6. Soil Classification and Description (condensed from a General Soils Map for the State of Washington, (U.S.D.A. 1968)

<u>Class</u>	<u>Soil Type</u>	<u>General Description</u>
1	Scabland soils	Shallow and moderately deep, loam and silt loam soils formed in wind-laid silts ^(a) , glacial outwash, volcanic ash, pumice and bedrock.
2	Loessal Upland soils	Very shallow to deep, silt loam, loam and clay loam soils, some of which are gravelly or stoney, formed in wind-laid silts, weathered basalt, glacial outwash and colluvium.
3	River Bottom soils	Deep, silt loam, sandy and sandy loam soils, some of which are gravelly or stoney, formed in colluvium, alluvium, glacial outwash, and wind-laid silts.
4	Sandy soils	Deep, sandy soils formed in wind-laid sands.
5	Glacial Deposit soils	Moderately deep and deep, sand, sandy loam and loam soils, some of which are gravelly or stoney, formed in glacial outwash and fill, alluvium, lake sediments, and wind-laid silts.
6	Upland soils	Shallow to deep, silt loam soils, many of which are stoney or cobbly, formed in wind-laid silts and weathered basalt.
7	Forest soils	Shallow to deep, mildly alkaline to strongly acidic, sandy loam to silt loam soils, formed in volcanic ash, glacial materials, wind-laid silts, and underlain by basalt.

(a) Wind-laid silts mean loess.

FIGURE B.12. General Soils Map for the Columbia Plateau (U.S.D.A. 1968)

Vegetation Type

The distribution of vegetation type was obtained from the publication entitled Well Location and Land-Use Mapping in the Columbia Plateau Area (Stephan 1979). The distribution has been digitized according to the vegetation classes listed in Table B.7 and a regional map is shown in Figure B.13.

Estimation of Ground-Water Recharge

The following considerations were used in the estimation of ground-water recharge:

Grid Size

The three-mile grid used in the regional ground-water model was also used for the estimation of ground-water recharge. For the Columbia River Basalt

TABLE B.7. Vegetation Class, Type, and General Description

Class	Vegetation Type	General Description
1	Semiarid Grassland	Rangeland covered with sagebrush and dry/grass (cheatgrass) vegetation
2	Forest	Mixed conifer, dominated by Ponderosa and Lodgepole pine
3	Dryland	Dominantly dryland wheat farming
4	Irrigated	Irrigated farmland

FIGURE B.13. Distribution of Vegetation Type in the Columbia Plateau (Stephan 1979)

the grid consists of 55 x 55 regular three-mile grids centered at 118.6286 degrees longitude and 47.0292 degrees latitude. A generalized mercator projection was used to develop the Cartesian coordinate system for this study.

Interpolation of Precipitation

From the actual data on precipitation at the weather stations (Figure B.8) some appropriate interpolation, or fitting scheme, is required to estimate precipitation at each grid point by accounting for location and elevation of the grid point and the actual measurements at the nearest stations.

The dependence of precipitation distribution on elevation is a well established phenomenon (Chow 1964). Because the precipitation varies from location to location (because of effects of more global weather factors such as the rain shadow of the Cascades and the rise of Rockies), no unique or approximate basinwide elevation effects could be obtained.

In this study a four-parameter interpolation, or fitting procedure, was used to estimate precipitation at each model grid point or node. A computer code was developed to obtain a precipitation estimate for each grid point based on different values of the following four parameters:

1. Minimum Number of Stations (MINSTRA): minimum number of stations required for use of the selected interpolation procedure. A maximum of the eleven closest stations to the node are used.
2. Neighborhood Radius (RADIUS): the number of stations that lie within the neighborhood radius are determined. If this number is less than the minimum number (MINSTRA) required for weighing or correlation, the neighborhood radius is expanded until at least the minimum number stations are obtained.
3. Minimum Correlation Coefficient (CORMIN): minimum correlation coefficient required for use of the precipitation-elevation correlation method. The annual precipitation at the stations within the neighborhood radius (a minimum of MINSTRA Stations) versus their elevations is fitted with the best straight line and the correlation coefficient is determined. When this correlation coefficient is greater than the minimum correlation

coefficient (CORMIN) then annual precipitation at the node is determined from the node elevation and the parameters of the straight line fit (Figure B.14). If the correlation with elevation is less than CORMIN, the selected base method out of the following three methods ($1/d$, $1/d^2$, or Tobler) is adopted.

FIGURE B.14. Example of Station Annual Precipitation Versus Station Elevation for the Closest Stations to a Given Node

4. Base Methods Used for Interpolation (BASE): If the best fit straight line does not satisfy the CORMIN requirement, one of the following weighting methods is used:

- a. $1/d$ Method:
$$V_n = \left(\sum_{i=1}^m V_{s_i} W_i \right) / \left(\sum_{i=1}^m W_i \right)$$

where

V_n = value at node

V_s = value at the station

m = number of stations used

W = weight factor = $1/d$

d = distance between node and the rain gage station.

b. 1/d² Method:

Same as 1/d method except $W = 1/d^2$.

c. Tobler Method (Turner 1968):

$$V_n = 0.5 \left(V_{cs} + \sum_{i=2}^m V_{s_i} W_i \right) / \left(\sum_{i=2}^m W_i \right)$$

where

V_{cs} = value at the closest station
 $W = 1/d$

Of the three weighting procedures, the Tobler method places greatest emphasis on the closest station.

The selected base method is invariably used for predicting the monthly rainfall from predicted annual rainfall at the node. Monthly rainfall quantities are normalized according to the annual total rainfall at each station and these monthly fractions are then weighted, using the selected base weighting method to determine the monthly expected fraction of the total annual rainfall at the model node.

When any interpolation procedure is used some estimate of the error associated with the interpolation scheme should be obtained. For a multiparameter interpolation technique such as this, an additional procedure is used for determining the optimum values for these parameters to get the best fit. Both a biased and an unbiased method for estimating this error, as well as a parameter optimization method, were developed. An unbiased estimate of error was developed by predicting the observed annual rainfall at a given weather station using only the data from the surrounding stations. Statistics on the average absolute, negative, and positive error, as well as the root mean square error (rms), were developed. A biased estimate of the error was also made by estimating the annual precipitation predicted for the station from the station location and the matrix of annual precipitation values determined for the nodes.

The optimum fitting parameter selection program was developed to use the unbiased error estimate (rms) to derive the optimum values of CORMIN and RADIUS

for a given value for MINSTA and a selected base fitting method. The limited range of values for BASE (1,2,3) and MINSTA (4-10) allowed a simpler two-parameter optimization program to determine the optimum values for our four-parameter interpolation procedure.

Irrigation Application

Alfalfa and small grains are the two crop types considered within the classification of irrigated vegetation to bound the maximum and minimum recharge inputs caused by irrigated acreage. Annual irrigation water requirements were determined from the U.S.D.A. SCS Irrigation Guide for the Columbia Basin (1973) by subtracting the 50% change effective rainfall from the consumptive use (Table B.8). This was compiled for each climatic zone, and then averaged.

TABLE B.8. Irrigation Water Requirements for Alfalfa and Small Grain

	Climatic Zone											
	1	2	3	4	5	6	7	8	9	10	11	
Irrigation Water Requirements of Alfalfa (inches)	41.88	36.33	31.93	31.07	27.73	26.65	30.83	26.94	23.40	17.13	26.34	29.11 in.
Irrigation Water Requirements of Small Grain (inches)	26.88	23.23	22.83	18.67	22.93	16.75	18.83	14.94	19.90	8.93	15.24	19.01 in

In addition to crop water requirements, the amount of water applied to the field is a function of estimated field efficiency. Estimated field efficiency of irrigation systems is the ratio of the quantity of water effectively put into the crop root zone and used by growing crops to the quantity actually delivered to the field. The annual irrigation water requirements were divided by the efficiency ratio to determine the amount of water to be applied from the irrigation system. The two systems considered in the recharge calculation are furrow and sprinkler irrigation, which have estimated field efficiencies of 65 and 70%, respectively (U.S.D.A. 1973).

The monthly irrigation application percentages were taken from a recent study performed for the U.S. Army Corps of Engineers (1978). These values

were computed using the total monthly and annual quantities of diverted surface water. The monthly percentage was applied to the annual total irrigation water requirement to determine the monthly irrigation application requirement during the growing season (Table B.9).

TABLE B.9. Monthly Irrigation Application for Alfalfa and Small Grain Crops for Different Estimated Field Efficiencies (inches)

70% Efficiency--Sprinkler Irrigation System								
	<u>April</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>August</u>	<u>Sept</u>	<u>Oct</u>	<u>Annual Total</u>
Alfalfa	2.50	6.65	8.73	9.15	7.49	4.99	2.08	41.50
Small Grain	1.63	4.35	5.70	5.98	4.89	3.26	1.36	27.16
Monthly Irrigation Application Percentage	6%	16%	21%	22%	18%	12%	5%	100%
65% Efficiency--Furrow Irrigation System								
	<u>April</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>August</u>	<u>Sept</u>	<u>Oct</u>	<u>Annual Total</u>
Alfalfa	2.69	7.16	9.40	9.85	8.06	5.37	2.24	44.78
Small Grain	1.76	4.68	6.14	6.44	5.27	3.51	1.46	29.25

Distribution of Potential Evapotranspiration

Monthly estimates of reference potential evapotranspiration within the modeled area, calculated using the Thornthwaite method, are available from a number of the weather stations shown in Figure B.9. For each node, monthly estimates of reference potential evapotranspiration are extrapolated using the same interpolation techniques previously discussed for rainfall, with the exception that elevation correlation is ignored. These PET estimates are for a reference crop of short green grass and must be adjusted, as described below, for each of the vegetation types before actual evapotranspiration is determined.

Irrigated Vegetation. Monthly consumptive use of selected crops within the modeled area are given in the U.S.D.A. SCS Irrigation Guide for the Columbia Basin (1973). The consumptive use (potential evapotranspiration) estimates are based on criteria outlined in U.S.D.A. SCS Engineering Division Technical Release 21 (1970), using a modified Blaney-Criddle formula. In this irrigation guide, the Columbia Basin has been divided into eleven climatic zones (Figure B.15), and a table giving monthly consumptive use of selected crops within each zone has been compiled. To determine the relationship between published PET data at the weather stations and the SCS guidelines for the various crops, the weather station PET data and SCS guidelines were plotted as illustrated in Figure B.16 for Zone 2. The similar shape of the weather station PET (Thornthwaite and Mather) data and the SCC (Blaney-Criddle) data for alfalfa, orchard (with cover), and pasture grass, indicated that the difference may be only a scaling factor. With this in mind a linear regression analysis was performed by pooling together all the SCS data for the region for each crop and plotting it against the weather station PET data to determine the most useful reference crop (Figure B.17a,b,c,d). The best fit straight line, $y = Bx$, with the origin at zero was used. This scaling factor B, the slope of the best fit line, was used to convert weather station PET (Thornthwaite and Mather) data to SCS (Blaney-Criddle) data.

Pasture grass is commonly used as a reference crop and was chosen for use in this study because its coefficient of correlation is the highest (0.98874). The slope of the line in Figure B.17a, $B = 1.14$, is taken as the scaling factor to convert Thornthwaite PET to ET_p .

Once the potential evapotranspiration estimates from the weather stations have been transformed to the SCS consumptive use for pasture grass, the potential evapotranspiration for other crops is obtained by using the crop coefficient (K_c), shown in Table B.3.

The distribution of crops within the irrigated vegetation type is variable and controlled by agricultural market fluctuations. The real percentages of crops are difficult to obtain. Therefore, the consumptive use of alfalfa and small grain are applied, giving a maximum and minimum potential evapotranspiration

FIGURE B.15. Irrigation Climatic Zones of the Columbia Basin, Washington (after U.S.D.A. SCS 1973)

for the irrigated portion of the modeled area. A comparison of monthly consumptive use of the row crop types can be seen from a comparison of the crop coefficients in Table B.3.

Dryland Vegetation. The portion of the modeled area classified as dryland vegetation is used primarily for dryland wheat farming. Most of this is "winter grain," which when planted in early fall, uses the winter and spring rains to grow and mature by August. As a result, the crop factors for "spring grain"

FIGURE B.16. Comparison of Monthly Potential Evapotranspiration of a Few Key Crops and Weather Station Data in Climatic Zone 2. 1 = Weather Station Data, 2 = Alfalfa, 3 = Orchard with Cover, 4 = Pasture Grass, and 5 = Small Grain.

listed in Table B.3 are not applicable to this vegetation type. Instead of deriving the crop factors for small grain in the SCS consumptive use tables, the monthly consumptive use for small grain is divided by the monthly consumptive use for pasture grass, equivalent to exchanging the crop coefficients. This has been done for all of the SCS climatic zones in Table B.10. The regional average is used to translate from pasture grass as a reference crop to small grain potential evapotranspiration.

Forest Vegetation. Forest vegetation is not treated by the SCS, which is primarily interested in agricultural lands. Other sources were evaluated, but information on monthly consumptive use was not available.

FIGURE B.17a. Graph of SCS (Blaney-Criddle Method) Versus Weather Station (Thornthwaite Method) Data for Pasture Grass

FIGURE B.17b. Graph of SCS (Blaney-Criddle Method) Versus Weather Station (Thornthwaite Method) Data for Alfalfa

FIGURE B.17c. Graph of SCS (Blaney-Criddle Method) Against Weather Station (Thornthwaite Method) Data for Orchard with Cover

FIGURE B.17d. Graph of SCS (Blaney-Criddle Method) Against Weather Station (Thornthwaite Method) Data for Small Grain. $B = 1.3382$ and $C = 0.98295$

TABLE B.10. Monthly Ratio of Small Grain Consumptive Use to the Consumptive Use of Pasture Grass as a Reference Crop. This has been derived for all eleven climatic zones, then averaged.

<u>Climatic Zone</u>	<u>Jan.</u>	<u>Feb.</u>	<u>Mar.</u>	<u>Apr.</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug.</u>	<u>Sept.</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>
1	0.625	0.633	1.713	1.573	1.435	1.019	0.321	0.275	0.369	1.156	1.122	0.615
2	0.609	0.600	1.737	1.578	1.448	1.054	0.341	0.274	0.371	1.196	0.979	0.615
3	0.600	0.633	1.480	1.579	1.445	1.034	0.316	0.362	0.805	1.904	1.520	0.636
4	0.636	0.607	1.319	1.581	1.451	1.015	0.319	0.274	0.318	1.139	0.921	0.625
5	0.619	0.630	2.280	1.576	1.461	1.215	0.594	0.372	0.867	2.140	0.719	0.636
6	0.571	0.679	0.438	0.754	0.910	1.043	0.685	0.308	0.749	2.718	0.742	0.609
7	0.611	0.955	0.984	1.584	1.452	0.963	0.272	0.274	0.406	1.261	0.677	0.619
8	0.600	0.600	0.935	1.584	1.452	0.963	0.272	0.274	0.406	1.261	0.613	0.619
9	0.600	0.640	1.269	1.628	1.468	1.149	0.529	0.323	0.597	1.826	0.633	0.619
10	0.611	0.591	0.628	1.565	1.527	1.140	0.329	0.857	0.574	1.472	0.615	0.600
11	0.611	0.591	0.633	1.590	1.469	1.092	0.306	0.274	0.569	1.340	0.615	0.600
Regional Average	0.608	0.650	1.230	1.508	1.411	1.072	0.398	0.352	0.547	1.583	0.832	0.618

Cearlock et al. (1975) give an annual evapotranspiration estimate for forest cover in the Ahtanum subbasin of 19.2 inches. The SCS tables were used to arrive at monthly potential evapotranspiration. As the consumptive use curves are similarly shaped in Figure B.16 (except small grain), the monthly consumptive use of pasture grass can be fractioned and applied to the annual consumptive use of forest cover (Table B.11). This results in monthly potential evapotranspiration of forest vegetation. The ratio to translate between pasture grass and forest cover is also provided.

Semiarid Grassland. Consumptive use of semiarid grassland (sagebrush and cheatgrass) was calculated by PNL staff in the Ecological Sciences and Atmospheric Sciences Departments. They measured monthly precipitation and infiltration at the Arid Lands Ecology (ALE) Reserve (representative of semi-arid grassland) for 1971 to 1974. Through a water balance relationship

$$\text{RAINFALL} = \text{EVAPOTRANSPIRATION} + \text{INFILTRATION} + \text{RUNOFF}$$

monthly evapotranspiration was determined (Figure B.18).

The total annual evapotranspiration determined by Hinds and Thorp^(a) for semiarid grassland at the ALE Reserve is 9.37 in. The Water Encyclopedia

(a) From The Aerial Environment (unpublished).

TABLE B.11. Average Monthly Values of Pasture Consumptive Use, Average Fractioned Pasture Grass Consumptive Use, Forest Cover Consumptive Use, and Ratio Between Forest Cover and Pasture Grass Consumptive Use

	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>April</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug</u>	<u>Sept</u>	<u>Oct</u>	<u>Nov</u>	<u>Dec</u>
Average Pasture Grass Consumptive Use	0.20	0.26	0.74	2.21	3.87	5.15	6.67	5.65	3.49	1.45	0.34	0.22
Average Fractional Pasture Grass Consumptive Use	0.007	0.009	0.024	0.073	0.128	0.170	0.220	0.187	0.115	0.048	0.011	0.007
Forest Cover Consumptive Use	0.13	0.17	0.46	1.40	2.46	3.26	4.24	3.59	2.21	0.90	0.21	0.15
Ratio of Forest Cover to Pasture Grass Consumptive Use	0.670	0.665	0.623	0.633	0.636	0.633	0.636	0.635	0.633	0.621	0.618	0.682

FIGURE B.18. Average Monthly Evapotranspiration at the ALE Reserve for the Years 1971 to 1974

(Todd 1970) gives estimated annual evapotranspiration for semiarid grass and shrub as 10.6 in., calculated by the Blaney-Criddle consumptive use formula. These two values are similar. Thus, monthly evapotranspiration determined at the ALE Reserve is treated as consumptive use.

The correlation of consumptive use for semiarid grassland with the Thornthwaite-calculated potential evapotranspiration (from the weather stations) should be similar to that of small grain (Figure B.17d). The ALE monthly consumptive use divided by the average monthly consumptive use of pasture grass was used to obtain the ratio to translate ET_p to semiarid grassland ET (Table B.12).

TABLE B.12. Average Monthly Consumptive Use of ALE Vegetation (Semiarid Grassland), Pasture Grass, and the Ratio Between the Two

	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>April</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug</u>	<u>Sept</u>	<u>Oct</u>	<u>Nov</u>	<u>Dec</u>
ALE Monthly Consumptive Use (inches)	0.32	0.90	1.26	1.14	0.98	1.46	1.06	0.32	0.20	0.87	0.43	0.43
Average Pasture Grass Consumptive Use (inches)	0.20	0.26	0.74	2.21	3.87	5.15	6.67	5.65	3.49	1.45	0.34	0.22
Ratio of ALE Vegetation To Pasture Grass	1.60	3.46	1.70	0.52	0.25	0.28	0.16	0.06	0.06	0.60	1.26	1.95

Actual Evapotranspiration

Potential evapotranspiration estimates are based on the assumption that water is not a limiting factor for crops of a given type and height. It provides a measure for the estimation of actual evapotranspiration. The relationship of potential to actual evapotranspiration is determined by crop type, its growth and root zone depth, available water capacity, and the soil-water status.

Soil Root-Zone Water-Holding Capacity. The root-zone depth of vegetation (ft) and available water capacity (in./ft) of the soil are input in a table that gives the soil root-zone water-holding capacity in inches (Table B.13). Available water capacity is a function of soil texture, structure, and mineralogy,

TABLE B.13. Soil Root-Zone Water-Holding Capacity in Inches,
as a Function of Soil and Vegetation Type

		<u>Vegetation Type and Root Zone Depth</u>						
		<u>Grassland</u> <u>(cheatgrass)</u> <u>3.77 ft</u>	<u>Forest</u> <u>2.08ft</u>	<u>Dryland</u> <u>(wheat)</u> <u>3.5 ft</u>	<u>Pasture</u> <u>Grass</u> <u>2 ft</u>	<u>Alfalfa</u> <u>5 ft</u>	<u>Orchard</u> <u>5 ft</u>	<u>Irrigated</u> <u>Small Grain</u> <u>3.5 ft</u>
1	1 ft = 2.8 in. 2 ft = 1.2 in.	4.00	4.00	4.00	4.00	4.00	4.00	4.00
2	1 ft = 2.3 in. 2 ft = 2.5 in. 3 ft = 2.5 in. 4 ft = 2.5 in.	9.23	5.00	8.55	4.80	9.80	9.80	8.55
3	1 ft = 2.0 in. 2 ft = 1.0 in. 3 ft = 1.0 in. 4 ft = 1.0 in. 5 ft = 1.0 in.	4.77	3.08	4.50	3.00	6.00	6.00	4.50
4	0.7 in./ft	2.64	1.46	2.45	1.40	3.50	3.50	2.45
5	1 ft = 2.0 in. 2 ft = 1.0 in. 3 ft = 1.0 in. 4 ft = 1.0 in. 5 ft = 1.0 in.	4.77	3.08	4.50	3.00	6.00	6.00	4.50
5	1 ft = 2.6 in. 2 ft = 2.6 in. 2.5 ft = 1 in.	6.20	2.76	6.20	5.20	6.20	6.20	6.20
7	2.36 in./ft	8.90	4.91	8.26	4.72	11.80	11.26	8.26

as well as organic matter content, and is defined as the adjusted water retention difference between field capacity and 15 atmospheres tension, the maximum suction exerted by most plants.

Root-zone depths for various crops are from the U.S.D.A. SCS Irrigation Guide for the Columbia Basin (1973). Crop root-zone depths were taken from the "Crop Adaptions" table and are based on the assumption that soil depth is not limiting. Available water capacities of the soils were calculated by the SCS from gravimetric field data gathered by the Bureau of Land Management in the Columbia Basin.

The available water capacity of forest soils and root zone depth of forest cover were obtained from the U.S. Forest Service (USFS) in this region. The USFS divides soil types into mapping units. In the Wenatchee National Forest,

included in the western border of the modeled area, the soils are grouped by common parent material (McColley 1976). The estimated range of soil root-zone water-holding capacity for basalt medium is 1.5 to 7.2 in. (4.35 in. average). In the Umatilla National Forest, covering part of the southeast section of the modeled area, the mapping units are designated as "water yield classes," which are an indication of the rate and amount of water expected from each soil (Ehmer 1978). In the Umatilla National Forest there are three water-yield classes and the most dominant has a soil root-zone water-holding capacity of 4.0 to 6.9 in. (5.45 in. average).

The soil root-zone water-holding capacity for forest soils used in the model is an average of the two, 4.91 in. The average root-zone depth, 2.08 ft, limited by soil depth is divided into the soil root-zone water-holding capacity to obtain an available water capacity of 2.36 in./ft (Table B.13).

Cheatgrass and sagebrush, considered as semiarid grassland, have a common monthly consumptive use determined from measurements on the ALE Reserve. They have different root zone depths: the rooting depth of cheatgrass is 1.64 ft (Harris 1967) and for sagebrush, 4.60 ft (Cline et al. 1977). To determine a common root-zone depth, total areas of each vegetation were obtained from Stephan (1979), and relative percentages of sagebrush (72% = 9887 sq mi) and cheatgrass (28% = 3930 sq mi) were used to compute a weighted average. The weighted root-zone depth for semiarid grassland is 3.77 ft (Table B.13).

Actual Evapotranspiration Estimation. Actual evapotranspiration can be determined from potential evapotranspiration by a number of different relationships. The soil moisture status, controlled by the soil root-zone water-holding capacity, is used in most of them. The two relationships used in these recharge calculations are the ON/OFF (Veihmeyer and Hendrickson 1955) and the Thornthwaite and Mather (1955) relationship, which are described earlier. These two methods should provide upper and lower bounds on the recharge estimates.

Estimation of Aquifer Recharge

The basic time step in terms of data is monthly. For each model node or grid point, estimates of monthly precipitation and PET (Thornthwaite-Mather)

from weather station data are made. These PET estimates are converted to Blaney-Criddle PET estimates for the reference crop of pasture grass with the scaling factor (1.14). The estimates are then adjusted according to the vegetation type for the node by the ratio of the appropriate crop coefficient for that month to the crop coefficient for pasture grass (Tables B.3, B.10, B.11, B.12). The root-zone water capacity is determined from Table B.13 according to the soil type and vegetation. If the node is an irrigated one, the irrigation water application amounts are selected from Table B.9, according to the assumed irrigation crop type and irrigation efficiency. The actual AET-Recharge plus runoff amounts are determined with a daily time step, according to the selected AET method (ON/OFF or linear decrease). Some initial January 1 estimate (0.9 times the root-zone water capacity) is used to start the cyclic annual calculations. The cycle is continued until the initial condition for January 1 soil-water status does not vary by more than 0.01 in. from the previous January 1 initial condition. This indicates that the calculations have converged. Table B.14 illustrates the results from this converged calculation summarized on a monthly basis for a typical model node.

Total annual recharge for the node is then determined by subtracting the estimated annual runoff, as determined from Figure B.11, from the annual sum of the recharge plus runoff column. For areas that are planted in dryland wheat, a two-year cycle is used rather than a one-year cycle because one season wheat is grown and the second season the land is fallowed. During the fallow season only the upper tenth of the root zone is made available from AET. This upper zone acts as a mulching layer. Table B.15 illustrates the results from a converged calculation for a dryland wheat node. Because dryland wheat areas within the modeled area receive almost enough rainfall to support a yearly wheat crop, some logic had to be introduced to determine when a dryland wheat node was fallowed. A fallow factor was introduced to allow this determination to be made. The annual rainfall estimate for a node was compared with the annual PET required for small grain at that node times a fallowing factor (0.75). When the annual rainfall was less than the product of the fallowing factor times the PET requirement for small grain, it was assumed that a two-year fallowing cycle was used.

TABLE B.14. Results from the Converged AET Calculation Summarized on a Monthly Basis for a Typical Model Node

Line = 1 column = 31

Thornthwaite-Mather Method (soil capacity = 8.55 in.)

January 1 soil moisture + 6.34 in.

<u>Month</u>	<u>Rain</u>	<u>Irr</u>	<u>PET</u>	<u>AET</u>	<u>Soil</u>	<u>Recharge + Runoff</u>
January	2.6315	0.0000	0.0000	0.0000	8.5500	0.4220
February	2.2754	0.0000	0.1622	0.1621	8.5500	2.1133
March	2.3782	0.0000	1.4814	1.4814	8.5500	0.8968
April	2.0078	0.0000	3.6673	3.5206	7.0372	0.0000
May	1.9827	0.0000	5.6117	4.4306	4.5893	0.0000
June	1.8826	0.0000	5.5546	3.4942	2.9777	0.0000
July	0.4251	0.0000	2.6685	1.1150	2.2879	0.0000
August	0.4352	0.0000	2.0243	0.8243	1.8987	0.0000
September	1.0950	0.0000	2.0390	1.2938	1.6999	0.0000
October	2.1663	0.0000	3.2029	2.3607	1.5054	0.0000
November	2.4817	0.0000	0.3976	0.3976	3.5895	0.0000
December	2.8494	0.0000	0.0983	0.0983	6.3406	0.0000
TOTALS	22.611	0.0000	26.9078	19.1787		3.4321

Annual Rainfall = 22.61

Annual Irrig. = 0.0000

Annual PET = 26.91

Annual AET = 19.18

Annual Runoff = 0.4694

Annual Recharge = 2.963

Discussion of Results

The available input data and methods discussed above were used to determine the following distributions within the modeled area:

- precipitation
- PET (for pasture grass, Thornthwaite-Mather)
- AET and recharge.

TABLE B.15. Results from the Converged AET Calculation
Summarized on a Monthly Basis for a Typical
Fallowed Dryland Wheat Node

LINE = 11 column = 31
Thornwaite-Mather Method (soild capacity = 8.55 inches)
Mulching Layer Capacity = 0.1 root zone capacity
Jan 1 soil moisture in mulch layer = 0.86 inches
Jan 1 soil moisture in lower layer = 3.51 inches

Mon	Rain	Irr	PET	AET	Soil 1	Soil 2	Soil	Recharge & Runoff
Jan	1.8560	0.0000	0.0000	0.0000	0.8550	5.3635	6.2185	0.0000
Feb	1.4459	0.0000	0.2009	0.2009	0.8550	6.6086	7.4636	0.0000
Mar	1.4496	0.0000	0.9495	9.495	0.8550	7.1087	7.9637	0.0000
Apr	1.1883	0.0000	2.0121	1.7222	0.3211	7.1087	7.4298	0.0000
May	1.2411	0.0000	3.4009	1.5392	0.0229	7.1087	7.1317	0.0000
Jun	1.0649	0.0000	4.4235	1.0875	0.0003	7.1087	7.1091	0.0000
Jul	0.2771	0.0000	5.7138	0.2775	0.0000	7.1087	7.1087	0.0000
Aug	0.3761	0.0000	4.9600	0.3761	0.0000	7.1087	7.1087	0.0000
Sep	0.6882	0.0000	2.0063	1.7062	0.6091	5.4817	6.0907	0.0000
Oct	1.3576	0.0000	3.1157	2.4932	0.4955	0.4597	4.9552	0.0000
Nov	1.7056	0.0000	0.4137	0.4137	0.6247	5.6224	6.2471	0.0000
Dec	1.8201	0.0000	0.0634	0.0634	0.8004	7.2034	8.0038	0.0000
Jan	1.8560	0.0000	0.0000	0.0000	0.8550	7.6950	8.5500	1.3098
Feb	1.4459	0.0000	0.1484	0.1484	0.8550	7.6950	8.5500	1.2875
Mar	1.4496	0.0000	1.3277	1.3277	0.8550	7.6950	8.5500	0.1219
Apr	1.1883	0.0000	3.4496	3.1830	0.6555	5.8998	6.5553	0.0000
May	1.2411	0.0000	5.4557	3.8085	0.3988	3.5890	3.9878	0.0000
Jun	1.0649	0.0000	5.3912	2.6588	0.2394	2.1545	2.329	0.0000
Jul	0.2771	0.0000	2.5854	0.8458	0.1825	1.6428	1.8253	0.0000
Aug	0.3761	0.0000	1.9849	0.6901	0.1511	1.3602	1.5113	0.0000
Sep	0.6882	0.0000	3.2261	0.8327	0.0066	1.3602	1.3668	0.0000
Oct	1.3576	0.0000	1.7312	1.3600	0.0043	1.3602	1.3645	0.0000
Nov	1.7056	0.0000	0.4374	0.4374	0.8550	1.7777	2.6327	0.0000
Dec	1.8201	0.0000	0.0903	0.0903	0.8550	3.5075	4.3625	0.0000
TOTAL	28.941	0.0000	53.0878	26.2121				2.7292

	SEASONAL AVERAGES	PLANTING AVERAGES	FALLOW AVERAGES
Annual Rainfall =	14.47	14.47	14.47
Annual Irrig. =	0.0000	0.0000	0.0000
Annual PET =	26.54	25.83	27.26
Annual AET =	13.11	15.38	10.83
Annual Runoff =	0.4104	0.4104	0.4104
Annual Recharge =	0.9542	2.319	0.0000

Sensitivity and optimization studies were performed to determine the effect that the various parameters, calculational methods, and fitting methods have on the predicted results. From these studies the base case, or best estimate, for the above distributions was selected.

Precipitation Distribution

The fitting parameter optimization program discussed earlier was used to determine the optimum fitting parameters and method for estimating precipitation distribution. One additional parameter was studied when elevation correlation methods were used. Weather stations' elevations were corrected from their actual observed elevation to the average elevation of the surrounding one-mile square and the surrounding three-mile square. The best fit obtainable without elevation correlation was for the $1/d^2$ method [root mean square (RMS) error = 15.53%]. When elevation correlation was used, the minimum RMS obtainable using actual station elevations was for the $1/d^2$ [RMS error = 13.38%]. The minimum RMS obtainable for one-mile corrected station elevations was 12.99% and the $1/d^2$ method.

The best RMS error values were obtained for the elevation correlation method with three-mile corrected station elevations. Table B.16 shows the optimum fits for the elevation correlation method with station elevation corrected to the average of the surrounding three-mile square. These results have been arranged in order of best fit as determined by comparing each predicted precipitation distribution with the other and by then choosing the best fit as the one that is most similar to the other four. For comparison purposes, two additional precipitation distributions were used in the sensitivity studies to illustrate the actual sensitivity to the fitting methods. These fits are characterized in Table B.17. Table B.18 shows the sensitivity of precipitation distribution characteristics to the various fitting methods. No great variation in precipitation distribution was observed for any of the fitting methods or parameters. With the exception of PF6, average rainfall differed by only 0.1 inches. Figure B.19 shows the precipitation distribution predicted for the best fit (PFBEST) and Figures B.20 and B.21 show the precipitation distributions for fits PF5 and PF6, to illustrate the extremes in the range in predicted precipitation distributions.

TABLE B.16. Five Optimum Fits Obtained by Various Fitting Methods Using Three-Mile Corrected Station Elevations and the Elevation Correlation Method

Precipitation Fit Description	RMS Error %	Average Error %	Radius (Miles)	Correlation Minimum	Minimum Points	Method (with Elevation Correlation)
PFBEST	12.20	8.83	16.49	0.6049	4	1/d
PF1	12.33	8.82	16.69	0.6395	5	1/d ²
PF2	12.40	8.71	12.78	0.6991	6	1/d ²
PF3	12.16	9.00	16.49	0.5020	3	1/d ²
PF4	11.99	8.85	16.49	0.5020	3	1/d ²

TABLE B.17. Best Tobler Fit With Elevation Correlation and Best Fit With No Elevation Correlation

Precipitation Fit Description	RMS Error %	Average Error %	Radius (Miles)	Correlation Minimum	Minimum Points	Method
PF5	13.11	9.41	12.09	0.6227	4	Tobler (with elevation correlation)
PF6	15.53	11.69	10.60	NA	3	1/d ² (no elevation correlation)

TABLE B.18. Sensitivity of Precipitation Distribution Characteristics to the Various Fitting Methods and Fitting Parameters

Precipitation Fit Description	Total (Millions of acre feet per year)	Maximum (inches/year)	Minimum (inches/year)	Average (inches/year)
PFBEST	12.2	51.6	5.11	13.1
PF1	12.2	52.4	5.11	13.1
PF2	12.2	53.4	5.81	13.1
PF3	12.2	54.7	5.11	13.2
PF4	12.2	54.7	5.11	13.2
PF5	12.2	52.4	5.11	13.1
PF6	11.9	42.5	6.36	12.8

FIGURE B.19. Base Case or Best Estimate of the Precipitation Distribution for the Modeled Area of the Columbia Plateau Basalt

The precipitation distribution shown in Figure B.19 was used as the base case for all subsequent AET and recharge sensitivity studies. Table B.19 shows the unbiased estimate of error for the selected fitting parameters and method used for the base case precipitation distribution (Figure B.19).

FIGURE B.20. Predicted Precipitation Distribution
for Precipitation Fit PF5

There is a good balance between the number of over (50) and under (44) estimates for the 94 weather stations within the modeled area. Average error and RMS error estimates were 8.8% and 12.2%, respectively. These statistics on the base case precipitation distribution, along with the data shown in Table B.18, indicate that the precipitation distribution is well defined.

FIGURE B.21. Predicted Precipitation Distribution for Precipitation Fit PF6 (the $1/d^2$ fitting method with no elevation correlation)

PET Distribution

The PET distribution was estimated in the same manner as the precipitation distribution except that elevation correlations were ignored. The parameter optimization program was used to determine the optimum fitting parameters and method. Table B.20 shows the results from the optimization program.

TABLE B.19. Statistics on the Unbiased Estimate of Error Associated
With the Selected Fitting Method and Fitting Parameters
for the Base Case Precipitation Distribution

Fit of precipitation

1/R Fitting method

Above fitting method for precipitation overridden

For all elevation correlations greater than or equal to 0.6049000

Above fitting method used only for PET and monthly distribution of rainfall

Radius of influence (miles) = 16.49000

Minimum number of stations for weighting = 4

Total number of gages = 94

Average correlation coefficient = 0.8279011

Number below the correlation minimum of 0.6049000 = 33

Fraction = 0.3510638

Number above = 61 Fraction = 0.6489362

Statistics in percent of observed

Average error 8.832663 Number = 94

Root mean square error = 12.20030

Average positive error = 8.777276 Number = 50

Average negative error = -8.895596 Number = 44

Maximum positive error = 33.82600

Maximum negative error = -52.88515

Range	Number	Total	Fraction
0.0 - 1.0	4	4	0.0426
1.0 - 2.5	12	16	0.1702
2.5 - 5.0	25	41	0.4362
5.0 - 10.0	24	65	0.6915
10.0 - 15.0	11	76	0.8085
15.0 - 20.0	10	86	0.9149
20.0 - 25.0	5	91	0.9681
25.0 - 30.0	0	91	0.9691
30.0 - 35.0	2	93	0.9894
35.0 - 40.0	0	93	0.9894
40.0 - 50.0	1	94	1.0000

The best fit selected for use as the base case PET distribution used the 1/d method, MINSTA = 3, and RADIUS = 29.79 miles. Table B.21 shows the unbiased estimate of error for the fitting method and the parameters selected for the base case PET distribution.

TABLE B.20. Results from the Parameter Optimization Program
Illustrating the Best Fitting Method and Parameters
for the PET Distribution (no elevation correlation)

Method	Tobler			1/R			1/R**2		
	Error in %			Error in %			Error in %		
MINSTA	RMS	Avg.	Radius	RMS	Avg.	Radius	RMS	Avg.	Radius
3	6.09	4.43	47.46	5.81	4.39	24.79	6.09	4.55	29.79
4	6.12	4.39	26.07	5.98	4.29	35.73	6.14	4.40	35.73
5	6.20	4.44	40.36	6.03	4.22	26.07	6.17	4.36	26.07
6	6.20	4.56	13.86	6.00	4.23	40.36	6.18	4.38	40.36
7	6.17	4.53	47.30	6.10	4.31	17.76	6.22	4.43	17.76
8	6.21	4.56	32.62	6.06	4.39	47.30	6.20	4.46	47.30

TABLE B.21. Statistics on the Unbiased Estimate of Error Associated
With the Selected Fitting Method and Fitting Parameters
for the Base Case PET Distribution

Fit on PET

1/R Fitting method

Radius of influence (miles) = 29.79000 32

Minimum number of stations for weighting = 3

Total number of gages = 32

Statistics in percent of observed

Average Error = 4.389300 Number = 32

Root mean Square error = 5.811997

Average positive error = 4.529682 Number = 17

Average negative error = -4.230201 Number = 15

Maximum positive error = 16.73779

Maximum negative error = -11.27771

Range	Number	Total	Fraction
0.0 - 1.0	2	2	0.0625
1.0 - 2.5	13	15	0.4687
2.5 - 5.0	8	23	0.7187
5.0 - 10.0	6	29	0.9062
10.0 - 15.0	2	31	0.9687
15.0 - 20.0	1	32	1.0000
20.0 - 25.0	0	32	1.0000
25.0 - 30.0	0	32	1.0000
30.0 - 35.0	0	32	1.0000
35.0 - 40.0	0	32	1.0000
40.0 - 50.0	0	32	1.0000

AET and Recharge Distributions

A variety of studies were performed to determine the sensitivity of the predicted AET and recharge distributions to the various values of input parameters, input distributions, and AET calculation methods. Table B.22 defines the input parameters, distributions, and AET method used in the two base case predictions for AET and recharge distributions, as well as the 12 sensitivity study predictions.

TABLE B.22. Definition of the Various Base Case and Parameter Sensitivity Case for Determining AET and Recharge Distributions

<u>Case</u>	<u>Irrigated Vegetation Type</u>	<u>Precipitation Distribution</u>	<u>PET Distribution</u>	<u>Sprinkler Efficiency</u>	<u>Fallow Factor</u>	<u>AET Calculation Method</u>
Base Case A	Alfalfa	PFBEST	Base Case	70%	0.75	Thorntwaite Mather
Base Case G	Small Grain	PFBEST	Base Case	70%	0.75	Thorntwaite Mather
Case 1	Alfalfa	PFBEST	Base Case	70%	0.50	Thorntwaite Mather
Case 2	Alfalfa	PFBEST	Base Case	70%	1.00	Thorntwaite Mather
Case 3	Alfalfa	PFBEST	Base Case	65%	0.75	Thorntwaite Mather
Case 4	Alfalfa	PFBEST	1/d ²	70%	0.75	Thorntwaite Mather
Case 5	Alfalfa	PFBWST	Tobler	70%	0.75	Thorntwaite Mather
Case 6	Alfalfa	PF1	Base Case	70%	0.75	Thorntwaite Mather
Case 7	Alfalfa	PF2	Base Case	70%	0.75	Thorntwaite Mather
Case 8	Alfalfa	PF3	Base Case	70%	0.75	Thorntwaite Mather
Case 9	Alfalfa	PF4	Base Case	70%	0.75	Thorntwaite Mather
Case 10	Alfalfa	PF5	Base Case	70%	0.75	Thorntwaite Mather
Case 11	Alfalfa	PF6	Base Case	70%	0.75	Thorntwaite Mather
Case 12	Alfalfa	PFBEST	Base Case	70%	0.75	On-Off

Two base case predictions were made to bracket the recharge quantity because of irrigated acreage. All irrigated acreage was assumed to grow alfalfa for Base Case A (maximum recharge) and small grain for Base Case G (minimum recharge). Twelve other sensitivity cases were used to investigate the effects of the following:

- fallowing practices (Cases 1 and 2)
- irrigation efficiency (Case 3)
- PET fitting method (Cases 4 and 5)
- precipitation fitting method (Cases 6 through 11)
- AET calculation method (Case 12).

The results of these sensitivity studies are in Table B.23 for AET and in Table B.24 for recharge. These tables summarize the average and total values predicted for the AET and recharge distributions. The insensitivity of predicted recharge and AET to the precipitation or PET fitting method is demonstrated by the fact that total recharge for Cases 4 through 11 varies by no more than $\pm 5\%$ from Base Case A predictions. Similarly, total AET varies by no more than $\pm 2\%$. A comparison of the predicted variations in total AET and total recharge indicates that AET estimates are less sensitive to parameter variations than is recharge. AET variation for all 14 predictions shown in Table B.23 differed by no more than $\pm 9\%$, with all but two of the runs within $\pm 2\%$. Recharge variations range from a high of 11% (Case 3) to a low of -14% (Case 12) with only eight of the 14 runs within $\pm 2\%$.

Figures B.22 and B.23 illustrate the areal distribution of AET and recharge, respectively, for the Base Case A predictions. Output shown in these figures is for the 55 x 55 grid used for these calculations. The numbers represent inches per year of AET or recharge at a given node location. In these two figures, only the nodes within the modeled portion of the basalt aquifers are displayed.

One additional recharge calculation was performed to estimate the pre-settlement recharge to the basalt. For these calculations all irrigated and dryland wheat vegetation areas were reverted to semiarid grass and sage brush.

TABLE B.23. AET Sensitivity to Parameter Variations

<u>Case</u>	<u>Total (millions of af/yr)</u>	<u>Maximum (in/yr)</u>	<u>Minimum (in/yr)</u>	<u>Average (in/yr)</u>
Base A	12.2	39.1	5.11	13.2
Base G	11.1	27.9	5.12	12.0
Case 1	12.4	39.1	5.12	13.4
Case 2	12.0	39.1	5.12	12.9
Case 3	12.2	39.1	5.12	13.2
Case 4	12.2	39.6	5.12	13.2
Case 5	12.2	37.9	5.12	13.1
Case 6	12.2	39.1	5.12	13.2
Case 7	12.2	39.1	5.81	13.1
Case 8	12.2	39.1	5.12	13.1
Case 9	12.2	39.1	5.12	13.2
Case 10	12.2	39.1	5.12	13.1
Case 11	12.0	39.1	6.37	13.0
Case 12	12.8	39.1	5.11	13.8

This prediction of 3.17 million acre feet per year of recharge was 19% higher than the Base Case A prediction. The increase is mainly caused by additional recharge in the eastern modeled area, which is now primarily dryland wheat.

The recharge and AET sensitivity studies indicate that these distributions are fairly well determined quantities because recharge estimates ranged only +15% from the base case estimate and AET by only +9%. The recharge distributions also seem to support the selection of regional hydrologic model boundaries made on the basis of structural and potentiometric evidence alone.

REGIONAL HYDROLOGIC MODEL

The purpose of hydrologic modeling for the basalt demonstration was to simulate the hydrogeology of the deep basaltic system beneath the Hanford Site from the horizon where the hypothetical waste repository would be located. To establish the boundary conditions for such a localized model, the hydrogeology

TABLE B.24. Sensitivity of Recharge to Parameter Variations

Case	Total (millions of af/yr)	Maximum (in/yr)	Average (in/yr)	Vegetation Type			
				Arid (millions of af/yr)	Forest (millions of af/yr)	Dryland (millions of af/yr)	Irrigated (millions of af/yr)
Base A	2.66	23.6	2.87	0.93	0.15	0.36	1.22
Base G	2.38	18.8	2.58	0.93	0.15	0.36	0.94
Case 1	2.48	23.6	2.68	0.93	0.15	0.18	1.22
Case 2	2.82	23.6	3.05	0.93	0.15	0.53	1.22
Case 3	2.95	26.8	3.19	0.93	0.15	0.36	1.51
Case 4	2.64	23.8	2.85	0.94	0.15	0.36	1.19
Case 5	2.68	22.8	2.89	0.93	0.15	0.37	1.23
Case 6	2.66	23.6	2.88	0.93	0.16	0.36	1.21
Case 7	2.67	22.3	2.89	0.94	0.16	0.36	1.21
Case 8	2.67	22.2	2.89	0.91	0.18	0.36	1.21
Case 9	2.68	22.2	2.89	0.91	0.18	0.37	1.21
Case 10	2.68	22.5	2.89	0.94	0.15	0.37	1.22
Case 11	2.54	22.5	2.74	0.89	0.093	0.33	1.22
Case 12	2.30	23.6	2.49	0.86	0.13	0.095	1.22

of the surrounding region must be understood. In particular, an understanding is necessary of the recharge and discharge mechanisms of the deep basalts:

1) the locations and amount of recharge and discharge at the basalt outcrops and perimeters, 2) the hydraulic connection between the various basalt flows, 3) the hydraulic connection between the confined aquifers in the basalts and the shallow unconfined aquifer systems, as well as between the basalts and the Columbia, Snake, and Yakima Rivers, and 4) the hydraulic connection across the lower boundary of the deep basalt layer.

Evaluation, Selection, and Preparation of Data

Geologic data were evaluated by using existing published and unpublished data sources. Published sources that provided the predominant portion of the information for areal distribution of the sedimentary units and the basalt

FIGURE B.22. Predicted Areal Distribution of AET in Inches Per Year Throughout the Modeled Area of the Regional Basalt Aquifers for the Base Case A Parameter Values

FIGURE B.23. Predicted Areal Distribution of Recharge in Inches Per Year Throughout the Modeled Area of the Regional Basalt Aquifers for the Base Case A Parameter Values

formations of the Columbia Plateau group are Rockwell-Hanford's RHO-BWI-ST-5 report (Gephart et al. 1979a) and RHO-BWI-C-60 report (Tanaka et al. 1979).

Transmissivity Data

Sources of hydrologic information were evaluated for timeliness of data, reliability, and completeness for layer 1. Gephart et al. (1979a) was selected because of its completeness, and because many sources were used to obtain the configurations shown on the plates in the report. To make the data applicable to the conceptual model and useful for computer simulation, the transmissivity values for the Saddle Mountains and Wanapum Basalts were added together. In some areas, data were not available, particularly along the boundaries, and contours were extrapolated into these areas.

Very few transmissivity values of the Grande Ronde Basalt are available to construct a regional transmissivity map for the Columbia Plateau. Therefore, a uniform transmissivity value was assumed for all nodes in order to start the model calibration process.

Potentiometric Data

Constructing the potentiometric map for layer 1 involved more interpretation than for the transmissivity maps. Again Gephart et al. (1979a) was used as the primary data source for constructing the composite potentiometric surface. Where potentials were identical, or nearly so, values remained the same or standard interpolation methods were used; however, in areas where potential values differed by more than 50 ft, considerable interpretation was necessary. Where significant potentiometric discrepancies occurred between the two formations, bias was given to the formation with the higher transmissivity, using a simple linear interpolation between contours. Therefore, the composite potentiometric map of the Saddle Mountains and Wanapum Basalt aquifers is a map that attempts to reflect the potentiometric surface of the most permeable strata within layer 1.

Because of the lack of potentiometric data for the Grande Ronde (layer 2) the composite Wanapum-Grande Ronde water-level trend map by Tanaka et al. (1979) was used for reference purposes and no Grande Ronde potentiometric surface was constructed.

Unconfined and Surface Water Elevation Data

The surface layer (above layer 1) consisted of the Pasco, Quincy, and Walla Walla Basins alluvial aquifers, major lakes and rivers, and basalt seepage faces along the Columbia and Spokane Rivers. Potentiometric data for the three basins were obtained from the following sources: 1) Pasco Basin-Hanford Project 1975 water levels (Rockwell-Hanford Operations) and interpreted well data; 2) Quincy Basin (Tanaka et al. 1974); and 3) Walla Walla Basin (MacNish and Barker 1976). Water levels for the lakes and rivers were obtained from USGS topographic maps and Dion et al. (1976).

Many of the lakes, rivers, and alluvial basins are connected to the deeper basalts and serve as a recharge/discharge areas. Table B.25 shows which layer is connected to which recharge/discharge areas in the model.

Ground-Water Withdrawal Data

Data regarding ground-water withdrawal from the basalt layers were obtained from: 1) U.S. Department of the Interior USGS Report, 1973; 2) Luzier et al. 1974; and 3) a compilation of unpublished pumping data. The total withdrawal as calculated for use in the model is 204300 AF/yr.

Regional Simulation Using the Variable Thickness Transient (VTT) Ground-Water Flow Code

A ground-water model describes mathematically, through partial differential equations, the physical forces that determine movement and potential energy of water beneath the earth's surface. A model effectively interrelates all the pertinent information gathered on the real system, and therefore incorporates all of the understanding of the interactions occurring in that system.

Different levels of hydrologic models operate at Pacific Northwest Laboratory. These models have the capability to assess a wide variety of ground-water flow systems, from very simple one-dimensional, homogeneous isotropic, single-aquifer flow conditions to the most complex three-dimensional anisotropic multilayer cases. The multiple layer two-dimensional Variable Thickness Transient (VTT) code (Reisenauer 1980) was selected as appropriate for the amount of data available and the conditions existing in the regional systems. This model

TABLE B.25. Model Recharge/Discharge Areas

<u>Seg. Name</u>	<u>Line</u>	<u>Column</u>	<u>Elevation</u>	<u>Frac. Node</u>
<u>Lakes Entrenched in the Saddle Mountains-Wanapum Basalts</u>				
Sylvan Lake	29	35	1599.	0.150
Bobs Lake	26	36	1442.	0.100
Sullivan Lake	25	37	1546.	0.040
Coffeepot Lake	29	39	1814.	0.100
Twin Lakes	30	40	1872.	0.060
Sprague Lake	37	33	1878.	0.200
Sprague Lake	37	34	1878.	0.150
Fourth of July-Alkali Lake 1887, 1874	38	33	1880.	0.080
Palm Lake	37	32	1851.	0.060
Green Lake	38	31	1784.	0.060
Cow Lake	35	30	1749.	0.050
Crane-Simms Lakes 1709, 1663	37	29	1663.	0.050
Medical-West Medical Lakes 2394, 2432	43	41	2394.	0.200
Silver-Clear Lakes 2341, 2342	43	40	2341.	0.100
Turnbull Wildlife Area	44	37	2250.	0.180
Turnbull Wildlife Area	45	37	2250.	0.100
Philleo Lake	46	37	2250.	0.060
Williams Lake	43	35	2052.	0.080
Chapman Lake	45	36	2154.	0.070
<u>Rivers Entrenched in the Saddle Mountains-Wanapum Basalts</u>				
Snake River	24	10	365.	0.100
Snake River	25	11	365.	0.150
Snake River	26	11	375.	0.100
Snake River	26	12	390.	0.120
Snake River	27	13	415.	0.100
Snake River	28	14	425.	0.080
Columbia River	7	22	486.	0.150
Columbia River	7	21	486.	0.250
Columbia River	7	20	486.	0.250
Columbia River	8	20	486.	0.200
<u>Saddle Mountains-Wanapum Basalt Seepage Nodes Along Northern Boundary</u>				
Seepage Group 1 WP	46	42	1900.	
Seepage Group 1 WP	45	43	1900.	
Seepage Group 1 WP	44	43	2000.	
Seepage Group 1 WP	43	43	2100.	
Seepage Group 1 WP	42	44	2200.	
Seepage Group 1 WP	41	45	2200.	
Seepage Group 1 WP	40	45	2200.	
Seepage Group 1 WP	39	45	2100.	
Seepage Group 1 WP	38	45	2100.	
Seepage Group 1 WP	37	45	2000.	
Seepage Group 1 WP	36	45	2000.	

Table B.25 (continued)

<u>Seg. Name</u>	<u>Line</u>	<u>Column</u>	<u>Elevation</u>	<u>Frac. Node</u>
(Saddle Mountains-Wanapum Basalt Seepage Nodes Along Northern Boundary)				
Seepage Group 1 WP	35	45	2100.	
Seepage Group 1 WP	35	46	2000.	
Seepage Group 1 WP	34	47	1800.	
Seepage Group 1 WP	33	47	1600.	
Seepage Group 1 WP	32	46	1400.	
Seepage Group 1 WP	31	46	1400.	
Seepage Group 1 WP	30	47	1600.	
Seepage Group 1 WP	29	48	1800.	
Seepage Group 1 WP	28	48	2000.	
Seepage Group 1 WP	27	48	2100.	
Seepage Group 1 WP	26	48	2100.	
Seepage Group 1 WP	25	48	2100.	
Seepage Group 1 WP	24	48	2150.	
Seepage Group 1 WP	23	48	2125.	
Seepage Group 2 WP	22	48	2100.	
Seepage Group 2 WP	22	50	2050.	
Seepage Group 2 WP	22	51	2100.	
Seepage Group 2 WP	21	52	2100.	
Seepage Group 2 WP	20	52	2100.	
Seepage group 2 WP	19	52	2150.	
Seepage Group 2 WP	18	52	2150.	
Seepage Group 2 WP	17	51	2200.	
Seepage Group 2 WP	16	51	2250.	
Seepage Group 2 WP	15	51	2300.	
Seepage Group 2 WP	14	51	2350.	
Seepage Group 2 WP	13	50	2400.	
Seepage Group 2 WP	12	50	2400.	
Seepage Group 2 WP	11	51	2400.	
Seepage Group 2 WP	10	51	2400.	
Seepage Group 2 WP	10	50	2450.	
Seepage Group 2 WP	10	49	2500.	
Seepage Group 2 WP	9	48	2550.	
Seepage Group 2 WP	9	47	2600.	
Seepage Group 2 WP	9	46	2600.	
Seepage Group 2 WP	8	45	2600.	
Seepage Group 2 WP	7	45	2600.	
Seepage Group 2 WP	6	45	2550.	

Table B.25 (continued)

<u>Seg. Name</u>	<u>Line</u>	<u>Column</u>	<u>Elevation</u>	<u>Frac. Node</u>
<u>Lakes Entrenched in the Grand Ronde</u>				
Billy Clapp Lake	18	39	1336.	0.100
Billy Clapp Lake	18	38	1336.	0.100
Brook Lake	18	37	1240.	0.070
Jameson Lake	13	43	1781.	0.130
Grimes Lake	13	44	1831.	0.060
Soap Lake	14	37	1074.	0.130
Lenore Lake	14	38	1074.	0.200
Lenore Lake	14	39	1074.	0.180
Blue Lake	15	40	1093.	0.100
Park Lake	16	41	1096.	0.100
Banks Lake	18	42	1570.	0.300
Banks Lake	18	43	1570.	0.250
Banks Lake	18	44	1570.	0.300
Banks Lake	19	45	1570.	0.250
Banks Lake	19	46	1570.	0.500
Banks Lake	20	47	1570.	0.800
Banks Lake	19	47	1570.	0.150
Banks Lake	20	48	1570.	0.200
Banks Lake	21	48	1570.	0.080
Banks Lake	21	49	1570.	0.100
Bonnie Lake	45	34	1790.	0.150
Rock Lake	43	32	1719.	0.200
Rock Lake	42	31	1719.	0.200
<u>Rivers Entrenched in the Grand Ronde</u>				
Wallula Gap	23	5	340.	0.200
Snake River	28	15	440.	0.100
Snake River	28	16	440.	0.080
Snake River	29	17	440.	0.100
Snake River	30	18	440.	0.100
Snake River	31	18	540.	0.100
Snake River	32	18	540.	0.080
Snake River	33	18	540.	0.080
Snake River	34	18	540.	0.080
Snake River	35	17	540.	0.040
Snake River	36	17	540.	0.080
Snake River	37	18	540.	0.080
Snake River	38	18	540.	0.100
Snake River	39	18	540.	0.150
Snake River	40	18	540.	0.200
Snake River	41	19	550.	0.200
Snake River	42	20	565.	0.150
Snake River	43	20	575.	0.150
Snake River	44	20	582.	0.120
Snake River	45	20	588.	0.100
Snake River	46	20	605.	0.120

Table B.25 (continued)

<u>Seg. Name</u>	<u>Line</u>	<u>Column</u>	<u>Elevation</u>	<u>Frac. Node</u>
(Rivers Entrenched in the Grande Ronde)				
Snake River	47	20	615.	0.100
Snake River	48	19	625.	0.080
Snake River	48	18	632	0.040
Snake River	49	18	642.	0.080
Snake River	50	17	655.	0.080
Snake River	50	16	665.	0.080
Snake River	50	15	675.	0.050
Snake River	51	14	685.	0.060
Snake River	52	14	695.	0.060
Snake River	53	14	710.	0.100
Snake River	53	13	722.	0.080
Snake River	53	12	737.	0.080
Snake River	54	11	753.	0.080
Snake River	55	10	763.	0.080
Snake River	55	9	768.	0.080
Snake River	55	8	773.	0.080
Snake River	55	7	778.	0.080
Snake River	54	6	783.	0.080
Columbia River	9	19	400.	0.100
Columbia River	8	19	400.	0.100
Columbia River	7	23	505.	0.100
Columbia River	7	24	505.	0.100
Columbia River	7	25	570.	0.100
Columbia River	7	26	570.	0.100
Columbia River	7	27	570.	0.100
Columbia River	6	28	570.	0.200
Columbia River	6	29	570.	0.180
Columbia River	6	30	570.	0.150
Columbia River	6	31	570.	0.120
Columbia River	6	32	570.	0.200
Columbia River	6	33	570.	0.010
Columbia River	5	33	570.	0.100
Columbia River	5	34	570.	0.080
Columbia River	5	35	570.	0.100
Columbia River	5	36	606.	0.050

Grande Ronde Seepage Nodes Along the Northern Boundary

Grande Ronde Seepage	47	42	1800.
Grande Ronde Seepage	46	43	1800.
Grande Ronde Seepage	45	44	1900.
Grande Ronde Seepage	44	45	2000.
Grande Ronde Seepage	43	46	2000.
Grande Ronde Seepage	42	46	2100.
Grande Ronde Seepage	41	46	2100.
Grande Ronde Seepage	40	46	2000.
Grande Ronde Seepage	39	46	2000.

Table B.25 (continued)

<u>Seg. Name</u>	<u>Line</u>	<u>Column</u>	<u>Elevation</u>	<u>Frac. Node</u>
(Grande Ronde Seepage Nodes Along the Northern Boundary)				
Grande Ronde Seepage	38	45	2100.	
Grande Ronde Seepage	37	45	2000.	
Grande Ronde Seepage	36	45	2000.	
Grande Ronde Seepage	35	45	2100.	
Grande Ronde Seepage	35	46	2000.	
Grande Ronde Seepage	34	47	1800.	
Grande Ronde Seepage	33	47	1600.	
Grande Ronde Seepage	32	46	1400.	
Grande Ronde Seepage	31	46	1400.	
Grande Ronde Seepage	30	47	1600.	
Grande Ronde Seepage	29	48	1800.	
Grande Ronde Seepage	28	48	2000.	
Grande Ronde Seepage	27	48	2100.	
Grande Ronde Seepage	26	48	2100.	
Grande Ronde Seepage	25	48	2100.	
Grande Ronde Seepage	24	48	2150.	
Grande Ronde Seepage	23	48	2125.	
Grande Ronde Seepage	22	48	2100.	
Grande Ronde Seepage	22	49	2000.	
Grande Ronde Seepage	22	50	2050.	
Grande Ronde Seepage	22	51	2100.	
Grande Ronde Seepage	21	52	2100.	
Grande Ronde Seepage	20	52	2100.	
Grande Ronde Seepage	19	52	2100.	
Grande Ronde Seepage	18	52	2150.	
Grande Ronde Seepage	17	51	2200.	
Grande Ronde Seepage	16	51	2250.	
Grande Ronde Seepage	15	51	2300.	
Grande Ronde Seepage	14	51	2350.	
Grande Ronde Seepage	13	50	2400.	
Grande Ronde Seepage	12	50	2400.	
Grande Ronde Seepage	11	51	2400.	
Grande Ronde Seepage	10	51	2400.	
Grande Ronde Seepage	10	50	2450.	
Grande Ronde Seepage	10	49	2500.	
Grande Ronde Seepage	9	48	2550.	
Grande Ronde Seepage	9	47	2600.	
Grande Ronde Seepage	9	46	2600.	
Grande Ronde Seepage	8	45	2600.	
Grande Ronde Seepage	7	45	2600.	
Grande Ronde Seepage	6	45	2550.	
Grande Ronde Seepage	5	44	2600.	
Grande Ronde Seepage	5	43	2600.	
Grande Ronde Seepage	4	42	2550.	
Grande Ronde Seepage	4	41	2550.	
Grande Ronde Seepage	3	40	2500.	
Grande Ronde Seepage	3	39	2400.	
Grande Ronde Seepage	3	38	2350.	
Grande Ronde Seepage	4	37	2100.	

uses a finite difference formulation to represent the partial differential flow equation with numerical expressions. Specifically, a horizontal x-y coordinate grid system is adopted to represent the study area. Model parameters defining the aquifer system are assigned to and evaluated at the center of each grid block (or node) and are considered representative of the whole grid block area. From these grid block values the model calculates the ground-water potential for each grid block (or node).

Data Requirements

All parameters defining the aquifer system are evaluated at and assigned to each grid block (or node) center and are considered representative of the whole grid (or node) area. These model parameters are made into data files accessible to the computer. The following is a list of the parameters and their associated units:

- altitude of the land surface (L above mean sea level)
- altitude of top of the regional aquifer for confined systems (L above mean sea level)
- altitude of the bottom of the aquifer (L above mean sea level)
- initial ground-water surface elevation (ground-water potential) of the aquifer (L above mean sea level)
- transmissivity (L^2/T) or hydraulic conductivity (L/T) of the aquifer
- storage coefficient (dimensionless) of the aquifer
- recharge (L^3/T) to the aquifer
- discharge (or pumping) rate (L^3/T) from the aquifer
- river stage (L above mean sea level).

Adaptation of the VTT Code

Once a conceptual model was developed, the next step was to put the conceptual model into a form that could be used by the VTT hydrologic flow model. The general procedure used to implement and apply the VTT ground-water flow code to the Columbia Plateau region required the following steps:

- determination of the boundary conditions for the region
- interpretation and refinement of published or unpublished data for input to the model
- utilization of the data to calibrate the model
- application of the model to predict water flow paths and quantity of water flowing into or out of the Pasco Basin from the regional system.

Finite Difference Grid and Boundary Conditions

The regional study area as defined for in the VTT model was divided into a 55 by 55 square pattern with each grid 3 miles (15,840 ft) on a side. The regional system was modeled as a held potential surface layer and two underlying basalt layers. The surface layer consists of a composite of held potential nodes representing large lakes; the Columbia, Snake, Walla Walla, and Yakima Rivers; basalt seepage faces; and alluvial water table systems in the Walla Walla, Quincy, and Pasco Basins. For modeling purposes the potential in the surface layer was held at the levels indicated by the field data. Therefore, the surface layer was not actually modeled but it was simulated to the extent that it did act as a recharge or discharge area for the deeper basalt layers.

Of the two layers that were actually modeled, layer 1 consisted of the Saddle Mountain Basalt and Wanapum Basalt. The VTT model region for layer 1 and its associated held nodes in the surface layer is shown in Figure B.24. The "x" calculational types shown in Figure B.24 represent the held nodes in the surface layer that are hydraulically connected to layer 1. These held nodes act as recharge or discharge areas for the Saddle Mountains and Wanapum Basalts. The layer 1 boundary representing seepage faces to the north and northwest is defined by the Columbia and Spokane Rivers. In addition to the held river and held lakes nodes there are held potential nodes representing the Walla Walla, Quincy, and Pasco Basins' alluvial systems shown in the surface layer of Figure B.24.

Layer 2 represents the Grande Ronde Formation hydrologic system. The VTT model region for layer 2 and its associated held nodes in the surface layer are shown in Figure B.25. The "x" calculational types shown in Figure B.25

FIGURE B.24. VTT Finite Difference Grid System Used to Model the Saddle Mountain-Wanapum Basalt Regional Aquifer System (Layer 1)

FIGURE B.25. VTT Finite Difference Grid System Used to Model the Grande Ronde Basalt Regional Aquifer System (Layer 1)

represent the held nodes in the surface layer that are hydraulically connected to layer 2. The northern and northwestern portion along the Columbia and Spokane Rivers shares a common seepage boundary with layer 1. The other held nodes are lakes or rivers that are incised into the Grande Ronde.

The remainder of the model area perimeter in both layers 1 and 2 is represented as a no-flow boundary; however, a rate of recharge or discharge can be specified if desired. Existing data indicate that little or no movement of water is occurring across these boundaries. The parameters defining the regional model study area were made into data files and input to the VTT code. These parameters are described below.

Interpreted Potentiometric Surfaces and Well Data

Potential, or elevation of the ground water above mean sea level, must be defined at each interior and boundary node of the model region. The interpreted water table surfaces for the three alluvial basins are shown in Figure B.26. The interpreted composite Saddle Mountain-Wanapum potential surface used to represent layer 1 is shown in Figure B.27. As mentioned earlier, no interpretation of the layer 2 or Grande Ronde potentiometric surface was constructed.

Three sets of water level measurements in wells were obtained from the data base. These measurements were the average water level measurements in the wells for the years 1958, 1968, and 1978. There are 162, 439, and 360 wells in the 1958, 1968, and 1978 data sets, respectively. These well measurements were compared to the interpreted composite potentiometric surface for the Saddle Mountain-Wanapum aquifer system. The average and root mean square error between the wells and the interpreted surfaces are:

- average = 79.2 rms = 116.4 (1958)
- average = 116.2 rms = 148.6 (1968)
- average = 108.2 rms = 146.4 (1978).

Regional flow of ground water tends to be southwestwardly across the model area, as shown in Figures B.26, B.27 and B.28. Exceptions to this general flow pattern occur:

FIGURE B.26. Interpreted Water Table Surfaces Used in the Regional VTT Model to Represent the Potential Surface in the Quincy, Pasco, and Walla Walla Alluvial Systems. (All water levels are in feet above mean sea level).

FIGURE B.27. Interpreted Potential Surface Used in the Regional VTT Model to Represent the Saddle Mountain-Wanapum Basalt Aquifer System. (All potentials are in feet above mean sea level).

[illegible]

FIGURE B.28. Interpreted Transmissivity Surface Used as Initial Input to the Regional VTT Model to Represent the Saddle Mountain-Wanapum Basalt Aquifer System. (Transmissivity units are in thousands of gal/day/ft²).

- at the northern perimeter of the Columbia Plateau Basalt where ground water tends to flow toward the edge of the plateau because of potentiometric highs within the model boundary
- in the Blue Mountains where ground water tends to flow northward and eastward toward the Snake River
- in the western portion of Pasco Basin where ground water tends to flow generally eastward toward the Columbia River.

Structural Surfaces. Structural surfaces (aquifer top and bottom) for the regional model layers were not used in the regional model because of the lack of good data. The principal reason for including these surfaces in the model is so that transmissivity values can be calculated from hydraulic conductivity values and the saturated thickness (transmissivity = hydraulic conductivity x saturated thickness). The need for the saturated thickness was eliminated by putting transmissivity values directly in the regional model. Because the purpose of the regional model is to determine flux and not to determine water travel time, using only transmissivity data presents no problem.

Recharge and Discharge. The VTT model can simulate all types of recharge to, or discharge from, the ground-water system. A detailed presentation of recharge data and calculations was provided in the previous section. In summary, the input includes weather station data on precipitation, temperature, and potential evapotranspiration, and related data on topography, stream runoff, and irrigation. A combination of these parameter distributions in a water balance relationship results in a distribution of annual aquifer recharge. Total recharge to the region is estimated to ~1.7 million acre ft/yr, and of this total, artificial recharge represents nearly one half.

Calculating the seepage (discharge) to or from the Columbia, Yakima, and Snake Rivers, or the lakes is not necessary for modeling purposes. Instead, the water level at the nodes representing the rivers and lakes is held at the field-determined elevations. The model simulates effluent or influent conditions, depending on how the river or lake level compares to the water table in the ground adjacent to the river or lake.

The major source of recharge to both layers 1 and 2 is in the Blue Mountains and in northern and eastern portions of the Columbia Plateau where the basalt flows are closer to the ground surface and the regional precipitation is greatest. Some recharge to the basalts also occurs over other portions of the plateau as a result of infiltration of irrigation water, precipitation, and storm runoff in channels that have cut down into the basalt.

Transmissivity. The layer 1 transmissivity contour map was prepared by adding the transmissivity values for the Saddle Mountains and Wanapum Basalts together. This surface was digitized and input directly to the VTT model (Figure B.28). An initial transmissivity value of 60,000 gpd/ft was uniformly set over the layer 2 model region.

Model Calibration

Once the boundary conditions and the other required data sets were established and input, the model was ready to predict ground-water potential surfaces that could be calibrated against the interpreted potential surface and the well measurement data taken from the USGS data base. The model was run in the steady-state mode.

Degrees of uncertainty surround even the most carefully measured or mapped physical data. Limited quantities of point data are interpolated to produce maps (potential, transmissivity, aquifer bottom). These maps help form a conceptual model of the system. Filtering of data occurs during this step as well as during the step of moving from the conceptual model to the computer model, where one must digitize the system onto a grid system of some kind. The calibration process involves a series of computer runs where the model inputs are modified within the accuracy limits of the data to make the model better represent the observed behavior of the system. The inherent uncertainty in the model input data, along with the associated uncertainties in the conceptual model, justifies making the necessary changes in the model input or conceptual model during the calibration process.

The parameter most commonly adjusted in the calibration process is transmissivity, or permeability, because it is often the parameter with greatest uncertainty as well as the least amount of data. The amount and distribution

of recharge/discharge usually has the greatest influence on the model output; therefore, estimates for these parameters must be made carefully. Changes are sometimes made in the boundary conditions and/or the aquifer top and bottom surfaces, if the conceptual model is refined or if errors are detected or additional data are obtained.

After each simulation, run model-predicted potentials were compared to the initial interpreted potentials for layer 1 (Figure B.27). In addition, point comparisons were made by checking the model-predicted potential values at wells to field-measured elevations as obtained for three different time periods discussed earlier. Based on these comparisons, transmissivities, interaquifer transfer coefficients, lake and river transfer coefficients, as well as seepage face transfer coefficients were adjusted within reasonable limits until a satisfactory level of agreement was obtained between predicted and observed (interpreted) potentials for layer 1 (Saddle Mountain-Wanapum).

The basis for determining the level of agreement was: When contouring the initial hand-drawn potential surface from data points at wells a certain amount of interpretation is necessary. The accuracy of the interpretation can be measured by calculating the average and the root-mean-square (rms) difference between the water level at all wells over the model region and the water level at those same wells as would be predicted from the interpreted potentiometric surface. When the comparison between the model-predicted potential surface and the wells gets equal to, or better than, the comparison between the interpreted potential surface and the wells, additional model calibration is somewhat meaningless. Therefore, the regional model was calibrated until the rms difference between the model-predicted potential surface and the well data was less than, or equal to, the rms difference between the interpreted potential surface and the well data. In the calibration process the error comparisons between model-predicted potentials in the Saddle Mountain-Wanapum aquifer system moved down from the following initial error estimates:

1958 well data	rms error = 246 ft
1968 well data	rms error = 402 ft
1978 well data	rms error = 367 ft
Interpreted potential	rms error = 701 ft.

For this initial model prediction the transmissivity of the Grande Ronde Basalt aquifer system was a uniform 60,000 gal/day/ft. The Saddle Mountain-Wanapum Basalt aquifer system was represented by the transmissivity surface shown in Figure B.28. Interaquifer transfer between layer 1 and layer 2 was represented by a vertical permeability of 10^{-3} ft/day. Transfer between layer 1 and the alluvial systems was represented by a vertical permeability of 10^{-2} ft/day. Transfer to lakes and rivers was controlled by sediment permeabilities of 10^{-2} ft/day. Basalt seepage faces were assigned 10^{-2} ft/day permeabilities.

During the numerous calibration runs these rms error comparison values between the well data and model predictions eventually became better than the error comparisons between the well data and the interpreted potential data (Figure B.27). Table B.26 shows the comparisons between well data and model, as well as well data and interpreted potential for layer 1. The rms error comparison between the interpreted and predicted potential surface for the calibrated model was 214 ft.

TABLE B.26. Average, rms, Maximum-Minimum Error Comparisons Between Well Data and Model Predictions and Well Data and the Interpreted Potentials for Layer 1 (all values in feet)

	1958		1968		1978	
	Model	Inter- preted	Model	Inter- preted	Model	Inter- preted
Average	4	79	96	116	105	108
rms	97	116	127	149	138	146
Maximum Positive Error	280	150	761	738	511	444
Maximum Negative Error	442	-649	-646	-471	-473	-519

For the calibrated model the average vertical permeability controlling interaquifer transfer between layer 1 and layer 2 was 1.01×10^{-3} ft/day with a maximum value of 7.0×10^{-3} ft/day. The average absolute value of the vertical Darcy flux between layer 1 and layer 2 was 4.04×10^{-3} in./day. Total transfer from layer 1 to layer 2 amounted to 0.64 million acre ft/yr. Transfer from layer 2 to layer 1 amounted to 0.32 million acre ft/yr for net loss from

layer 1 of 0.32 million acre ft/yr. The average vertical permeability controlling movement between the alluvium and layer 1 was 6.9×10^{-3} ft/day with a maximum value of 0.36 ft/day. The average absolute Darcy flux between layer 1 and the alluvial systems was 1.6×10^{-2} in./day. Total transfer to the alluvium from layer 1 amounted to 0.71 million acre ft/yr. Transfer from the alluvium to layer 1 amounted to 0.11 million acre ft/yr for a net loss of 0.60 million acre ft/yr from the layer 1 basalts to the alluvium.

Layer 1 losses to the modeled rivers not entrenched in alluvium amounted to 0.13 million acre ft/yr, or approximately 8.0 cfs/river mile. Layer 1 losses to the 18 modeled lakes entrenched in layer 1 amounted to 0.035 million acre ft/yr. Total seepage face along the northern boundary of layer 1 amounted to 0.011 million acre ft/yr.

Layer 2 losses to modeled rivers amounted to 0.59 million acre ft/yr. Columbia River losses along the western boundary averaged ~ 0.8 cfs/river mile. Snake River losses in the mid to eastern half of the modeled area averaged ~ 5.5 cfs/river mile. Total losses to lakes entrenched in layer 2 amounted to 0.12 million acre ft/yr. Seepage face losses along the northern boundary amounted to 0.015 million acre ft/yr.

The calibrated model-predicted losses to lakes is in the range of the +40-inch range measured for annual lake evaporation rates. Seepage face estimates along the northern boundary are on the order of 9.9×10^{-2} cfs/mile or 4.4 - (10 gpm springs/mile). The water balance and general flow directions of the regional model seem reasonable.

The interpreted transmissivity surface for layer 1 (Figure B.28) averaged $\sim 25,000$ gal/day/ft and layer 2 initial value was 60,000 gal/day/ft. The average transmissivity values for layers 1 and 2 for the calibrated model are 85,000 gal/day/ft and 51,000 gal/day/ft, respectively. The increase in average transmissivity values for the calibrated model over those in the interpreted input of Figure B.28 is not uncommon. The transmissivity values used in the preparation of the interpreted surface generally are not a measure of the entire modeled aquifer system and therefore can generally be expected to be lower than the calibrated model transmissivity.

Figures B.29 and B.30 illustrate the model-predicted potentials for the Saddle Mountain-Wanapum Basalt aquifer system and the Grande Ronde aquifer system, respectively. The general shape of the model-predicted potential surface for layer 1 one agrees fairly well with the interpreted shape. The calibrated regional flow model was used to predict the northern and eastern boundary conditions (recharge and discharge) for the local model of the Pasco Basin.

FIGURE B.29. Regional Model-Predicted Potential for Layer 1 (Saddle Mountain-Wanapum Basalt Aquifer System). Potentials are in feet above mean sea level.

FIGURE B.30. Regional Model-Predicted Potentials for Layer 1 (Grand Ronde Basalt Aquifer System). Potentials are in feet above mean sea level).

Data Deficiencies

In all modeling efforts deficiencies exist, and therefore, model limitations exist. Typically, the larger the model region, the greater the data deficiencies and limitations. Although many of the data deficiencies have

already been identified, they are summarized below. Additional data requirements are briefly discussed.

Much of the data used in this modeling effort deals with specific aspects of the hydrogeology of the Columbia Plateau region, or deals with the hydrogeology and stratigraphy of only a small portion of the region. Several of the reports used to provide data deal specifically with ground-water management of sub-basins or parts of sub-basins within the regional study area. As can be expected, the best data exists in the more heavily populated areas and in the areas irrigated by ground water. Additional hydrogeologic and stratigraphic data is needed. Among some of the most promising work that will ultimately enable an accurate qualitative and quantitative picture of the regional ground-water flow system of the Columbia Plateau is the stratigraphic definition obtained by integrating surface and subsurface stratigraphic data. Recent work sponsored by the Basalt Waste Isolation Program and presented in Myers et al. 1979 and Gephart et al. 1979a suggest that substantial progress is being made in developing many of the hydrogeologic and stratigraphic cross-sections that are needed.

Similar patterns of geographic distribution of data have been found for all types of hydrologic well data, including: water-level data, geophysical well log data, driller's logs, and transmissivity data. These hydrologic data are widespread throughout the Columbia Plateau, but are irregularly distributed, except in the Pasco Basin. The concentration of data is restricted to areas that have the greatest amount of irrigation using ground water and where good soil is available for cultivating crops.

In general, the quality and completeness of hydrologic and geologic data for the shallower basalt formations (layer 1) are far superior than the Grande Ronde (layer 2) data or maps. In certain areas the superior quality of deep geologic and hydrologic data is primarily due to the thrust of investigative work conducted by WSDOE in cooperation with the WSU geophysical logging program and Rockwell-Hanford Operations BWIP studies. However, the paucity of deep wells and their irregular spatial distribution often necessitates patterning the Grande Ronde hydrogeologic surfaces after the layer 1 surfaces or constructing composite hydrologic surfaces.

Many of the published reports reviewed and evaluated are based on information shown on well logs submitted by water well drillers to WSDOE models studies and, to a lesser degree, on geophysical log data obtained from WSU. Transmissivity maps presented in these documents are based on water well driller reports of questionable hydrologic data accuracy. Depending on the completeness of the water well report, information may be provided on both static and dynamic water levels. The dynamic or pumping water level is frequently described on the well reports without indication of the duration of pumping test. Consequently, reported specific capacity values for most wells are only approximate at best. In addition, transmissivity data are often not reliable in cases where the well penetrates several aquifers or formations. Most often the proper steps have not been taken to properly pump test individual units or layers.

Additional Data Requirements. For the regional model of the Columbia Plateau additional data for the Grande Ronde Formation is essential. Some stratigraphic and hydrogeologic data do exist, and although the accuracy and reliability of this data are excellent, the spatial distribution is concentrated in limited areas in the Pasco Basin, Odessa area, Sagebrush Flats, and southern Spokane County. Information on overlaying hydrologic systems is much better areally distributed, although in many cases the accuracy of the data is in question.

To meet the needs of a mathematical model that will adequately reflect the movement of ground water in the Columbia Plateau, the following recommendations for interpretation are made.

First, all existing hydrologic and geologic well data for the Grande Ronde Formation should be compiled and then supplemented by field data from existing wells penetrating the Grande Ronde Formation. After all Grande Ronde geologic and hydrologic data are collected, structural, potentiometric, and transmissivity contour maps of the region should be constructed. Additional data collection and field testing efforts should be designed to fill the data gaps identified in the previous step.

PASCO BASIN MODEL

The local model simulates a subregion of the regional model in greater detail. The subregion of particular interest is similar in areal extent to the Pasco Basin and is the area surrounding the hypothetical site for a nuclear waste repository. Simulating this smaller region allowed for more resolution around the repository and along the potential ground-water pathways from the repository to the point or points of discharge into the biosphere.

Both hydrologic-flow and contaminant-transport models were implemented for simulation of the local region. The local flow model, which was used to predict ground-water flow paths and travel times from the repository to the biosphere, is discussed below. The local contaminant transport model, which simulates the movement of radionuclides in the ground water, is discussed in Chapter 7.

Sources and Interpretation of Hydrogeologic Data

Because the local model is a subregion of the regional model, the sources and interpretation of hydrogeologic data are very similar. The data used in the local modeling effort are consistent with those for the regional model but were resolved in greater detail.

Model Boundaries

The local conceptual model covers approximately 1870 square miles in the southwestern corner of the regional model area (Figure B.31). The southern and western boundary of the local model region is identical to the regional model boundary. The geologic basis for this boundary selection was discussed earlier in the section on the regional model.

The northern and eastern boundary was arbitrarily chosen and approximates the northern and eastern Pasco Basin boundary. The hydrogeologic properties of this boundary were defined from the regional model to account for the influx of water to the local model area from the regional system.

Evaluation, Selection, and Preparation of Structural Surface Data

Local stratigraphy in the conceptual model was grouped according to the major basalt formations (Saddle Mountains, Wanapum, and Grande Ronde) and an

FIGURE B.31. Map Showing the Relationship Between the Regional and Local Boundaries (Photo No. 81B323-6)

uppermost layer, which is a composite of surface water systems (rivers and lakes) and the alluvial/sedimentary ground-water system. The areal extent of the four layers is shown in Figure B.32. The origin of the data used to define the layers is discussed below.

FIGURE B.32. Map of the Local Model Region Showing the Areal Extent of the Various Geologic Units Within the Local Model Boundary

Alluvium. The areal extent of the alluvium within the Pasco Basin was determined from Hanford Project data (Kipp et al. 1972) and from USGS topographic contour maps. Figure B.33 illustrates the digitized topography in the local model area along with the local model boundary.

FIGURE B.33. Digitized Topography in the Local Model Area and the Local Model Boundary. Contours are in feet above MSL.

Saddle Mountains Basalt. The stratigraphic surface (top) of the Saddle Mountains Basalt was developed from a hybridization of Plates 4A (1 and 2) Myers et al. (1979) and Plate 3 from Tanaka et al. (1979). These references were used almost exclusively because of their completeness and because a multiple source data base was used to prepare the maps. Figure B.34 illustrates the digitized top of the basalt stratigraphic surface used in the local modeling effort.

Wanapum Basalt. The references selected to construct the stratigraphic surface and areal extent maps of the Wanapum Formation are Myers et al. (1979) and Tanaka et al. (1979). The final stratigraphic contour and unit boundary maps were constructed and digitized in a similar manner as for the Saddle Mountains Basalt, using Plates III 4B (1 and 2) from Myers et al. (1979) and Plate 4 of Tanaka et al. (1979). Figure B.35 shows the digitized stratigraphic surface for the top of the Wanapum that was used in the local modeling effort.

Grande Ronde Basalt. The work required to obtain the Grande Ronde stratigraphic surface included: gathering published data from local sources (PNL and Rockwell-Hanford), scrutinizing the data and sources to resolve numerical value conflicts, determining the most reliable data values, and constructing maps of the upper and lower stratigraphic surface of the Grande Ronde Basalt and the Umtanum Flow within the Grande Ronde. Because only nine or fewer data points were available for constructing each of the upper three stratigraphic surfaces (i.e., top of the Grande Ronde, top of the Umtanum, and base of the Umtanum), the contour maps of the Wanapum Basalt, which are based on a considerably greater number of data points, were used to guide construction of the stratigraphic surfaces of the deeper units. This methodology is based on the assumption that the variation in the thickness of the Wanapum and Grande Ronde Basalt units is relatively small. By mimicking the proportions and configurations of the Wanapum contours while allowing for observed modest variations in the thickness of each unit, the upper stratigraphic surface of the Grande Ronde was completed. Figure B.36 shows the digitized top of the Grande Ronde structure map used in the local modeling effort.

FIGURE B.34. Digitized Stratigraphic Surface for the Top of the Saddle Mountains Basalt. Contours are in feet above MSL.

FIGURE B.35. Digitized Stratigraphic Surface for the Top of the Wanapum. Contours are in feet above MSL.

FIGURE B.36. Digitized Stratigraphic Surface for the Top of the Grande Ronde. Contours are in feet above MSL.

The completed top of the Grande Ronde contour map was used to construct the upper surface of the Umtanum Flow and the bottom stratigraphic surfaces of the Grande Ronde Basalt and Umtanum Flow. The stratigraphic contour maps of the bottom of the Umtanum unit and the Grande Ronde Basalt were constructed using 8 and 1 data points, respectively, rather than the 9 available for the upper surfaces. Obviously, the accuracy of the bottom of the Grande Ronde Basalt is suspect. Using the single data point at RHS-1, which was the estimated depth to Grande Ronde Basalt [approximately 5,000 ft (Raymond and Tillson 1968; Gephart et al. 1979b)], and the assumption of nearly accordant surfaces for the Grande Ronde top and base, the base structure map was constructed. This assumption may prove to be in error; however, without additional data points for preparing the contour map, this seems to be a reasonable approach.

After completion of the upper Grande Ronde structure surface, information regarding the depth and elevation of the top of the Grande Ronde Basalt at well DC-12 was received and checked against our predicted value. The elevation of the top of the Grande Ronde Basalt was estimated to be 1730 ft below mean sea level on the hand-contoured maps, which varied only one percent from the actual measured value of 1712 ft below mean sea level. Such close correlation between the predicted value and the actual field value suggests the "mimic" methodology is valid for at least one area of the Pasco Basin.

Evaluation, Selection, Interpretation, and Preparation of Hydrologic Data

The preparation of the transmissivity and potentiometric data for each layer in the local region is described below. The sources of data were almost exclusively the Rockwell-Hanford reports: Gephart et al. 1979a and Tanaka et al. 1979. This section contains a discussion of data sources and problems associated with vertical to horizontal hydraulic conductivity ratios and effective porosity, along with a detailed description of pumping data used to determine ground-water withdrawals from the basalt for municipal and irrigation uses in the local region, and a final section dealing with pertinent river system data.

The equivalent porous medium concept is being applied in both the regional and local modeling effort. The basalts, as has been discussed, are composed

of many aquifers (interflows, interbeds) and aquitard (dense basalt, some interbed) layers. On a regional or local scale the size of the Pasco Basin, it is not possible nor is it necessary to model or characterize in detail each of these aquifer or aquitard systems. For modeling purposes, these more complex systems can be represented as a lesser number of equivalent systems, as has been done for the basalt modeling effort presented in this paper. The similarities in geologic, hydrologic, and geochemical properties have been used to determine one appropriate grouping of these layers. To relate the laboratory- and field-determined values of permeability (both horizontal and vertical), effective porosity, and observed potential or head data to the actual model input values required to model a typically more complex real system, an understanding of the equivalent porous medium concept and the associated compositing process is needed. In addition, an understanding of the interrelationship between anisotropy, heterogeneity, and scale is needed because this also affects how laboratory and field data are interpreted for input into a hydrologic model.

Transmissivity Data. Initially, transmissivity contour maps were prepared for the four layers of the local model. These data were later converted to equivalent porous media hydraulic conductivities by dividing by the saturated thickness of the layer as determined from potential and structural data. The transmissivity maps of the Saddle Mountains and Wanapum aquifers were copied from existing contour maps, whereas the Grande Ronde transmissivity map was constructed from values available from three data points within the basin.

The transmissivity maps of the Saddle Mountains and Wanapum represent transmissivity values obtained by a variety of test methods of varying duration, by different data collection procedures, by different parameter monitoring instrumentation, and often by the simplest methods of analysis. In addition to the wide variation in the reliability and accuracy of the results reported, the tests within the same geologic formation rarely represent the total transmissivity of all aquifers within that formation. Each of the transmissivity values within a portion of the local model area may represent different aquifers or combinations of aquifers. Some wells, despite the presence of casing (which should indicate isolation of overlying aquifers), obtain water

from the overlying geologic formation as well as from the unit it is reported to represent. As a result, exaggerated values for transmissivity may be obtained.

More often the opposite is true: the transmissivity values represent only a portion of the total transmissivity of the composite of all the aquifers in a geohydrologic formation because the wells are not fully penetrating. (Drilling is terminated once adequate water supplies are obtained for the purpose intended by the well owner. Nonetheless, a large number of wells do exist that fully penetrate the upper geologic formations; therefore, good reference points do exist.

Transmissivity data for the alluvial material were obtained from Hanford Project data (Kipp et al. 1972) and from other data gathered for the Riverview Area. A contour plot of the digitized transmissivity surface used in the modeling effort is shown in Figure B.37.

Except for minor peripheral modification of the transmissivity contours to facilitate use of the CIRMIS digitization program, this surface was taken from Plate II-11 of Gephart et al. (1979a). The digitized transmissivity surface used in the modeling effort is shown in Figure B.38.

The source for the Wanapum transmissivity contour surface was Plate II-12 of Gephart et al. (1979a). Some of the contours were extended to permit accurate digitization. The digitized Wanapum transmissivity surface used in the modeling effort is shown in Figure B.39.

The transmissivity contour map of the Grande Ronde Basalt was constructed entirely from data presented in Gephart et al. (1979a). Only four sites, DC-1, DC-2, DC-6, and RSH-1, exist that have suitable data, as shown in Figure B.40. For each site, several values of transmissivity and hydraulic head are reported. The criteria used to select representative values at each site were as follows:

1. Select the most accurate hydraulic head and conductivity (transmissivity) values. If practical, choose equivalent layers for parity of parameters.

FIGURE B.37. Digitized Transmissivity Surface
for the Alluvium in gpd/ft

FIGURE B.38. Digitized Transmissivity Surface
for the Saddle Mountain Basalt
in gpd/ft

FIGURE B.39. Digitized Transmissivity Surface
for the Wanapum Basalt in gpd/ft

FIGURE B.40. Map of the Local Model Region Showing the Location of Some of the DB and DC Wells Used in This Study (Photo No. 81B323-1)

2. Choose a representative aquifer based on the highest transmissivity and, therefore, the more likely flow path from a hypothetical breach of the repository.

Interpretive liberties were exercised in constructing the Grande Ronde transmissivity map because of the limited amount of data. The transmissivity contour map of the overlying Wanapum formation was used as a guide, based on the assumption that the two formations are similar. This seems to be a reasonable assumption, based on the similarities in the transmissivity and potential values at the few sites where data exist for both formations.

The digitized transmissivity map for the Grande Ronde Formation is shown in Figure B.41.

Vertical Hydraulic Conductivity Data. Modelers of basalt hydrology in areas surrounding the local model region (Luzier and Skriván 1975; MacNish and Barker 1976; Tanaka et al. 1974) have found that a significant amount of vertical water movement exists and that to estimate the amount and distribution of vertical movement is quite difficult. Luzier and Skriván (1975, p. 23), who modeled the Odessa-Lind area, stated, "The model is quite sensitive to recharge variations. During the study, vertical leakage was the parameter that was most often varied and which posed the biggest problem."

There is probably vertical movement of water through the basalt layers within the local model region. Quantifying this vertical movement of ground water within the layers is necessary to accurately represent the ground-water flow system.

Much effort has been put into determining the nature of anisotropy in hydraulic conductivity, but there is little data. Piper (1975) generalized from water-well yields that large vertical piezometric gradients are not common and that yield increases with depth in major water-producing wells. In certain areas hydraulic continuity may exist across layers of different ages because of the highly complex distribution of fractures. The basalt sequence might approach isotropy on a very coarse scale.

FIGURE B.41. Digitized Transmissivity Surface for the Grande Ronde Basalt in gpd/ft

On the other hand, La Sala et al. (1973, p. 25) reason that since flow-tops and interbeds transmit water, "the average permeability of the rock section as a whole is therefore much greater in the direction concordant with the dip than in the discordant or cross-bed direction. In an area uncomplicated by structural features, water will tend to move more readily in a horizontal rather than a vertical direction."

Based on the results of La Sala et al. (1973), Ledgerwood and Deju (1976) state that the vertical permeability of the interbeds is an order of magnitude lower than that in the horizontal direction. INTERA (1977, p. 15) concurs that such anisotropy is generally the case for aquifers containing interbedded shale or clay.

Tanaka et al. (1974) estimated vertical hydraulic conductivity at 2×10^{-5} ft/day and MacNish and Barker (1976) estimate 4×10^{-3} ft/day. The regional modeling effort discussed earlier required an average value of 1×10^{-3} ft/day, which lies between the range of Tanaka and MacNish and Barker. Hydraulic conductivity measurements across columnar zones in the basalt range from 10^{-3} to 10^{-8} ft/day (Gephart et al. 1979a). The vertical hydraulic conductivity values determined from our regional modeling effort are within a reasonable range when the effects of modeling scale, heterogeneity, and the compositing process required to determine an equivalent porous medium vertical hydraulic conductivity are considered over the areal extent of a model node or element. To put this into perspective, consider a typical model node that covers many acres. If, for each acre of the model node, the rock is completely impervious except for a square area 6.5 ft on a side that has a permeability of typical oil rock (1 ft/day), then the equivalent porous medium vertical hydraulic conductivity is 1×10^{-3} ft/day. This concept of scale and the compositing required to determine equivalent porous medium parameters must be kept in mind when comparing parameters used in modeling and parameters measured in the field at smaller scales.

Obviously, vertical hydraulic conductivity data are lacking. Therefore, vertical hydraulic conductivity was adjusted during model calibration to arrive at an estimate for this parameter and its areal distribution.

Effective Porosity Data. Pore water (or conservative contaminant) velocity and arrival-time calculations depend on effective porosity in transport modeling. A low estimate of porosity results in a shorter estimated water, or conservative contaminant, travel time from the repository to the point of entry into the biosphere.

Extensive measurements (field or otherwise) of effective porosity are lacking. La Sala and Doty (1971) report values of effective porosity for different basalt types and interbeds that were estimated by Fenix and Scisson, Inc. (1974) from geophysical logs: 1% for "dense" basalt, 5% for vesicular basalt, and 10% for basalt with closely spaced fractures. La Sala and Doty (1971) expressed some doubt about the applicability of these geophysical techniques to dense, massive rocks, and about whether a correction for hole diameter had been applied.

Obviously, the amount of effective porosity data is limited. Therefore, an initial estimated effective porosity was set in the model and the distribution of this parameter was adjusted in the model calibration process.

Equivalent porous media effective porosity estimates were developed for use in this reference site initial analysis from data on lithology and effective porosity in Table III-20, Table II-13 and page III-153 of Gephart et al. 1979a, along with data from Staff, BWIP (1980--page III-50), and in Table 11, 13, and 14 of Staff, BWIP (1981). From data on the thickness and effective porosities of the various general basalt lithologic units, estimates of the equivalent porous medium effective porosity were made for the modeled basalt units. Table B.27 shows the average, maximum, and minimum values of effective porosity required for modeling the basalt.

Potentiometric Data. The potentiometric trend maps of the Saddle Mountains and Wanapum Basalts in Tanaka et al. 1979 and the composite aquifer potential maps in Gephart et al. 1979a were used to construct the potentiometric contour maps for the local region. The Gephart report was the primary source of data. The Tanaka report was used primarily as a cross reference.

TABLE B.27. Equivalent Porous Medium Effective Porosity Estimates
Developed for Use in the Reference Site Initial Analysis

<u>Modeled Hydrologic Unit</u>	<u>Equivalent Porous Medium Effective Porosity</u>		
	<u>Minimum</u>	<u>Average</u>	<u>Maximum</u>
Alluvium	--	0.10	--
Saddle Mountain	0.06	0.095	0.12
Wanapum	0.05	0.07	0.10
Grande Ronde	0.05	0.06	0.07

The alluvial potentiometric data were obtained from a 1975 Hanford Project water table map (Rockwell-Hanford Operations) and from other data for the area east of the Columbia River. The initial alluvial potential surface used in the local model is shown in Figure B.42.

The potentiometric map for the Saddle Mountains Basalt within the local model region, as shown in Figure B.43 was digitized from Plate III-7 of Gephart et al. 1979a.

The Wanapum potentiometric map, as shown in Figure B.44, for the local model region was digitized from the postirrigation contours on Plate II-8 of Gephart et al. 1979.

The potentiometric contour maps of the Grande Ronde Basalt, as shown in Figure B.45, for the local model region was constructed entirely from data presented in Gephart et al. 1979a. The four sites with suitable data, DC-1, DC-2, DC-6, and RSH-1, are shown in Figure B.40. It was assumed that the contour configuration of the Grande Ronde geologic unit was similar to that of the Wanapum Basalt.

The areal extent of the saturated zone for each of the four layers was inferred from their interpreted structural and potential surfaces. A composite overlay map of the saturated zones for the four layers is shown in Figure B.46. The saturated thicknesses were tapered down to near zero along these boundaries where they were within the local model region.

FIGURE B.42. Digitized Potential Surface for the Alluvium.
Contour levels are in feet above MSL.

FIGURE B.43. Digitized Potential Surface for the Saddle Mountains Basalt. Contour levels are in feet above MSL.

FIGURE B.44. Digitized Potential Surface for the Wanapum Basalt. Contour levels are in feet above MSL.

FIGURE B.45. Digitized Potential Surface for the Grande Ronde Basalt. Contour levels are in feet above MSL.

FIGURE B.46. Map of the Local Model Regional Showing the Areal Extent of the Saturated Zones in Each of the Four Local Model Layers

Ground-Water Withdrawal Data. About 3000 wells exist in the Pasco Basin external to the Hanford Site. Of those, Summers and Weber (1978) have tabulated about 800 that penetrate (to or into) basalt. However, many of those bottom on basalt and yield little or no water from the basalt aquifers.

More than 600 wells have been tabulated that penetrate into and produce water from the basalt (including many not listed by Summers). Their test yields have been recorded, although their production in use is not known. They have been used in this study in a preliminary attempt to estimate the relative importance of the aquifers in the basalt sequence. The data are of special interest in that the yields can be compared to the yields of the water table aquifers, and to the volumes of surface water used for irrigation purposes.

Dion and Lum (1977) calculated the total ground water and surface water use in Franklin and Benton Counties by municipalities, by industry, and for irrigation. They did not include domestic wells. For irrigation they used the acreage irrigated multiplied by the estimated water application.

In this modeling study, the volumes of water used were calculated from the estimated well yields. The assumption was made, probably erroneously in some instances, that wells were drilled until the well yields were adequate to irrigate the given tract of land. Thus, if an irrigation well can yield 3000 gpm, two such wells would be drilled in a section to provide the normally needed 8.5 gpm/acre, or the 42 to 48 in. of water normally used per irrigation season.

Direct comparison to the figures derived by Dion and Lum are possible only in part, for they accumulated the data by Franklin and Benton Counties. Much of Benton County and part of Franklin County lie outside the Pasco Basin, and Burbank and Black Rock Valley are in the Pasco Basin but in Walla Walla and Yakima Counties, respectively.

High-yield irrigation wells producing from aquifers in the basalt sequence in the Pasco Basin are primarily concentrated in three locales. Two other high-yield areas are nearby but are outside the Pasco Basin. A few other high-yield wells are present in the Basin but are randomly scattered among the lower yield wells.

The high-yield areas are:

- the Cold Creek-Dry Creek-Black Rock Valley area
- the Badger Mountain-Badger Plateau area
- the Rye Grass Coulee-Smith Canyon area. This lies partly outside the Pasco Basin but the waters are contiguous with waters in the Basin.

High-yield areas outside the Basin are the Dead Canyon area in the Horse Heaven Hills and the lower Yakima Valley, where several high-yield zones are identified.

Currently, the Cold Creek-Dry Creek-Black Rock Valley area yields an estimated 17,500 gpm, the Badger Mountain-Badger Plateau area yields an estimated 10,000 gpm, and the Rye Grass Coulee-Smith Canyon area yields an estimated 4500 gpm. On an annual basis, production is probably about 9000, 5400, and 2300 acre-ft, respectively (a total of 16,700 acre-ft), assuming 4 months of irrigation in the 6-month growing season, and 42 to 48 in. of water application.

About 350 domestic wells have been tabulated. Each is low in yield. If, however, each produces the 5000-gpd yield permitted beyond which water rights are required, the total yield may be about 2000 acre-ft/yr.

More than a hundred other wells, categorized as municipal, industrial, and small-scale irrigation, yield a total of 16,000 acre ft/yr (roughly equal to the high-yield irrigation wells).

The domestic, municipal, industrial, and small-scale irrigation wells are uniformly distributed in the southernmost part of the Columbia Basin Irrigation Project (the south half of the South Columbia Basin Irrigation District), the Pasco greenbelt area, the Burbank area, the Kennewick to Finley area, and the West Richland to Kiona and Benton City area.

The aquifers in the basalt sequence penetrated by wells are almost wholly the Saddle Mountains and Wanapum Formations. A few wells in western Black Rock Valley evidently penetrate into the Grande Ronde Formation, but the wells produce from both the Wanapum and Grande Ronde Formations. The yield is considered to be from the Wanapum Formation.

Generally, the high-yield wells produce predominantly from the Wanapum Formation. In the Badger Mountain-Badger Plateau area and in the Rye Grass Coulee-Smith Canyon area, the yield is entirely from the Wanapum Formation. In the Cold Creek-Dry Creek area, about half the yield is from the Saddle Mountains Formation and half from the Wanapum Formation (roughly 8750 acre-ft each). A very high percentage of the smaller-yield wells (domestic, municipal, industrial, small-scale irrigation) produce from the Saddle Mountain Formation.

A summary of the ground-water withdrawal data for the general model area appears in Table B.28. Figure B.47 shows the location of large pumping wells within the local model region and identifies the approximate borders of an area in which a larger number of domestic and low-yield irrigation wells are present. The yield of all the low-yield wells in the circled area totals about 13,000 acre-ft/yr.

TABLE B.28. Summary of Ground-Water Withdrawal Data

<u>Type of Well</u>	<u>Formation</u>	<u>Yield (acre ft/yr)</u>
High-yield irrigation	Saddle Mountain and Wanapum (equal parts)	9000 - Cold Creek 5300 - Badger Mountain 2300 - Rye Grass Coulee
Domestic	Saddle Mountains	2000
Municipal, Industrial Small-Scale Irrigation	Saddle Mountains	<u>16,000</u>
TOTAL		34,600

Ground-Water Flow Modeling

Essentially three modeling technologies are involved in assessing the water pathways release consequence: 1) hydrologic models that define the ground-water flow field and provide water flow paths and travel times, 2) engineered barriers and leach rate models that predict the rate at which waste from a breached repository enters the flow system, and 3) transport models that describe the movement and concentration of radionuclides in the flow field. The hydrologic model used to simulate the local region is discussed here.

FIGURE B.47. Location of Large Pumping Wells Within the Local Model Region. The dotted line identifies the approximate border of an area in which a large number of domestic and low-yield irrigation well are present. Pumping rates are in acre-ft/yr. (Photo No. 81B323-3)

Model Selection

The Finite Element Three-Dimensional Ground-Water Model (FE3DGW) developed by Gupta et al. (1980) was selected for modeling the local region. A three-dimensional finite element code was selected so that the area surrounding the repository and the multiple layers associated with the ground-water system could be modeled in more detail. The FE3DGW model uses the Galerkin finite element method with deformable quadrilateral elements.

Finite elements provide a different method of approximation than the finite difference methodology. The finite difference method needs special formulas for describing boundaries in many instances, the size of the grid is not changed as easily, and accounting for inhomogeneities and anisotropy can involve further complications. In finite element methodology the whole domain can be divided into irregular subdivisions as dictated by physical geometry of the problem. The advantage of irregular subdivisions is especially important when the spatial domain is complex. The size of each subdomain (element) can be varied easily; small elements can be used in areas of rapid change and large elements where variations are less severe. Furthermore, inhomogeneities and anisotropy are easily accommodated.

Geohydrologic systems and surface-water bodies (e.g., lakes, rivers) usually have irregular boundaries, and the finite element method provides a powerful tool for space and boundary definition. The spacing of the nodes near the repository, pumping wells, or surface-water bodies can be decreased, and the hydraulic conductivities can change abruptly from element to element so that fault zones and confining layers can be represented.

Some of the complex generic and site-specific geologic configurations consist of multiaquifer systems separated by semiconfining layers, and these aquifers respond conjunctively to stresses imposed on either aquifer. Such coupling of aquifers requires modeling all of the layers simultaneously. A three-dimensional model provides a realistic means of representing the kind of multilayered aquifers or aquifer systems associated with generic or specific repository sites.

Finite Element Grid Development

The finite element grid for the local (Pasco Basin) model was constructed using the structural and potentiometric surface contours from each of the four layers presented and discussed earlier. Discontinuities, major breaks in slope or thickness, and faults in any of these surfaces were used to guide the development of the grid. Nodes necessary to define each surface individually, both at the saturated and geologic boundaries, were identified. Then all nodes were combined into one surface grid. Additional surface nodes were placed along surface water bodies, at important recharge/discharge areas, and in areas of heavy pumping from wells. The resultant two-dimensional grid consists of 606 surface nodes and 555 surface elements, as shown in Figure B.48.

Model Boundary Conditions

The northern and eastern boundary of the local model was defined as a held potential boundary with the values being obtained from the regional model. In the finite difference regional model the potential is defined at the nodes and one vertically centered node represents each horizontal layer. In the finite element local model the potential is also defined at the nodes, but nodes are used to define the top and bottom of each horizontal layer. Also, more layers are defined in the local model than in the regional model. Therefore, an interpolation scheme was developed for obtaining the local model held boundary potentials from the regional model. Actual estimates of the flux into the local model area from the regional model will be presented later.

The southern and western boundary, which represents the rest of the local model boundary, was defined as a no-flow boundary based on evidence of ground-water divides related to elevation and structure.

Data Adaptation to the FE3DGW Code

The input data structure of the FE3DGW model is based on hydrogeologic data normally compiled for ground-water systems. Because the accuracy of the results is a function of the quality of the input, the input data must be thoroughly understood and be verifiable by field geologists, hydrologists, and modelers. The reader should have an understanding of the equivalent porous

FIGURE B.48. Plan View of the Surface Node and Element Map
Used in Three-Dimensional Finite Element Model
of the Local (Pasco Basin) Area (Photo No. 81B323-5)

medium concept as well as the effects of scale and the relationship between scale, isotropy, and heterogeneity to relate model input parameter values to field measurements.

Structural Surfaces. Once the two-dimensional element surface grid is prepared, the vertical dimension is defined by well logs at each node. This technique simplifies data preparation because the well logs required at each surface node correspond nicely to actual field data format.

The vertical dimension was defined by the four layers discussed in the previous section. Vertical nodes were placed below each surface node to represent the structural tops and bottoms of the alluvial and basalt layers. Four layers (alluvium, Saddle Mountains Basalt, Wanapum Basalt, and Grande Ronde Basalt) were modeled in the local region model.

The different layers (alluvium, Saddle Mountain, Wanapum, and Grande Ronde) do not all extend to the boundaries of the primary finite element grid nor to the boundaries of the geologic extent of the layer. Therefore, nodal descriptions were prepared that define the hydrologic areal extent of each layer. Figure B.32 depicts the geologic areal extent of the layers within the local model area. The relationship between the hydrologic (saturated) areal extent of the layers is shown in Figure B.46, as interpreted from geologic structure and potential interpretations.

Potential Surfaces. The potential surfaces for each layer, as discussed in the hydrogeologic data section, were digitized and input to the model. The initial potential values in the top layer (alluvium, rivers, lakes) were held constant in all model runs. In areas where the saturated alluvial layer did not exist at the surface, the surface potential value was chosen to be consistent with the uppermost saturated layer. For the layers that did not exist over the entire model region, both the structural and saturated thicknesses were tapered down to near zero along their respective boundaries.

Hydraulic Conductivity. Transmissivity maps were prepared for each of the four layers, as discussed in the hydrogeologic data section. An interpolation scheme was developed that assigned hydraulic conductivity (K) values

to the nodes in the finite element model based on the saturated thickness at the node and the transmissivity. The K for each element was then computed by averaging the K values at the four nodes comprising the element. The K 's varied from element to element over each surface, and from layer to layer vertically.

Porous-medium equivalent estimates of horizontal hydraulic conductivity for the modeled basalt layers (Saddle Mountains, Wanapum, and Grande Ronde) can be made from the published lithological data and hydraulic conductivity estimates and ranges (Gephart et al. 1979a; Staff BWIP 1980; Staff BWIP 1981). The equivalent porous medium hydraulic conductivity estimates made for the various layers are shown in Table B.29. Also shown in Table B.29 are the ranges (maximum-minimum) and average values determined from the model input interpretations for saturated thickness and transmissivity. Model input values agree with the estimated values based on lithology measurements and measurements for hydraulic conductivity.

Vertical Hydraulic Conductivity. Field data distinguishing vertical (K_v) from horizontal (K_h) hydraulic conductivity for the basalts are lacking. Therefore, the K_v distribution was determined in the model calibration process. Initially, the K_v to K_h ratio was set at 0.1 in the alluvium and 0.01 in all other layers over the model region. This distribution was adjusted in the model calibration process to better represent areas where the K_v to K_h ratio might be suspected to vary because of folding, fracturing, or other similar geologic phenomena features.

Effective Porosity. Field measurements of effective porosity were lacking. The porosity distribution was set as shown in Table B.27 and maintained throughout the model calibration process.

Ground-Water Recharge. Recharge data was calculated for two different time periods, called "preman" and "current conditions." The preman time period accounted for recharges to the alluvium and basalts before any influence by man. The current condition scenario accounts for the recharge and discharge that is occurring today. The principal difference is that the current condition scenario accounts for stresses associated with agricultural, irrigation, and pumping practices.

TABLE B.29. Equivalent Porous Medium Horizontal Hydraulic Conductivity Estimates for the Various Modeled Layers

Description/ Source of Estimate	Published Sources ^(a)	Staff BWIP (1980)	Staff BWIP (1981)	Model Input Interpretations
Saddle Mountain (ft/day)				
Average	--	4.0	5.0	2.96
Minimum	0.046	--	--	--
Maximum	27.4	--	--	17.2
Wanapum (ft/day)				
Average	--	4.0	0.008	1.73
Minimum	0.008	--	--	0.28
Maximum	12.3	--	--	4.52
Grande Ronde				
Average	--	0.104	0.0027	0.75
Minimum	0.00015	--	--	0.10
Maximum	117.0	--	--	4.18

(a) Staff BWIP (1981)

In the preman scenario the total amount of precipitation estimated to fall on the modeled region is 772,000 AF/year (7.75 in./yr over the local model area). Of this total precipitation, the majority of it (717,000 AF/yr--7.20 in./yr), is lost back to the atmosphere as actual evapotranspiration. The remainder, 55,000 AF/yr (0.55 in./yr), was input to the model as the total recharge to the basalt and alluvial systems. The calculation of this recharge is discussed in more detail in the section on aquifer recharge. Figure B.49 shows the calculated areal distribution of the preman aquifer recharge.

In the current condition scenario, man-induced stresses (irrigation return flow and pumping, municipal, and domestic wells) were considered. Alfalfa and small grains are the two crop types considered as irrigated vegetation to bound the maximum and minimum ground-water recharge. The recharge from irrigating alfalfa is greater than that for small grains. Therefore, in the interest of

FIGURE B.49. Areal Distribution of Recharge Used to Simulate the Preman Calibration Scenario. Values represent in yr. Underlined values have been multiplied by 1000.

taking the conservative approach (i.e., more recharge resulting in steeper gradients and shorter travel times), the recharge estimates associated with alfalfa were used in the local model.

The total precipitation in the current condition scenario was the same as in the preman scenario, 772,000 AF/yr (7.75 in./yr over the local model area). The amount of water used to irrigate alfalfa acreage provided an additional 859,000 AF/yr (42.0 in./yr) to the total water applied at the surface. Of this total input amount, 1,344,000 AF/yr (13.5 in./yr) was calculated as the amount lost to actual evapotranspiration, and 27,000 AF/yr was our estimate for pumping from the basalts within the modeled area. The basalt pumping distribution used in the model is shown in Figure B.50, and the recharge distribution is shown in Figure B.51. No water was assumed lost to runoff within the Pasco Basin. A water balance calculation shows a net flux of 287,000 AF/yr (2.88 in./yr) recharging the ground-water system within the local model area. This amount of recharge was used in the local model for the current condition scenario. The more detailed water balance estimates made in this study agree with the earlier estimates made by Gephart (1979a) for the Pasco Basin. They estimate precipitation at 756,000 AF/yr, surface irrigation at 907,600 AF/yr, and recharge from artificial mechanisms at 250,000 AF/yr. The more detailed estimates made for this study also allow us to infer areal distribution of recharge, which is important to the ground-water modeling effort.

Model Calibration

Once the conceptual model has been formulated and the model grid, the boundary conditions, and the hydrogeologic data have all been prepared and put into the model, the next step is to calibrate the model against observed field data. Model calibration is accomplished by adjusting the model input parameters, boundaries, and the conceptual model within reasonable bounds. These bounds are dictated by the uncertainty in these quantities, until the model can accurately simulate what has been observed in the field.

A model used in the early stages of a field study can help determine what data are most important, the amount of data necessary, and where the data should be collected. The model can also be used to improve the conceptual model and

our understanding of the hydrologic system. The calibration phase of the AEGIS technology demonstration in basalt also serves as a sensitivity analysis for ongoing data-gathering efforts.

As in the regional modeling effort, a detailed estimate of the recharge distribution was used to bound the transmissivity values of the deeper basalt systems. In the calibration process, two steady-state conditions or scenarios were used. The preman scenario simulated conditions that existed before man's influence. The second condition, called the current condition scenario, simulated present day conditions. Both scenarios used identical initial model input data with the exception of the recharge/discharge distribution.

The preman simulation was necessary to infer model-predicted water ages and the source for waters sampled from the Mabton unit at various DB wells. Data on total dissolved solids, other geochemical properties, and radioisotopic data presented in Gephart (1979a) have been used to infer water ages and general water movement patterns. In the model calibration process, an effort was made to match model-predicted water movement and age with the inferred water movement patterns and water ages based on field data. The inherent dangers (Bentley and Davis 1980) associated with inferred radiocarbon water dates were considered, especially in light of bicarbonate ground waters and the calcite precipitation (Gephart 1979a) that goes on within the Mabton unit. From the inferred water dates for the DB wells (11,000 to 23,000 yr), the water traveled along most of its path to its current site before man began influencing the hydrologic system, thus, the need for the preman scenario.

The current conditions scenario was used to match model-predicted potential distribution with the potential distribution inferred from the well data on water levels.

In model calibration or sensitivity study the procedure is somewhat the same. The model input parameters, model boundaries, boundary conditions, and portions of the conceptual model that are subject to dispute must be ranked according to the uncertainty associated with them. Reasonable ranges for this uncertainty must be identified. The next step is to investigate the importance of the uncertainty through an iterative series of model runs.

Table B.30 indicates our assessment of the areas of greatest uncertainty for the local model region. Most of these have been addressed in the model calibration-sensitivity results presented here. This table was prepared at the conclusion of this study and has been biased by the authors' knowledge of the results.

TABLE B.30. Subjective Assessment of the Areas of Uncertainty with Respect to the Available Hydrologic Modeling Parameters and the Hydrologic Model Presented in this Report

Area of Uncertainty	Layer (a)	Subjective Assessment of:			Estimate of Reasonable Range for the Parameter or Area of Uncertainty
		Quality of Information (b)	General Uncertainty (c)	Degree of Importance to Model Purpose (d)	
Vertical Hydraulic Conductivity	Al	4	2	1.5	Range for $K_v/K_h = 1.0-0.01$ Range for $K_v/K_h = 1.0-10^{-5}$ Range for $K_v/K_h = 1.0-10^{-5}$
	SM-WP	4.5	3	3	
	GR	5	3	3	
Effective Porosity	Al	3.5	2	1.5	0.05 - 0.2
	SM-WP	4.5	2	3	0.01 - 0.1
	GR	4.5	2	3	0.01 - 0.1
Storage Coefficient	Al	3 - 3.5	2	1	0.05 - 0.2
	SM-WP	4 - 4.5	3	1.5 - 2	0.1 - 10^{-5}
	GR	5	3	1.5 - 2	0.1 - 10^{-5}
Horizontal Hydraulic Conductivity	Al	2.5	1.5	1.5	$0.1-2 \times 10^5$ ft/day
	SM-WP	3.5	2.5 - 3	3	$0.01 - 10^2$ ft/day
	GR	4.5	2.5 - 3	3	$10^{-4} - 10^2$ ft/day
Hydrogeologic Structure or Geologic	AL-SM	2.5 - 3	1.5 - 2	2	
	WP	3	2	3	
	GR	4	2.5 - 3	3	
Potential Distribution	AL	2.5 - 3	1.5	2.5 - 3	
	SM-WP	3 - 3.5	2	3	
	GR	4 - 5	2.5 - 3	3	
Recharge and Pumping	All	2.5 - 3	1.5	3	$\pm 20\%$
Northern-North-Eastern Boundary and Boundary Conditions	All	2.5 - 3	1.5 - 2	2.5	
Southern-South-Eastern Boundary and Boundary Conditions	All	3 - 3.5	2	2.5 - 3	
Overall Conceptual Model of Hydrologic System	All	2.5 - 3	1.5 - 2	3	

(a) Layer designations are AL = Alluvium, SM = Saddle Mountains, WP = Wanapum, and GR = Grande Ronde.

(b) Quality of information is a subjective assessment based on the amount of available data and their general quality. A few good data points might be, for example, ranked the same as many poor data points. The ranking is on a scale of 1 to 5. 1 = excellent, 2 = good, 3 = probably satisfactory, 4 = poor, 5 = estimated or nonexistent.

(c) Subjective assessment of uncertainty on a scale of 1 to 3 and relative to this problem: 3 = highest degree of uncertainty, 2 = medium degree of uncertainty, 1 = lowest degree of uncertainty.

(d) Subjective assessment of the degree of importance of the parameter or area of uncertainty to the purpose of this modeling effort on a scale of 1 to 3: 3 = major importance, 2 = medium importance, 1 = minor importance.

When performing a calibration-sensitivity study for a first cut analysis the best estimates for the most certain parameters are used and the range for parameter values for the least certain parameters are investigated to narrow the range. Model calibration involves making use of the available data and an understanding of hydrology to control the manner in which the uncertain parameter ranges are searched. This is done to determine a value for that parameter or parameter distribution that maximizes the agreement between model predictions and observations.

As estimated in Table B.30 the first three parameter distributions (vertical hydraulic conductivity, effective porosity, and storage coefficient) are of poor quality. However, storage coefficient distribution is not used in this study because we are using a steady-state model and there is no time-dependent water level data to match. Effective porosity, while extremely important to model-predicted travel times, has no influence on model-predicted head distributions and flow paths, which is the primary measure of model calibration used in this study. There are Carbon-14 water dates, but "an error of 100% or more is likely" unless the flow system is understood and extensive corrections can be made (Bentley and Davis 1980). As a result, the Carbon-14 water dates, along with inferred water flow directions from other geochemical and water quality data, were only used in a qualitative sense as a measure of model calibration. Effective porosity data were addressed in sensitivity analysis runs once the model was calibrated. These data were not adjusted in the calibration process because: Carbon-14 water dates cannot be considered accurate to more than $\pm 100\%$; water flow directions are not influenced by porosity; the range of available porosity data is limited; and the equivalent porous medium effective porosity values calculated from the scanty data, as described above, are reasonable.

Because of the limited data available to measure model calibration quantitatively, only two parameter distributions were varied to achieve model calibration. These were the vertical hydraulic conductivity distribution and the horizontal hydraulic conductivity distribution. The effect of the uncertainty in the other parameters in Table B.30 and in the conceptual model itself was

addressed by further model sensitivity studies on the calibrated model, and by the following discussion, which is based on model responses observed during model calibration and sensitivity study.

The only quantitative measures of model calibration were the statistics on the level of agreement between model-predicted potential distribution and the inferred potential distribution for both the preman and current conditions scenario. Qualitative measures included the general agreement between model-predicted water flow paths for the preman scenario and those inferred from water quality data within the Mabton. Carbon-14 dates were used for comparison purposes only.

The principal model calibration parameter was the vertical hydraulic conductivity distribution. After a best estimate was determined for the vertical hydraulic conductivity distribution, some final iterations were performed, in which the horizontal hydraulic conductivity distribution was varied in conjunction with the vertical to obtain a better match with observed data. As stated by Mercer and Faust (1980), "no hard and fast rules exist to indicate when a satisfactory match is obtained." The number of runs required to produce a satisfactory match depends on the objectives of the analysis, the complexity of the flow system, and the length of the observed history system, as well as the patience of the hydrologist. Also, the quality of the match should be consistent with the quality and uncertainty of the input data.

Initial calibration runs assumed a constant K_v/K_h ratio for each model layer. Our calibration runs, made in the same way (i.e., by holding the K_v/K_h ratio constant on a layer by layer basis), indicated that a ratio of 0.01 produced the best match of the interpreted potential distributions. Our studies, however, showed the same trends as Rockwell with regards to overall level of potentials: the smaller the K_v/K_h ratio, the higher the potential levels predicted for the deeper basalts in the mid or discharging sections of the Pasco Basin. In addition, in the recharge areas of the upper basalt zones, the model-predicted potentials were too high.

Potential comparison statistics are shown in Table B.31 for two illustrative calibration runs of this type (Run 1 and Run 2). The comparison statistics

TABLE B.31. Summary of Comparison Statistics Between Model-Predicted Potential Distributions and the Potential Distributions Interpreted from Water Level Data for Four Illustrative Model Calibration Runs and the Base Case. (Comparisons are shown for both the current condition scenario and the preman scenario. All comparisons are in feet.)

Run Description	Scenario Description	Number of Positive Differences	Maximum Positive Difference	Average Positive Difference	Number of Negative Differences	Maximum Negative Difference	Average Negative Difference	Average Absolute Difference	Root Mean Square Difference
Run 1	Current Conditions	742	1454	66	1124	-674	-125	101	142
	Preman	778	1144	60	1088	-685	-119	94	133
Run 2	Current Conditions	1014	2965	135	852	-809	-148	141	214
	Preman	1060	2341	137	806	-733	-143	140	203
Run 3	Current Conditions	895	1021	75	971	-688	-133	105	134
	Preman	933	795	72	933	-698	-125	98	124
Run 4 (Base Case)	Current Conditions	991	948	100	875	-658	-135	116	135
	Preman	1050	735	95	816	-666	-125	108	119
Run 5	Current Conditions	995	627	87	871	-576	-122	103	112
	Preman	1066	971	96	800	-583	-118	106	118

relate how well the interpreted and predicted potential distributions compare for all modeled layers. Run 1 had the K_v/K_h ratio set at 0.1 in the alluvium and 0.01 in all basalt layers. Run 2 was the same in the alluvium, but the basalt ratios were 0.001. All the measures degenerate as the K_v/K_h ratio decreases.

There was a recognizable pattern. Even for Run 1 ($K_v/K_h = 0.01$), a problem occurred in the recharge areas. Model-predicted potentials in the upper basalt zones were considerably higher than interpreted. We needed justification for increasing the K_v/K_h ratio in the recharge zones. The following test from Apps et al. (1979) provided the justification.

Folding the faulting may affect groundwater flow in various ways. Newcomb generalized from this experience in the area that: 1) recharge may be facilitated where water-bearing rocks are brought near the surface and fractured; 2) tilting may control groundwater gradient; 3) lateral permeability may be reduced by gouge-filled fault zones, causing zones of confined water; 4) faulting and folding controls the shape of groundwater basins; and 5) deformation increases vertical circulation between zones (Newcomb 1969, p. 32; Newcomb et al. 1972). La Sala et al. (1973) found that sharp folds and faults may be barriers to lateral flow. Ledgerwood and Deju (1976, p. 26) found that the layers comprising the "uppermost confined aquifer" (from the lower Ringold Formation down to the Mabton Formation) appear to be connected along the Gable Mountain anticline axis. Some hydrologically significant folding is buried beneath sediments in the northern part of the Reservation (Ledgerwood and Deju 1976).

It is clear that deformation may result in vertical faults or fractures; whether such tectonically caused fractures act mainly to increase vertical permeability or to decrease horizontal permeability might depend on whether particular faults and tectonic joints are filled with gouge. Rockwell (1977) found mylonitic material at the surface in a shear zone at Wallula Gap. MacNish and Barker (1976)

attributed low transmissivities in the Horse Heaven Hills area to the effects of deformation, and generalized that fractures due to tight folding are likely to reduce groundwater flow, due to offsetting of permeable zones and plugging by pulverized rock.

The second observation from the initial sequence of model calibration runs (supported by subsequent model runs) was related to the equivalent porous media vertical hydraulic conductivities, K_v . Much higher K_v values were required to achieve a reasonable comparison between predicted and interpreted potential distributions than can be deduced by assuming a layered system with the lithology and permeabilities as measured in the field.

This problem of scale was alluded to earlier in the section on vertical hydraulic conductivity data. The layers of dense basalt or interbeds, when undisturbed, act as effective aquitards. Disturbed, however, they can become more permeable to make this layered basalt system more hydraulically connected in the vertical direction. Earlier, we pointed out that just a 44 ft² area of 1 ft/day permeability rock in every acre of completely impervious rock transmits water in an equivalent manner to a uniform 0.001 ft/day porous medium. According to Apps et al. (1979), these kinds of discontinuities are possible.

Due to the highly complex distribution of fractures, hydrologic continuity may exist across layers of different ages in certain areas. From a hydrologic point of view, such hydraulic continuity may have far greater importance than the geologic correlation of a single layer over long distances. Porous or fractured zones of various sorts--flow-top breccias, vertical and horizontal cooling joints, vesicular zones, and tectonically caused joints--control groundwater movement in the basalt and are likely to have considerable lateral variation (La Sala et al. 1973, p. 22; National Research Council 1978, p. 138-140).

The interbeds themselves may act more as barriers to groundwater movement than as conduits (Newcomb et al. 1972; National Research Council 1978, p. 140). La Sala et al. (1973, p. 22-23) found that most permeable zones in the basalt sequence to be not interbeds, but

fractured upper contacts of certain flows. Knowledge of exactly which types of rock contribute to deep flow could be improved in some cases by better correlation of hydrologic and lithologic data in deep holes (Piper 1975, p. 35-37).

This does not mean that basalt is not a good medium for storage; it simply means that these zones contributing to vertical hydraulic continuity need to be accounted for, particularly during the construction phase. These zones do not necessarily represent large areas, nor ones of extremely high permeability. In the above hypothetical example, only one-thousandth of the total area at a 1 ft/day permeability would give rise to the kind of composite vertical permeability indicated by the current regional and local modeling efforts presented in this study. These kind of zones need not significantly affect travel times because the effective porosity of the more porous interflow and interbed zones dominates total travel time. In a recent paper on "Hydrologic Issues in Repository Siting" Remson (1980) suggest pressure testing of each emplacement hole for repositories sited in low permeability, hard, rock-like granite or dense basalt.

Based on the hypothesis that vertical permeability should increase closer to an area of tight folding, the structural map of the top of the basalt and the top of the Grande Ronde was used to prepare the map shown in Figure B.52. The zones on this map were interpreted to represent zones of equal deformation, based on the changes in slope near the anticlines. Figure B.53 represents zones of equal deformation interpreted for the synclines. The zones are rated on a scale of 0 to 1, with zero representing no deformation. These maps only represent an interpretation based on structure maps and do not represent any field data on deformation or stresses. They allowed us to investigate the above hypothesis. If, as indicated in the earlier discussion from Apps, the horizontal permeability also decreases in deformation zones, then the K_v/K_h ratio should increase considerably.

The next series of model calibration runs were performed by assigning, on a layer by layer basis, a constant K_v/K_h ratio for each deformation class. In all these runs, the alluvium was held at a K_v/K_h ratio of 0.1. These runs

FIGURE B.52. Inferred Zones of Equideformation Associated with Anticlinal Structures Within the Local Model Area. (Scale is from 0 to 1 with 1 representing areas of greatest inferred deformation) (Photo No. 81B554-2)

FIGURE B.53. Inferred Zones of Equideformation Associated with Both Anticlinal and Synclinal Structures Within the Local Model Area. (Scale is from 0 to 1 with 1 representing areas of greatest inferred deformation). (Photo No 81B554-1)

indicated that somewhat better results were achieved when both anticlines and synclines were considered. Illustrative Run 3 represents the best run of this type. The statistics for the comparison between interpreted and predicted potential distributions are shown in Table B.31 along with the other illustrative run statistics. Figure B.54 illustrates the distribution of K_v/K_h ratio used in Run 3.

FIGURE B.54. Diagram Illustrating the Distribution of the K_v/K_h Ratio Used in Run 3

The calibration runs of this type did not produce the decrease in the average and rms error statistics we had hoped for. An examination of the K_V (equivalent porous medium) hydraulic conductivity distribution indicated that it was generally too high. Using a constant K_V/K_h relationship to set K_V , makes the assumption that K_V is correlated with K_h . One can convincingly argue that in a layered system, such as the basalts, this is not the case. In fact, the hypothesis above, related to a decreasing K_h and increasing K_V in deformation areas, is the complete opposite. In general, one would expect K_V to be controlled by discontinuities in the dense basalts and tight interbeds, because these layers act as aquitards. One would also expect these areas of discontinuity to be somewhat limited, and that K_h , the (equivalent porous medium) horizontal hydraulic conductivity, is controlled by the properties of the interflow zones and the more permeable interbed zones. Quite the opposite of K_V , relatively large connected areas of high permeability material are required to produce a high (equivalent porous medium) horizontal hydraulic conductivity.

In the next set of model calibration runs we no longer used the K_V/K_h ratio method except in the alluvium, which remained at a K_V/K_h ratio of 0.1. In this set of calibration runs, we set the K_V distribution directly. The initial runs of this type used values in our zero deformation zones of 0.0015 ft/day in the Saddle Mountains and Wanapum layers and 0.0012 ft/day in the Grande Ronde, because these numbers were consistent with the average values determined in the regional modeling. The best run of this class is listed as Run 4 in Table B.31, and the K_V distribution used is shown in Figure B.55. Whereas this class of calibration runs showed some improvements in the extremes, it was not markedly better in potential comparison statistics.

The very last set of calibration runs showed the most improvement in potential comparison statistics of the preceding two classes of model calibration runs. In this set of calibration runs we adjusted the K_h and K_V distributions according to an error map between predicted and interpreted potentials for each of the three basalt layers modeled. In low recharge areas we decreased K_h and K_V , and in high recharge areas we increased both. The potential comparison statistics for Run 5 are shown in Table B.31.

FIGURE B.55. Diagram Illustrating the K_y Distribution Used in Run 4.
(Values in key represent permeabilities in ft/day)

Whereas Run 5 showed a marked improvement in the potential comparisons, the majority of the increase was caused by improvement in areas away from good well data control. In the regional modeling we exercised the same caution by first matching to the interpreted potentials and finally to the actual well data. The potentials predicted by the model represent steady state and the interpreted potentials represent a transient state, which may not be in equilibrium with the current state of system recharge and pumping that was modeled. Given the current data on both the K_v and K_h distributions, as well as the head distribution in the deep basalts, and the purpose of this study, we considered the model calibrated at this point. Further calibration runs would not reduce the uncertainties.

Run 4 was selected as the base case for the following reasons:

- The model-predicted travel times from the repository to the biosphere and the predicted water dates for DB wells were similar for both Runs 4 and 5.
- The transmissivity distribution of Run 4 was consistent with that used in the regional modeling.
- The assignment of the K_v distribution is consistent with the hypothesis that K_v and K_h are not necessarily correlated in a layered system such as the basalts.
- Run 4 supports the hypothesis that as deformation zones are approached, K_v increases and K_h decreases.

Figures B.56 through B.60 illustrate the model-predicted potential distributions for the base case (Run 4) for the current conditions scenario for the potentials at the top of the alluvium, top of the Saddle Mountains, top of the Wanapum, top of the Grande Ronde, and base of the Grande Ronde formations, respectively. Figures B.61 through B.64 illustrate the model-predicted base case potential distributions for the preman scenario. (Alluvium is excluded because it is held everywhere within the model area and is the same for both cases.) Figure B.65 illustrates the location of the four representative cross-sections for which plots of the base case vertical potential distributions have been prepared for both the current conditions scenario and the preman scenario.

FIGURE B.56. Constant Head Boundary Conditions for the Top of the Alluvium Under Current Conditions Scenario. Heads are in feet above MSL.

FIGURE B.57. Model-Predicted Heads for the Base Case (Run 4) at the Top of the Saddle Mountains for the Current Conditions Scenario. Heads are in feet above MSL.

FIGURE B.58. Model-Predicted Heads for the Top of the Wanapum for the Base Case (Run 4) for the Current Conditions Scenario. Heads are in feet above MSL.

FIGURE B.59. Model Predicted Heads for the Top of the Grande Ronde for the Base Case (Run 4) for the Current Conditions Scenario. Heads are in feet above MSL.

FIGURE B.60. Model-Predicted Heads for the Base of the Grande Ronde for the Base Case (Run 4) for the Current Conditions Scenerio. Heads are in feet above MSL.

FIGURE B.61. Model-Predicted Heads for the Base Case (Run 4) at the Top of the Saddle Mountains for the Preman Conditions Scenario. Heads are in feet above MSL.

FIGURE B.62. Model-Predicted Heads for the Top of the Wanapum for the Base Case (Run 4) for the Preman Conditions Scenario. Heads are in feet above MSL.

FIGURE B.63. Model-Predicted Heads for the Top of the Grande Ronde for the Base Case (Run 4) for the Preman Conditions Scenario. Heads are in feet above MSL.

FIGURE B.64. Model-Predicted Heads for the Base of the Grande Ronde for the Base Case (Run 4) for the Current Conditions Scenario. Heads are in feet above MSL.

FIGURE B.65. Location of Four Representative Cross-Sections

Cross-section 1 is shown in Figure B.66 and cross-sections 2, 3, and 4 are shown in Figure B.67. Figures B.68 through B.70 are the plan view (X-Y), west-east cross-section (X-Z), and the south-north cross-section view (Y-Z), respectively, showing the model-predicted streamlines that were generated to determine the source and age of the Mabton basalt waters (the DB wells) for the calibrated (or base case) run with the preman stress conditions. Table B.32 illustrates the model-predicted water ages and sources for the Mabton waters for the base case along with observed Carbon-14 estimates of water age. Figures B.71 through B.73 show the same views as above, but the streamlines represent the path that water leaving a fractured repository would taken on its natural discharge site (for the base case under current conditions). Table B.33 shows the model-predicted travel times for water moving along the two streamlines shown in Figures B.71 through B.73 to migrate from a hypothetical repository at the -3100-ft level to the model-predicted natural discharge site in the Columbia River.

Hydraulic Head Comparisons

This section compares field-measured to model-predicted hydraulic heads and addresses how the heads within individual basalt formations compare at several wells within the local model region. A comparison of these heads provides an additional check on the accuracy of the model results.

Figure B.74 shows a comparison of head values at 14 wells within the local model region, as reported by Rockwell-Hanford (Gephart et al. 1979a, Staff BWIP 1980), to head values predicted by the local region flow model. The head values shown are for the water table, Rattlesnake Ridge Flow within the Saddle Mountains Basalt, and the Mabton Flow, which is at the top of the Wanapum Basalt sequence.

The water table was held in the local flow model; therefore, the model water table levels are very similar to the Rockwell values. The model-predicted water levels are in close agreement with the observed values within the Mabton Flow. The average difference at 10 wells where values are reported is 46 ft. The Rattlesnake Ridge Flow also shows a better comparison between observed and field data, with the average difference for five wells being 30 ft.

FIGURE B.66. Contour Plot Showing the Model-Predicted Vertical Potential Distribution (in feet) Along the Cross-Section 1A-1B for Both the Current Conditions Scenario and the Preman Scenario. Potentials are referenced to MSL and the contour spacing is 25 ft.

FIGURE B.67. Contour Plot Showing the Model-Predicted Vertical Potential Distribution (in feet) Along the Cross-Sections 2A-2B, 3A-3B, 4A-4B for Both the Current Conditions Scenario and the Preman Scenario. Potentials are referenced to MSL and the contour spacing is 25 ft.

FIGURE B.68. Plan View (X-Y) of Streamlines Flowing to the DB Wells

FIGURE B.69. East-West Cross-Section View (X-Z) of Streamlines Flowing to the DB Wells

FIGURE B.70. North-South Cross-Section View (Y-Z) of Streamlines Flowing to the DB Wells

TABLE B.32. Summary of the Comparisons Between Model-Predicted Water Dates for the DB Wells with Water Ages Interpreted from Mabton (Gephart et al. 1979a) Water Samples. (The results are shown for the base case--Run 4--as well as the four illustrative calibration runs. These predictions are made based on the preman scenario.)

Deep Basalt Well	Run Number	Model-Predicted Age (yr)	Distance Traveled (ft)	Average Water Velocity (ft/yr)	Source of Water
DB-1 (23000 yr)	1	1595	74330	47	R(a)
	2	1797	80520	45	R
	3	1562	74925	48	R
	4	1597	79754	50	R
	5	1417	79083	56	R
DB-2 (23000 yr)	1	1097	69322	63	R
	2	1310	70470	54	R
	3	1091	69403	64	R
	4	1156	69948	61	R
	5	1019	69715	68	R
DB-4 (18000 yr)	1	3222	38303	12	L(b)
	2	2870	97009	34	R
	3	3300	95861	29	R
	4	2908	96171	33	R
	5	2994	96295	32	R
DB-5 (19800 yr)	1	15277	98825	6	L
	2	4739	101670	21	R
	3	24332	10220	0.4	L
	4	5372	102183	19	R
	5	4992	102360	21	R
DB-7 (14400 yr)	1	2384	26782	11	L
	2	8338	134906	16	R
	3	2800	27489	10	L
	4	13188	142312	11	R
	5	14701	133656	9	R
DB-9 (11600 yr)	1	64582	141935	2	L
	2	5228	101873	19	R
	3	5321	17411	3	L
	4	6801	102390	15	R
	5	6508	99147	15	R

(a) R = Regional

(b) L = Local

Table B.32 (continued)

Deep Basalt Well	Run Number	Model-Predicted Age (yr)	Distance Traveled (ft)	Average Water Velocity (ft/yr)	Source of Water
DB-12 (13000)	1	5581	95206	17	L(a)
	2	5191	93569	18	L
	3	5257	89640	17	L
	4	9366	95676	10	L
	5	12447	100638	8	L
DB-14	1	1543	38599	25	L
	2	3280	67263	21	L
	3	1907	38208	20	L
	4	2503	43309	17	L
	5	2862	39439	14	L

(a) L = Local

TABLE B.33. Summary of Predicted Travel-Time Results from the Hypothetical Repository Site to the Natural Discharge Site for the Various Illustrative Calibration Runs and the Base Case (Run 4) for the Current Conditions Scenario. (Note that these average times and velocities are based on the analysis of only two streamlines.)

Run Number	Average Water Travel Time (yr)	Average Distance Traveled to Discharge or near Discharge Site (ft)	Average Water Velocity (ft/yr)
1	35769	26966	0.8
2(a)	--	--	--
3	40751	20870	0.5
4 (Base case)	15176	46575	3.0
5	14918	43994	3.0

(a) Results were not obtained because the hypothetical repository was too near a stagnation point.

FIGURE B.71. Plan View (X-Y) of Two Streamlines Originating at the Repository

FIGURE B.72. East-West Cross-Section View (X-Z) of Two Streamlines Originating at the Repository

FIGURE B.73. North-South Cross-Section View (Y-Z) of Two Streamlines Originating at the Repository

FIGURE B.74 . Comparison Between Model-Predicted and Observed Heads

A comparison of heads within the individual basalt layers at the 13 wells supports the model predictions. Twelve of the 13 wells show that head increases or stays the same with depth. Well DB-14, located close to Dry Creek, is the only site where the elevation of the unconfined water table is significantly greater than in the lower interbeds. The model predictions were similar, with DB-14 having the only declining head with depth. The amount of increase or decrease in head as predicted by the model was generally in agreement with the difference observed in the field (Figure B.74).

Additional hydraulic head data exists for wells ARH-DC-1 and RSH-1 (Figure B.40). National Research Council (1978, p. 162) has stated that the head DC-1 uses a little with depth. Raymond and Tillson (1968) and LaSala and Doty (1971) state that the head decreases with depth in DC-1. Gephart et al. (1979a) found that the heads increase slightly with depth, from 402 ft to 407 ft when going from about 250 ft to 1700 ft below sea level. The model results did not agree with the observed values. Instead, the model showed the head increasing with depth, from 435 ft of head at about 200 ft below sea level to about 495 ft of head at 1500 ft below sea level.

Measurements in deep hole RSH-1 (Raymond and Tillson 1968; LaSala and Doty 1971) showed a progressively decreasing head with depth. The model also showed a decrease in head with depth at well RSH-1.

Discussion of Conclusions on Hydrologic Modeling

This study has demonstrated the usefulness of ground-water modeling as a tool to aid the hydrologist in understanding a complex hydrologic system. The simulation results, while not providing a precise hydrologic model (data limited) for final prediction purposes, allow for approximate predictions required for an AEGIS technology demonstration. More importantly, ground-water modeling provides a tool that can assess various system conceptualizations and the sensitivity of approximate predictions to various field data. These model results should guide further data gathering and system characterization studies.

Much past work has been aimed at understanding and modeling (either conceptually or numerically) various parts of the geohydrologic system in the

Columbia Plateau Basalt. A summary review of these works can be found in Gephart (1979a, pp. II-4 and 5, III-18 through 21, and III-189 through 194). In addition to the hydrologic simulation presented here, other modeling efforts include development of a coarse grid model of the Columbia River Basalts by the USGS, and the development of a model of the Pasco Basin (Gephart 1979a; Staff BWIP 1979; Staff BWIP 1980) by RHO as part of the BWIP program.

The AEGIS basalt demonstration and understanding of the regional basalt hydrologic system was aided by discussions with USGS personnel. There is general agreement that the northern and eastern boundary of the Pasco Basin is a flow boundary, with the Pasco Basin receiving waters from the regional system. Some disagreement exists regarding the hydrologic description of the southern and western boundary. According to our understanding of the USGS model, the area corresponding to the southern and western Pasco Basin boundary is a groundwater divide (i.e., no flow boundary), the exact location of which is controlled by structure and recharge conditions. The AEGIS hydrologic simulation supports this type of boundary (with some exceptions that will be discussed in succeeding paragraphs). RHO suggest that this boundary in the southern part might act as a local discharge boundary (see Figure B.75), and that the western part may be receiving regional input from the west and northwest. (The AEGIS demonstration indicates that this needs further investigation.) All of the conceptual models indicate that the Pasco Basin is a discharge area. The differences regarding discharge within the Pasco Basin stem from a disagreement as to the exact location and character of the discharge area within the basin. In the RHO conceptual model of the Pasco Basin (Gephart et al. 1979a, p. III-199) the discharge areas are as follows:

"Major recharge and discharge occur only where the basalt formations are at or near ground level or makes contact with a surface water body; although the head of an aquifer may be above the heads in overlying aquifers or those in a river, no fluid transfer is assumed unless the systems are in physical contact; exceptions may occur when structural or stratigraphic complexities exist;..."

FIGURE B.75. Areas of Probable Recharge Contributions and Discharge Locations for Aquifers in the Wanapum and Grande Ronde Basalts (Gephart et al. 1979a)

A clear understanding of the character of the discharge areas in the USGS model is lacking, but the Columbia and Snake Rivers can receive discharge regardless of whether they are in contact with the basalts. The AEGIS concept of the discharge area encompasses both of the above and adds the alluvial aquifer systems that exist within the Pasco Basin. The USGS model, as we understand it, probably embraces this alluvial discharge because they discharge through the alluvial system to the Columbia and Snake Rivers. The difference between our conceptual model and the USGS model may only be related to model implementation. We believe that discharge occurs both where the basalts are in contact with the river or a surface water body (with appropriate gradients) and where the basalts are in contact with a saturated alluvial aquifer system (with appropriate gradients). We support these beliefs with the following reasons:

- The very existence of an alluvial aquifer system in highly permeable sediments in such an arid environment supports this discharge concept.
- Calculations indicate that under current conditions, little if any natural recharge occurs in the area of the low lying alluvial systems.
- Historical evidence supports the existence of the alluvial ground-water system before man-induced recharge supplied by Hanford Project Activities and wide-scale irrigation.
- A tremendous amount of flow system convergence would be required for discharge to occur only in areas where the basalt is in, or nearly in contact with surface water bodies.

Before continuing the above discussion regarding Pasco Basin boundaries and discharge we will need to discuss our water balance estimates, the inferred source of recharge to the basalts, and the agreement of these factors with observed and modeled transmissivity values. Our assessments of the regional model area indicated that 1,700,000 AF/yr recharged the basalts and 204,000 AF/yr were pumped from the basalts in the late 1960s. Given this estimated recharge/withdrawal distribution, the transmissivity distribution in the Saddle Mountain-Wanapum Basalts' layer required by the model to match the observed potentials was approximately three times higher on the average than

estimated from the available specific capacity data and the few true pump test data. It is not uncommon for model calibrated transmissivities to be greater than those inferred from measurements because wells seldom are fully penetrating or screened over the entire saturated thickness of the modeled unit. The transmissivity distribution required for the Grande Ronde was, on the average, about 60% of that required for the Saddle Mountain-Wanapum units. The above observations support our hypothesis that the source of recharge for the Columbia Plateau Basalts lies within the regional modeling area, which is contrary to the hypothesis "that very little recharge to the regional groundwater system occurs within the plateau itself" (Gephart et al. 1979a).

We observed the same kind of agreement in our local modeling effort (between our independently determined recharge distribution, interpreted transmissivity distribution, and regional model-dictated flow from the north and east) as was observed in the regional modeling effort. The PNL estimate of approximately 600,000 AF/yr discharge to the rivers within the Pasco Basin, however, disagrees with the Rockwell estimates of 2,700,000 AF/yr (Gephart et al. 1979a).

Our transmissivity values for the Pasco Basin are in the range of those supported by measurements and by long-term pumping experience elsewhere within the Columbia Plateau Basalt. Our indicated vertical permeabilities are on the high side compared to many of the estimates for dense basalt, although they are in the range with at least one other modeling effort (MacNish and Barker 1976). Our recharge estimates and all these independently determined distributions seem to balance and give a reasonable estimate of potential distributions. This set of observations gives us confidence in our analysis and also points out the usefulness of bracketing transmissivities with careful recharge estimates. Concerning the discrepancy in discharge estimates, we believe that our explanation regarding the necessary balance between transmissivities, flux, and gradients or potential distributions indicates that the 2,700,000 AF/yr is too high, especially in light of the model-supported regional recharge to the basalts estimate of only 1.7 million acre feet.

Our initial hydrologic analyses support the hypotheses:

- that the regional basalt ground-water system receives the great majority (if not all) of its recharge within the modeled area of the Columbia Plateau
- that transmissivity values for the Grande Ronde on a regional basis are roughly the same order of magnitude (approximately 40% less) as they are for the Saddle Mountains-Wanapum system
- that vertical permeabilities on the order of 0.001 ft/day, as required to obtain reasonable model calibration in both the regional and local modeling efforts, are reasonable for basalts over large regions.

The following discussion concerns the southern Horse Heavens Hills and western Rattlesnake Hills and Hog Ranch Axis boundaries, along with the question of discharge location and the character of the discharge area within the Pasco Basin. Many of the earlier studies (LaSala et al. 1973; Ledgerwood and Deju 1976; National Research Council 1978) conceptualize that the shallow basalt aquifer systems receive their recharge in the Rattlesnake Hills and Horse Heaven Hills areas. LaSala et al. (1973) also conclude that tight folding and faulting associated with the major topographic divides such as Rattlesnake Hills, Saddle Mountains, and the Horse Heaven Hills form a barrier to ground-water flow. Our ground-water modeling effort and the associated hydrologic analysis supports these earlier conceptual modeling efforts.

The hydrologic analysis and modeling efforts presented here support the hypothesis that the Rattlesnake anticline and the Hog Ranch Axis form a local and a regional ground-water divide. Because this is a structural and a recharge-related ground-water divide, the exact position of the divide may lie further to the west than modeled because of the asymmetry in the structure and the associated recharge. This boundary may shift somewhat with time because of changes in recharge and system stresses elsewhere within the system, but this is probably of little importance. The existence of this area as a recharge zone and ground-water divide is supported by:

- the existence of springs in the Rattlesnake Hills area
- lower ground-water potentials in the areas to the west and east of the divide
- decreasing ground-water potentials with depth
- field evidence that supports structurally related increases in vertical conductivity with coincident decreases in horizontal conductivity along with model support for this hypothesis
- actual increased precipitation and model-predicted recharge in sufficient quantities to support a ground-water divide.

The hydrologic analysis and modeling efforts presented here also indicate that the Saddle Mountains do not receive enough recharge to greatly affect potentials and probably only act as a permeability barrier that moderates flow into the basin from the regional system to the north.

Our analysis also indicates that the Horse Heavens Hills boundary to the south is a weak ground-water divide. Our preman modeling scenario appears to support this area as a divide in terms of recharge. Additionally, the tectonic deformation appears to have effectively reduced the horizontal permeabilities in proximity with the axial traces of the Red Mountain, Badger, and the Horse Heavens Hills anticlines. The impedance caused by the deformation may allow it to remain a divide, despite the current pumping in the southern part and the plans for increased irrigation development in the Horse Heaven Hills. Although our analysis and modeling point to its weakness as a continuing divide, the head controlling nature related to the direct contact of the basalts with the river in this southern part of the basin, coupled with the permeability barrier associated with the deformation induced by the anticlinal structures, seem to support a hypothesis that as long as a repository is sited in the northern part of the basin, this southern Horse Heaven Hills boundary uncertainty makes little difference.

The analysis presented in this report supports our model concept regarding the location and nature of the discharge area within the Pasco Basin. This concept supports both the saturated alluvial aquifer system and the rivers,

when in contact with basalts, as potential discharge areas when the gradients support discharge. The stronger flow from the regional system to the north and east is opposed by flow from the south and west, which results from the buildup in heads associated with the recharge and low permeability boundaries. These opposing flows form a northwest to southeast trough in the ground-water potentials west of the Columbia River. This balancing of opposing flows causes the heads to increase with depth in this central area of the basin, making vertical flow an important aspect of the hydrology in this area. The location of this balanced potential discharge area is sensitive to both the horizontal and vertical hydraulic conductivity distribution as well as recharge and stress conditions.

This distributed discharge and balanced potential concept can also explain the apparent discrepancy related to vertical movement and hydrochemical data, which indicate chemically distinct ground waters within the basalts (Gephart et al. 1979a; Staff BWIP 1980). Figure B.76 from Gephart et al. (1979a) and the following paragraph from page III-189 of the same document illustrate the Rockwell hypothesis regarding vertical communication:

"Hydrochemical data for ground water within the lower Saddle Mountains Basalt (Mabton interbed) and Grande Ronde Basalt beneath the Hanford Site are presented in Figure III-49.^(a) This figure illustrates the areal similarity in chemical type within and the major differences in chemical type between stratigraphic intervals. The distinct areal difference in chemical type suggests a lack of communication between aquifers of the Saddle Mountains and Grande Ronde Basalts."

Our distributed discharge area concept does not require large vertical fluxes at any given point in the system, but only slow vertical movement on the order of 0.004 cubic inches per square inch of vertical transfer area per day. This quantity of vertical flux when mixed with the higher horizontal fluxes of a layer would, we believe, result in undetectable changes in the water chemistry of the layer, and the changes that it does induce would be so areally distributed that they would not be associated with vertical movement.

(a) Figure B.76 of this report.

FIGURE B.76. Hydrochemical Facies Map for the Mabton Interbed and Grande Ronde Basalt Flow Systems (from Gephart et al. 1979a)

During the calibration studies, model-predicted sources of the water for some of the centrally located DB wells shifted between the regional and local model areas. For these same sensitivity studies the predicted discharge site for the hypothetical repository flow lines varied from the Columbia River east and somewhat south of Gable Mountain, to the Gable Mountain pond area, to the site in the Columbia River essentially north of the hypothetical repository (as predicted by the calibrated model). These same sensitivity studies also indicated a general consistency in model-predicted travel times (when the same porosity distribution was used). The minor variance is indicated in Table B.32.

These reference site initial hydrologic analysis studies indicate the following:

1. A better understanding of the nature of the vertical permeability within the basalt systems is needed. Vertical permeability data are needed on a large scale to assess potential vertical movement on the scale required for a ground-water modeling effort. We must also be able to assess what features (if any) give rise to the relatively large vertical permeabilities (compared to estimates for dense basalt) that were required for model calibration. There is a need to measure and understand the nature of the permeability (if any) in the dense basalts because (as indicated by Remson 1980) the appropriate pressure testing of emplacement holes in nearly impermeable hard rocks can greatly reduce the uncertainty associated with nuclear waste disposal.
2. Porosity measurements are required because little field data exist. We need field data to support the concept that horizontally conducting layers having high porosity act together with the low permeabilities of the low porosity dense basalt layers (these dense layers control vertical flux) to dominate travel time. The kind of field tracer tests required to verify this concept can also provide information on hydrodynamic dispersivity. The high storage coefficients estimated and observed in the basalts supports the relatively high range in porosity deduced for this initial assessment study.

3. Potential measurements deep within the Grande Ronde are needed to verify the boundary conditions and regional flow effects deduced through this study.
4. A collection of historical records of potentials, pumping, and irrigation data is needed to use history-matching techniques to model, adjust, and determine vertical and horizontal permeability distributions.
5. The measurement of recharge in the Rattlesnake Hills and Horse Heaven Hills area is needed to affirm or refute the character of these boundaries.
6. Further field evidence regarding the deformation-induced decreased horizontal and increased vertical permeability is necessary as the axis of an anticline (and any deformation zones associated with synclines) is approached.

In summary, the site characterization studies conducted by BWIP have provided us with more data than we have had in the previous reference site assessment studies performed. This does not imply that all the data necessary for a complete licensing assessment are currently available. Further data gathering as outlined above and further sensitivity studies to investigate the effects of repository heating on the predicted flow paths and travel times and to investigate the disappearance of the Horse Heaven Hills boundary.

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APPENDIX C

SCENARIO CALCULATIONS

SCENARIO CALCULATIONS

INCREASED RECHARGE SCENARIO

Assumptions

- 1) Hydraulic conductivity of Umtanum unit = 3.048×10^{-7} m/day
- 2) Thickness of Umtanum unit = 82 m
- 3) Hydraulic head differential = $\Delta H = 10$ m

Calculations

$$Q = AK \frac{\Delta H}{\Delta L} \quad (C.1)$$

K = hydraulic conductivity

A = unit cross-sectional area (1 km^2)

ΔH = hydraulic head differential

ΔL = flow pathlength

Therefore:

for $\Delta H = 10$ m

$$\begin{aligned} Q &= (3.048 \times 10^{-7} \text{ m/day})(10^6 \text{ m}^2) \frac{10 \text{ m}}{82 \text{ m}} \\ &= 0.037 \text{ m}^3/\text{day}/\text{km}^2 \end{aligned}$$

FAULT INTERSECTION SCENARIO

Assumptions

1. Unit length of fault zone in repository = 1 km
2. Effective width of fault zone = 2 m
3. Hydraulic conductivity of fault zone = 0.02 m/day
4. Hydraulic head differential = 2 m, 10 m
5. Repository horizon thickness = 82 m
6. Flow volume through repository horizon given by equation (C.1); i.e.,

$$Q = AK \frac{\Delta H}{\Delta L}$$

where

Q = flow volume

A = unit cross-sectional area of fault zone through repository horizon (1 km^2)

K = hydraulic conductivity of fault zone

ΔH = hydraulic head differential between aquifer systems

ΔL = pathlength through repository horizon assuming 30° fault dip

Calculations

if, $\Delta H = 2 \text{ m}$
 $Q = (2,000 \text{ m}^2)(0.02 \text{ m/day})(2 \text{ m}/164 \text{ m})$
 $Q = 0.488 \text{ m}^3/\text{day}$ per km of fault length for 2-m-wide fault zone

or, $Q = 244 \text{ m}^3/\text{day}/\text{km}^2$ of fault rupture area

if, $\Delta H = 10 \text{ m}$
 $Q = (2,000 \text{ m}^2)(0.02 \text{ m/day})(10 \text{ m}/164 \text{ m})$
 $Q = 2.44 \text{ m}^3/\text{day}$ per km of fault length for 2-m-wide fault zone

or, $Q = 1220 \text{ m}^3/\text{day}/\text{km}^2$ of fault rupture area

WEIGHTED AVERAGE CALCULATION

<u>Rock Type</u>	<u>Percent of Section</u>	<u>K (ft/day)</u>	<u>Weight Factor (Based on % of Section) (F_w)</u>	<u>$F_w \times K$</u>
Dense basalt	59	0.003	10	0.030
Vesicular basalt	12	0.008	2	0.016
Basalt - weathered, fractured, brecciated	23	0.08	4	0.320
Other	6	0.003	<u>1</u>	<u>0.003</u>
			$\Sigma 17$	$\Sigma 0.369$

Average = $0.369/17$
= 0.02171 ft/day
= 0.0066 m/day

Average K = 0.007 m/day

ROCK FRACTURING SCENARIO CALCULATION

Assumptions

1. Hydraulic conductivity of disrupted zone = 0.007 m/day
2. Hydraulic head differential = 2 m, 10 m
3. Repository horizon thickness = 82 m
4. Ground-water flow volume through repository horizon is given by Equation (C.1)

$$Q = AK \frac{\Delta H}{\Delta L}$$

where

Q = flow volume

A = unit area of disrupted zone (1 km^2)

K = average hydraulic conductivity of disrupted zone

ΔH = hydraulic head differential between upper and lower aquifer systems

ΔL = pathlength through repository horizon

Calculations

if, $\Delta H = 2 \text{ m}$

$$Q = (10^6 \text{ m}^2)(0.007 \text{ m/day}) \frac{2 \text{ m}}{82 \text{ m}}$$

$$Q = 171 \text{ m}^3/\text{day}/\text{km}^2 \text{ of disrupted area}$$

and,

if, $\Delta H = 10 \text{ m}$

$$Q = (10^6 \text{ m}^2)(0.007 \text{ m/day}) \frac{10 \text{ m}}{82 \text{ m}}$$

$$Q = 854 \text{ m}^3/\text{day}/\text{km}^2$$

BOREHOLE PENETRATION SCENARIO

Equation Derivation

The well-known Thiem equation in simplified form is:

$$Q = \frac{2\pi T(h-h_w)}{\ln(r/r_w)} \quad (C.2)$$

where

Q = flow rate

T = transmissivity

h = height of potentiometric surface at distance, r , from well

h_w = height of water in well of radius r_w

This equation can be applied to the steady-state exchange of water between two aquifers penetrated by the same well and having different transmissivities and potentiometric surfaces. The flow Q_L from a lower aquifer becomes Q_u upon entering the upper aquifer. Then,

$$Q_L = -Q_u = |Q| = Q$$

The lower aquifer has a transmissivity of T_L and the upper aquifer of T_u . At some distance r_L and r_u for the lower and upper aquifers, respectively, the heights of the potentiometric surfaces will be unaffected by aquifer discharge and will be h_L and h_u , respectively. The height of the water in the well, h_w , will be common for both aquifers and will be a function of their transmissivities and potentiometric surfaces.

Assuming that h_L is greater than h_u and representing the head difference by Δh ,

$$Q_L = \frac{2\pi T_L (h_L - h_w)}{\ln(r/r_w)}$$

$$Q_u = \frac{2\pi T_u (h_u - h_w)}{\ln(r/r_w)}$$

$$h_L - h_w = \frac{Q_L \ln(r_L/r_w)}{2\pi T_L}$$

$$h_u - h_w = \frac{Q_u \ln(r_u/r_w)}{2\pi T_u}$$

$$h_w = h_L - \frac{Q_L \ln(r_L/r_w)}{2\pi T_L}$$

and

$$h_w = h_u - \frac{Q_u \ln(r_u/r_w)}{2\pi T_u}$$

so

$$h_L - \frac{Q_L \ln(r_L/r_w)}{2\pi T_L} = h_u - \frac{Q_u \ln(r_u/r_w)}{2\pi T_u}$$

but

$$Q_L = Q_u = |Q| = Q$$

so

$$h_L - h_u = \frac{Q \ln(r_L/r_w)}{2\pi T_L} + \frac{Q \ln(r_u/r_w)}{2\pi T_u}$$

or

$$\Delta h = \frac{Q}{2\pi} \frac{\ln(r_L/r_w)}{T_L} + \frac{\ln(r_u/r_w)}{T_u}$$

$$\frac{2\pi\Delta h}{Q} = \frac{\ln(r_L/r_w)}{T_L} + \frac{\ln(r_u/r_w)}{T_u}$$

$$\frac{2\pi\Delta h}{Q} = \frac{T_u \ln r_L - T_u \ln r_w + T_L \ln r_u - T_L \ln r_w}{T_L T_u}$$

Assuming $r_L \approx r_u = R$ = radius of influence in both aquifers

$$\frac{2\pi\Delta h}{Q} = \frac{T_u \ln R - T_u \ln r_w + T_L \ln R - T_L \ln r_w}{T_L T_u}$$

$$\frac{2\pi\Delta h}{Q} = \frac{(T_u + T_L)(\ln R) - (T_u + T_L)(\ln r_w)}{T_L T_u}$$

$$\frac{2\pi\Delta h}{Q} = \frac{(T_u + T_L)(\ln R - \ln r_w)}{T_L T_u} = \frac{(T_u + T_L) \ln(R/r_w)}{T_L T_u}$$

$$\frac{2\pi\Delta h}{Q \ln(R/r_w)} = \frac{T_u + T_L}{T_L T_u}$$

or, factoring

$$\frac{2\pi\Delta h}{Q \ln(R/r_w)} = \frac{T_u}{T_L T_u} \frac{1 + T_L}{T_u}$$

$$Q = \frac{2\pi T_L}{\ln(R/r_w)} \cdot \frac{\Delta h}{1 + T_L/T_u} \quad (C.3)$$

or

$$Q = \frac{2\pi T_u}{\ln(R/r_w)} \cdot \frac{h}{1 + T_u/T_L} \quad (C.4)$$

Average Hydraulic Conductivity of the Saddle Mountains Formation and the Wanapum Formation Penetrated by Well ARH-DC-1 (Data from LaSala and Doty 1971)

	Thickness, t (ft)	Hydraulic Conductivity, k_h (ft/day)	Transmissivity, T (ft ² /day)
<u>Saddle Mountains Formation</u>			
Dense basalt	425	0.03	12.75
Fractured, weathered, or brecciated basalt	15	0.03	0.45
Sand, gravel, clay	<u>330</u>	2.0	<u>660</u>
Totals	770		673.2
<u>Wanapum Formation</u>			
Dense basalt	855	0.002	1.71
Vesicular basalt	25	0.007	0.18
Fractured, weathered, or brecciated basalt	105	0.09	9.45
Tuff	220	0.01	2.20
Sand, gravel, clay	<u>85</u>	1	<u>85</u>
Totals	<u>1290</u>		<u>98.54</u>
	2060		771.74
Saddle Mountains Fm.T + Wanapum Fm.T =	673.2 ft ² /day + 98.54		
771.74 ft ² /day			

Saddle Mountains Fm. thickness	770.0 ft
+ Wanapum Fm. thickness =	<u>1290.0</u>
	2060.0 ft

The average hydraulic conductivity is:

$$\begin{aligned} K_{\text{have}} &= T/t \\ &= \frac{771.74 \text{ ft}^2/\text{day}}{2060 \text{ ft}} \\ &= 0.3746 \text{ ft/day} \\ &= 1.14 \times 10^{-1} \text{ m/day} \end{aligned}$$

Average Hydraulic Conductivity of the Grande Ronde Formation Penetrated Well ARH-DC-1 (Data from LaSala and Doty 1971)

	Thickness, t (ft)	Hydraulic Conductivity, k_h (ft/day)	Transmissivity, T (ft ² /day)
Dense basalt	1420	0.003	4.26
Vesicular basalt	270	0.008	2.16
Fractured, weathered, or brecciated basalt	505	0.08	40.4
Tuff	105	0.003	0.32
Sand, gravel, clay	<u>35</u>	<u>0.003</u>	<u>0.11</u>
Totals	2335		47.25

$$\text{Average } K_h = \frac{47.25 \text{ ft}^2/\text{day}}{2335 \text{ ft}} = 0.0202 \text{ ft/day}$$

Transmissivity of the Lower Aquifer System (T_2)

$$T_L = K_h \times \text{thickness}$$

$$K_h = 6.2 \times 10^{-3} \text{ m/day (from Grande Ronde calculation above)}$$

thickness = 510 m (from ARHCO 1976)

$$T_1 = (6.2 \times 10^{-3} \text{ m/day})(510 \text{ m}) = 3.162 \text{ m}^2/\text{day}$$

Transmissivity of the Upper Aquifer System (T_1)

The upper aquifer system includes 173 m of the Saddle Mountain Formation, 340 m of the Wanapum Formation, and 265 m of the Grande Ronde Formation.

The average K_h for the Saddle Mountains Formation and Wanapum Formation = 1.14×10^{-1} m/day (from previous page).

Thickness of Saddle Mountains Fm. and Wanapum Fm. = 173 m
(ARHCO 1976) + 340 m
513 m

Therefore, the transmissivity of the Saddle Mountains Formation and Wanapum Formation portion of the upper aquifer system is:

$$(1.14 \times 10^{-1} \text{ m/day})(513 \text{ m}) = 58.48 \text{ m}^2/\text{day}$$

Transmissivity of the Grande Ronde Formation portion of the upper aquifer system is:

$$(6.2 \times 10^{-3} \text{ m/day})(265 \text{ m}) = 1.64 \text{ m}^2/\text{day}$$

Therefore,

$$T_u = (58.48 \text{ m}^2/\text{day}) + (1.64 \text{ m}^2/\text{day}) = 60.12 \text{ m}^2/\text{day}$$

Data

The diameter of the drill bit used on Well ARH-DC-1 was 9-7/8 in. However, the bore of the well became considerably eroded during drilling operations (LaSala and Doty 1971, p. 4). Therefore, a radius (r_w) of 5 in. was used (5 in. = 0.127 m).

$\Delta h = 2$ m (ARHCO 1976, p. 88) or 10 m under conditions of the increased recharge scenario.

Gephart et al. (1979 p. 39) estimated the radius of influence for deep basalts in the Well RSH-1 as approximately 1 m. Their estimate was used here.

Transmissivity of the lower and upper aquifer systems was calculated from data taken from LaSala and Doty (1971), ARHCO (1976), and Gephart et al. (1979). The calculations are shown on previous pages.

Calculation of Flow Rate (Q)

Present Hydrologic Conditions, $\Delta h = 2$ m

$$Q = \frac{2\pi T_L}{\ln(R/r_w)} \cdot \frac{\Delta h}{1 + T_L/T_u} \text{ (Derived from Theim equation in earlier section).}$$

$$Q = \frac{(2)(\pi)3.162 \text{ m}^2/\text{day}}{\ln(1\text{m}/0.127 \text{ m})} \cdot \frac{2 \text{ m}}{1 + 3.162 \text{ m}^2/\text{day}/60.12 \text{ m}^2/\text{day}}$$

$$Q = 18.293 \text{ m}^3/\text{day}$$

Increased Recharge $\Delta h = 10 \text{ m}$

$$Q = \frac{2\pi T_L}{\ln(R/r_w)} \cdot \frac{\Delta h}{1 + T_L/T_u}$$

$$Q = \frac{(2)(\pi)3.162 \text{ m}^2/\text{day}}{\ln(1 \text{ m}/0.127 \text{ m})} \cdot \frac{10 \text{ m}}{1 + 3.162 \text{ m}^2/\text{day}/60.12 \text{ m}^2/\text{day}}$$

$$Q = 91.465 \text{ m}^3/\text{day}$$

BASE CASE GROUND-WATER FLOW

Assumptions

- 1) Hydraulic conductivity of Umtanum unit = $0.048 \times 10^{-7} \text{ m/day}$
- 2) Thickness of Umtanum unit = 82 m
- 3) Hydraulic head differential = Q, 2, 5.49, 5.18 m
- 4) Flow rate can be calculated from

$$Q = KA \frac{\Delta H}{\Delta L}$$

Calculations

A = unit cross-sectional area (1 km^2)

K = hydraulic conductivity

ΔH = hydraulic head differential

ΔL = flow pathlength

Therefore,

for $\Delta H = 0 \text{ m}$, $Q = 0$

for $\Delta H = 2 \text{ m}$

$$\begin{aligned} Q &= (3.048 \times 10^{-7} \text{ m/day})(10^6 \text{ m}^2) \frac{2 \text{ m}}{82 \text{ m}} \\ &= 0.007 \text{ m}^3/\text{day}/\text{km}^2 \end{aligned}$$

for

$$\Delta H = 5.49 \text{ m}$$

$$Q = (3.048 \times 10^{-7} \text{ m/day}) (10^6 \text{ m}^2) \frac{5.59 \text{ m}}{82 \text{ m}}$$
$$= 0.020 \text{ m}^3/\text{day}/\text{km}^2$$

for

$$\Delta H = 5.18 \text{ m}$$

$$Q = (3.048 \times 10^{-7} \text{ m/day}) (10^6 \text{ m}^2) \frac{5.18 \text{ m}}{82 \text{ m}}$$
$$Q = 0.019 \text{ m}^3/\text{day}/\text{km}^2$$

APPENDIX C - REFERENCES

- ARHCO. 1976. Preliminary Feasibility Study on Storage of Radioactive Wastes in Columbia River Basalts. ARH-St-137, v. 1, Atlantic Richfield Hanford Company, Richland, Washington.
- Gephart, R. E., et al. 1979. Hydrologic Studies Within the Columbia Plateau Washington. An Integration of Current Knowledge. RHO-BWI-ST-5, Rockwell Hanford Operations, Richland, Washington.
- LaSala, A. M., Jr., and G. C. Doty. 1971. Preliminary Evaluation of Hydrologic Factors Related to Radioactive Waste Storage in Basaltic Rocks at the Hanford Reservation, Washington. U.S. Geological Survey Open File Report No. 71-180, Tacoma, Washington.

APPENDIX D

EQUIVALENT POROUS MEDIA PROPERTIES

EQUIVALENT POROUS MEDIA HYDRAULIC PROPERTIES
OF A GIVEN HYDROGEOLOGIC UNIT CONSISTING OF
SUBLAYERS OF VARIABLE GEOLOGIC MATERIALS

In regional and subregional ground-water simulation, the major hydrogeologic units are primarily considered. Each of these hydrologic units normally consist of discontinuous sublayers of variable permeability and porosity. The equivalent hydraulic properties of these composite hydrogeologic units are estimated from the properties of the included sublayers. The methods of property estimation and the overall effect on travel time of each sublayer is described below. The illustrative calculations for each parameter are done using the data of Table D.1.

TABLE D.1. Illustrative Saddle Mountain Basalt
Data Used in Sample Estimations

Sublayer	Fractional Thickness <u>d</u>	Hydraulic Conductivity		Porosity <u>b</u>
		Horizontal <u>K_h (ft/day)</u>	Vertical <u>k_v (ft/day)</u>	
Dense Basalt	0.6	1.0×10^{-6}	1.0×10^{-6}	0.006
Interbed	0.2	10.0	10.0	0.105
Interflow	0.2	10.0	10.0	0.200

EQUIVALENT POROUS MEDIA HORIZONTAL HYDRAULIC CONDUCTIVITY K_h

The equivalent horizontal conductivity K_h (Figure D.1) for a given hydrogeologic unit is estimated by using the thickness-weighted conductivity of each layer:

$$K_h = \Sigma (k_{hi} d_i) / D \quad (D.1)$$

where

k_{hi} = horizontal hydraulic conductivity of the i^{th} layer (L/t)

d_i = thickness of the i^{th} layer (L)

D = total thickness (Σd_i) of the hydrogeologic unit (L)

FIGURE D.1. Schematic Representation of a Horizontally Layered System with Different Conductivities and Thicknesses

Using the above relationship and the data from Table D.1, the estimated K_h is

$$k_h = (10^{-6} \times 0.6) + (10 \times 0.2) + (10 \times 0.2) = 4 \text{ ft/day}$$

EQUIVALENT POROUS MEDIA VERTICAL HYDRAULIC CONDUCTIVITY K_v

The equivalent vertical hydraulic conductivity (K_v) in a given hydrogeologic unit is calculated using analogous principles of electric resistance in series. Resistance (r) per unit thickness is the inverse of hydraulic conductivity:

$$r_i = 1/k_{vi} \quad (\text{D.2})$$

where

k_{vi} = vertical hydraulic conductivity of the i^{th} layer (L/t) and the total resistance of each layer is $d_i r_i$ or d_i/k_{vi} . The equivalent vertical conductivity, K_v is given by:

$$K_v = D/(\sum d_i/k_{vi}) \quad (\text{D.3})$$

Using the data from Table D.1, the equivalent K_v for the Saddle Mountain Basalt is

$$\begin{aligned} K_v &= 1.0 / (0.6/10^{-6} + 0.2/10.0 + 0.2/10.0) \\ &= 1.66 \times 10^{-6} \text{ ft/day} \end{aligned}$$

EQUIVALENT POROSITY OF A GIVEN HYDROGEOLOGIC UNIT

The equivalent porosity (P) for a given hydrogeologic unit is estimated by weighting the porosity of each sublayer by the layer thickness:

$$P = \Sigma(d_i p_i) / D \quad (D.4)$$

where

p_i = porosity of the i^{th} layer.

The equivalent porosity of the Saddle Mountain Basalt is

$$P = 0.6 \times 0.01 + 0.2 \times 0.105 + 0.2 \times 0.2 = 0.067$$

TRAVEL TIME IN EACH SUBLAYER OF A COMPOSITE HYDROGEOLOGIC UNIT FOR A GIVEN RATE OF DARCIAN FLOW

The above discussion addresses the estimation of equivalent hydraulic conductivity (horizontal and vertical) and porosity of a hydrogeologic unit having sublayers of variable hydraulic properties. In the simulation of regional and subregional ground-water flow, the equivalent values describe the distribution of hydraulic head (driving force) throughout the entire system. In travel time estimation, the individual sublayers are not considered and the resultant travel rate is an average for the whole unit.

For theoretical purposes, the time taken by a water particle to traverse a hydrogeologic unit under a given Darcian flow rate is examined below. It is again stressed that the sublayers of a given hydrogeologic unit, though identified separately, are not continuous. As previously illustrated, vertical flow is primarily governed by the sublayer with the lowest hydraulic conductivity.

The Darcian vertical flow, Q_v , is a function of the hydraulic head difference between the top and the base of the composite hydrogeologic unit and its equivalent vertical hydraulic conductivity. Over a given vertical section of a hydrogeologic unit, Q_v will be constant. The pore water velocity (v_i) in sublayer i is obtained by dividing the flow rate by the porosity of the sublayer:

$$v_i = Q_v / p_i \quad (D.5)$$

From Equation (D.5) it is evident that for a given Q_v , v_i decreases as p_i increases. Based on the data from Table D.1, the water particle travel velocity in each sublayer is:

<u>Sublayer</u>	<u>Porosity</u>	<u>Pore Water Velocity (v_i)</u>
Dense Basalt	0.01	Q_v 100 ft/day
Interflow	0.105	Q_v 9.52 ft/day
Interbed	0.2	Q_v 5.00 ft/day

Considering the fractional thickness of each sublayer (dense basalt, interflow, and interbed) the time taken by a water particle to traverse each submaterial is:

Dense basalt	$0.6 D/Q_v \times 100 = 0.006 \times (D/Q_v)$ days
Interflow	$0.2 D/Q_v \times 9.52 = 0.021 \times (D/Q_v)$ days
Interbed	$0.2 D/Q_v \times 5.00 = 0.40 \times (D/Q_v)$ days

For a given D and Q_v the fractional time spent by a water particle in each sublayer is approximately 9%, 31%, and 60% for dense basalt, interflow, and interbed zones, respectively. In this type of layered system, horizontally conducting layers with high porosity (interflow-interbed) act together with the low permeabilities of the low porosity (dense basalt) layers to control vertical flux and to dominate travel time.

APPENDIX E

ANALYTICAL GEOCHEMISTRY DATA AND CALCULATED DISEQUILIBRIUM INDICES

ANALYTICAL GEOCHEMISTRY DATA AND
CALCULATED DISEQUILIBRIUM INDICES

To provide a link between the modeling results and the data source, Table E.1 to E.4 equate the modeling number for each analysis used in this study with the water sample number assigned in the original reference. The measured pH values, calculated cation/anion balances, and the calculated disequilibrium indices (log AP/K) for selected minerals and amorphous compounds are also included.

TABLE E.1. Calculated Disequilibrium Indices
(LaSala et al. 1973, Table 1)

Modeling Number	Sample Number	pH	Cation/ Anion Balance %	Log AP/K					
				Calcite	Dolomite	Sepiolite	SiO ₂ (A,qf)	Allophane	Gibbsite
5050	11P1	8.1	+0.0	-0.27	-0.69	-1.22	0.00		
5051	15J1	7.9	+0.3	-0.43	-1.02	-1.82	+0.04		
5053	34H1	9.0	-1.0	-0.01	-0.77	+0.91	+0.10	-0.03	-0.21
5054	13H1	8.6	+0.5	-0.19	-0.71	-0.68	0.00	+0.21	-0.17
5055	34R1	8.8	+0.3	-0.46			+0.09	+0.76	+0.55
5057	25E1	8.0	+0.6	+0.08	+0.21	-0.02	-0.01	+0.76	+0.72
5058	30G1	8.1	+1.2	+0.16	+0.34	-0.37	-0.04	+0.43	+0.46
5059	35H1	8.6	+0.2	-0.24	-1.09	-1.29	-0.07	+0.69	+0.36
5060	13N1	8.6	-0.7	-0.66	-1.33	-0.15	+0.01	-0.30	-0.37
5061	36J1	8.8	-0.9	+0.01	-0.73	+0.26	+0.05		
5063	3J1	8.2	+0.4	-0.16	-0.29	-0.22	+0.03		

TABLE E.2. Calculated Disequilibrium Indices
(LaSala and Doty 1971, Table 7)

Modeling Number	Sample Number	pH	Cation/ Anion Balance %	Log AP/K					
				Calcite	Dolomite	Sepiolite	SiO ₂ (A,gl)	Allophane	Gibbsite
5265	362-712	8.5	+2.0	-0.28	-1.15	-1.29	-0.04	+1.25	+1.15
5266	362-890	9.6	-0.5	+0.41	+0.40	+3.17	-0.07	+0.19	-0.11
5267	362-1190	9.6	+0.5	+0.39	-0.32	+1.45	+0.02		
5268	362-2242	9.6	-0.4	+0.50	-0.08	+2.16	-0.07	-1.17	-0.05
5269	450-530	8.9	-0.2	+0.01	-0.58	-0.32	-0.21	+0.26	-0.03
5270	540-620	8.6	-0.1	-0.20	-0.98	-1.09	-0.11	+0.40	+0.21
5271	636-726	8.9	+0.1	-0.03	-0.41	+0.49	-0.05	+0.16	-0.09
5272	720-810	9.3	-0.5	-0.04	-0.15	+3.10	+0.04	+0.28	
5273	980-1120	9.7	+0.8	+0.04	+0.02	+3.70	-0.05		
5274	1090-1280	10.5	+8.8	+0.83	+0.18	+4.06	-0.59	-0.65	-0.79
5275	3146-3236	10.1	-1.8	+0.08			-0.62	-2.00	-1.16
5276	3166-3196	9.8	-0.2	+0.04	-0.39	+3.38	-0.32	-1.60	-0.82
5277	3206-3246	9.7	-1.2	-0.02	-0.44	+1.35	-0.36	-1.63	-0.81

TABLE E.3. Calculated Disequilibrium Indices
(Van Denburgh and Santos 1965, pp. 40-91)

Modeling Number	Sample Number	pH	Cation/ Anion Balance %	Log AP/K			SiO ₂ (A,gl)
				Calcite	Dolomite	Sepiolite	
5185	20	7.7	-2.7	-0.28	-0.99	-2.16	+0.08
5186	21	7.5	-1.0	-0.46	-1.18	-3.17	+0.03
5187	22	7.8	-1.0	-0.24	-0.70	-2.10	+0.01
5188	24	7.7	+5.7	-0.03	-0.12	-1.25	+0.02
5189	25	9.2	+6.0	+0.53	+0.89	+1.83	-0.48
5190	30	7.9	-2.0	+0.12	-0.12	-1.22	-0.02
5191	39	7.8	+0.0	-0.08	-0.09	-0.56	+0.06
5192	49	7.8	-1.3	-0.10	-0.21	-0.93	+0.07
5193	41	7.7	-0.1	-0.22	-0.41	-1.12	+0.07
5194	42	7.6	+0.7	-0.46	-0.93	-2.37	-0.12
5195	44	7.8	+0.4	-0.08	-0.14	-0.58	-0.00
5199	92	8.1	+2.2	+0.08	+0.11	-0.22	+0.01
5201	93	7.7	+1.1	+0.17	+0.04	-2.05	+0.08
5202	94	8.2	+0.4	-0.13	-0.34	-0.58	+0.03
5204	96	8.0	-5.4	-0.31	-0.70	-0.54	+0.14
5205	97	7.8	+2.4	-0.26	-0.68	-2.03	+0.02
5207	99	8.0	-2.7	-0.15	-2.82	-5.46	+0.23
5208	100	8.0	-2.7	-0.14	-0.28	-0.65	+0.11
5217	101	7.9	+0.2	+0.68	+1.39	+0.01	-0.03
5218	102	7.7	+4.1	+0.05	-0.14	-2.34	-0.21
5219	103	8.0	+3.6	+0.07	+0.09	-0.54	-0.00
5221	104	7.9	+1.0	-0.07	-0.27	-0.95	-0.01
5279	4	8.2	-2.2	-1.26	-0.83	-1.06	+0.17
5280	5	8.1	-0.5	-0.41	-0.87	-1.85	-0.12
5281	6	8.6	-1.2	-0.16	-0.64	+0.06	+0.04
5282	7	7.9	-1.8	-0.34	-0.40	-0.60	+0.06
5283	8	8.2	+1.1	-0.21	-0.17	-0.10	-0.05
5284	9	8	+0.1	-0.23	-0.70	-1.84	-0.08

Table E.3 (continued)

Modeling Number	Sample Number	pH	Cation/ Anion Balance %	Log AP/K			SiO ₂ (A,gl)
				Calcite	Dolomite	Sepiolite	
5285	10	8.0	-1.2	-0.18	-0.33	-1.37	-0.12
5286	11	8.1	-2.3	-0.10	-0.29	-1.39	-0.19
5287	12	7.8	-0.6	-0.05	-0.73	-2.76	-0.07
5288	13	8.0	-1.4	-0.04	-0.27	-1.32	-0.01
5289	14	8.2	+1.9	+0.85	+1.73	+1.37	-0.14
5290	15	7.9	-0.7	-0.17	-0.39	-2.00	-0.12
5291	16	7.8	+3.0	+0.04	-0.15	-1.34	-0.04
5292	17	8.0	-2.9	-0.15	-0.51	-1.01	+0.06
5293	80	7.7	+2.3	+0.20	+0.37	-0.95	-0.13
5294	109	8.0	-0.6	-0.20	-1.33	-2.43	-0.02
5295	111	7.9	+3.2	-0.15	-0.50	-1.15	+0.06
5296	112	7.6	-2.9	-0.54	-1.20	-1.93	+0.13
5297	114	7.9	+0.8	+0.38	+0.78	-0.07	-0.03
5298	115	7.7	-0.2	+0.16	+0.37	-0.71	+0.02
5299	117	7.9	+1.0	+0.13	+0.36	-0.39	+0.04
5301	120	8.4	-1.9	+0.06	-0.23	+0.40	+0.15
5302	121	8.4	-1.7	+0.10	-0.20	+0.39	+0.15
5303	122	7.8	+3.4	+0.06	+0.07	-0.74	+0.08
5304	126	7.9	+3.0	+0.23	+0.43	-0.14	+0.11
5305	128	8.1	+2.0	+0.25	+0.58	+0.28	+0.02
5306	129	7.9	-0.4	+0.23	+0.27	-0.83	+0.05
5307	130	7.9	+1.0	+0.17	+0.43	+0.06	-0.02
5308	133	7.8	+0.6	+0.10	-0.02	-1.06	+0.08
5309	139	8.7	-0.6	-0.18	-1.30	-0.95	+0.13
5310	141	8.3	-2.3	-0.16	-0.74	-0.82	+0.13
5312	142	8.1	-1.6	-0.37	-0.97	-1.59	-0.11
5313	144	7.8	+1.0	+0.02	+0.06	-0.74	+0.02
5314	145	8.0	+0.1	-0.01	+0.08	-0.26	+0.04
5319	152	7.6	+1.0	+0.03	-0.23	-2.73	-0.09

Table E.3 (continued)

Modeling Number	Sample Number	pH	Cation/ Anion Balance %	Log AP/K			SiO ₂ (A,gl)
				Calcite	Dolomite	Sepiolite	
5320	154	7.5	-0.3	-0.60	-1.45	-2.76	+0.13
5321	156	8.1	+1.6	+0.18	+0.30	+0.00	+0.09
5322	157	8.1	-1.0	-0.08	-0.34	-0.95	-0.01
5323	158	8.2	-0.2	+0.05	-0.12	-0.57	-0.04
5324	159	8	+1.2	+0.07	-0.11	-0.90	-0.01
5324	161	7.5	-0.2	-0.36	-1.16	-2.95	+0.04
5326	162	7.4	+0.0	-0.45	-1.05	-2.81	+0.13
5327	163	7.5	+0.3	-0.51	-1.23	-2.73	+0.09
5328	164	7.8	+1.4	+0.37	+0.51	-1.26	-0.03
5329	165	7.5	+2.7	-0.75	-1.76	-3.33	+0.00
5330	166	7.4	+0.5	-1.08	-2.35	-3.76	+0.08
5331	167	8.1	-1.1	-0.03	-0.19	-0.70	+0.04
5332	301	7.8	-1.0	-0.04	-0.17	-1.50	-0.02
5333	423	7.3	-0.9	-0.81	-2.14	-4.18	+0.14
5334	425	8.0	+0.8	+0.03	-0.24	-1.21	+0.02
5335	426	7.8	-1.3	-0.08	-0.59	-2.93	-0.41
5336	427	7.9	-0.5	-0.79	-1.98	-2.74	-0.05
5337	429	7.7	+0.6	-0.26	-0.89	-2.38	+0.07
5338	430	8.0	-2.7	-0.16	-0.48	-1.22	+0.04
5339	431	7.8	-2.4	-0.14	-0.40	-1.56	+0.03
5340	432	7.8	-1.5	-0.25	-0.82	-2.03	+0.01
5341	487	8.2	-0.1	-0.03	+0.03	+0.11	+0.10
5346	495	7.7	-0.5	-0.69	-1.67	-2.66	+0.10
5347	496	8.1	-3.0	-0.69	-1.67	-2.66	+0.10
5348	497	8.2	-1.2	+0.14	+0.04	+0.21	+0.05
5349	498	8.2	+0.4	+0.11	-0.11	-0.49	-0.01
5352	503	8.0	+1.2	-0.30	-0.89	-1.18	+0.12
5353	546	7.7	-1.7	-0.42	-0.79	-1.27	-0.03
5354	548	7.9	-1.7	-0.47	-1.19	-1.76	+0.09

Table E.3 (continued)

<u>Modeling Number</u>	<u>Sample Number</u>	<u>pH</u>	<u>Cation/ Anion Balance %</u>	<u>Log AP/K</u>			<u>SiO₂ (A,gl)</u>
				<u>Calcite</u>	<u>Dolomite</u>	<u>Sepiolite</u>	
5355	548	7.9	-1.7	-0.47	-1.19	-1.76	+0.09
5355	549	7.9	+0.2	-0.58	-1.23	-1.78	-0.09
5356	559	7.9	+0.0	-0.23	-0.37	-0.77	+0.01
5357	561	7.7	-1.3	-0.40	-0.88	-1.00	+0.02

TABLE E.4. Calculated Disequilibrium Indices
(Apps et al. 1979, Table III-2)

Modeling Number	Well Designation	pH	Cation/ Anion Balance %	Log AP/K					
				E_{pt}^H (V)	Calcite	Dolomite	Sepiolite	SiO ₂ (A,gl)	Fe(OH) ₃ (A)
5468	DC-2	9.9	-0.1	-0.05	-0.39			-0.16	+0.24
5555	DC-6	10.1	+4.7	-0.03	+0.07	+0.63	+6.27	-0.74	-0.02
5556	Ford Well	8.0	-11.7	+0.15	+0.07	+0.11	-0.35	-0.02	+1.99
5557	McGee Well	8.0	-7.9	+0.09	+0.09	+0.08	-0.23	-0.04	+1.22

APPENDIX E - REFERENCES

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