

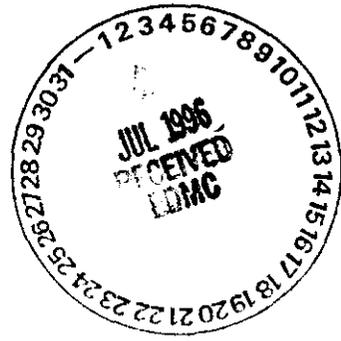
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# Hanford Sitewide Groundwater Flow and Transport Model Calibration Report



Prepared for the U.S. Department of Energy  
Office of Environmental Restoration and  
Waste Management

**Bechtel Hanford, Inc.**  
Richland, Washington

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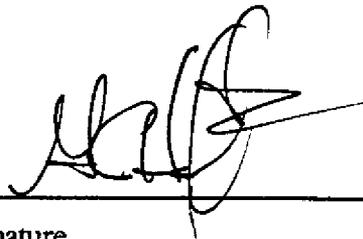
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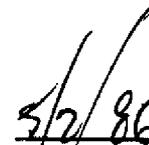
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# Hanford Sitewide Groundwater Flow and Transport Model Calibration Report

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Date Published  
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## ACRONYMS

BWIP	Basalt Waste Isolation Project
CERCLA	<i>Comprehensive Environmental Response, Compensation, and Liability Act of 1980</i>
DOE	U.S. Department of Energy
DOE-RL	U.S. Department of Energy, Richland Operations Office
ERC	Environmental Restoration Contractor
HGIS	Hanford Geographic Information System
RCRA	<i>Resource Conservation and Recovery Act of 1976</i>
Tri-Party Agreement	<i>Hanford Federal Facility Agreement and Consent Order</i>
USGS	U.S. Geological Survey

## 1.0 INTRODUCTION

This report presents the results of the development and calibration of a three-dimensional, finite element model (VAM3DCG) for the unconfined groundwater flow system at the Hanford Site. This flow system is the largest radioactively contaminated groundwater system in the United States. Eleven groundwater plumes have been identified containing organics, inorganics, and radionuclides. Because groundwater from the unconfined groundwater system flows into the Columbia River, the development of a groundwater flow model is essential to the long-term management of these plumes.

The Hanford Site is a U.S. Department of Energy (DOE) installation located in southcentral Washington State (Figure 1-1) and has been in operation since 1943. Since 1987, the mission of the Hanford Site has been environmental restoration with the goals of controlling the spread of groundwater contamination and protection of the Columbia River.

Cost effective decision making requires the capability to predict the effectiveness of various remediation approaches. Some of the alternatives available to remediate groundwater include: pumping contaminated water from the ground for treatment with reinjection or to other disposal facilities; containment of plumes by means of impermeable walls, physical barriers, and hydraulic control measures; and, in some cases, management of groundwater via planned recharge and withdrawals. Implementation of these methods requires a knowledge of the groundwater flow system and how it responds to remedial actions.

### 1.1 BACKGROUND

The DOE Richland Operations Office (DOE-RL) first recognized the need for a new Sitewide groundwater model of the unconfined system in 1991, approximately two years after signing the *Hanford Federal Facility Agreement and Consent Order* (Tri-Party Agreement) (Ecology et al. 1989). Groundwater contamination was found in over 518 km<sup>2</sup> (200 mi<sup>2</sup>) of the unconfined aquifer on the Hanford Site. Initial estimates indicated that tens of years would be needed to remediate the known plumes. The overall effectiveness of the remediation efforts contained considerable uncertainty. It was recognized that groundwater cleanup would require the capability to estimate the effectiveness of alternative groundwater cleanup approaches. In addition, the reduction of liquid effluent being discharged to the soil has caused profound changes to the groundwater flow system that needed to be incorporated into groundwater remediation planning and implementation. Fifty years of study has yielded voluminous quantities of data describing the aquifer and soil matrix that make up the unconfined flow system. These data have required new interpretations to support the cleanup mission of the Hanford Site.

Implementation of this work lead to the development of two milestones (DOE-RL 1991a; DOE-RL 1991b) contained in the Tri-Party Agreement. Under Milestone M-29-01,

"Description of Codes and Models to be Used in Risk Assessment," a combined DOE, contractor, and regulator committee was formed to exchange opinions and experiences relating to the use of various numerical codes. A total of 12 numerical codes covering both saturated and unsaturated flow and transport phenomena were identified and evaluated.

The second milestone, M-29-02, stated "submit a plan for development of area-wide groundwater models to support risk assessment and to evaluate impacts of changing groundwater flow fields" (DOE-RL 1991b). As a result of this milestone, the VAM3DCG numerical code<sup>1</sup> was selected and an implementation plan proposed to guide model development (DOE-RL 1991b). The implementation plan called for an evaluation of the existing database, incorporating new data, model calibration and testing, and simulating future scenarios. This report documents model calibration and testing.

## 1.2 PURPOSE AND REPORT ORGANIZATION

This report presents the model development, calibration, and testing process for the new Sitewide groundwater model of the unconfined aquifer using VAM3DCG. It provides the foundation for the model's use to assess groundwater remediation alternatives and other sitewide issues related to groundwater. The report is separated into five sections as follows.

**Section 1.0** provides an introduction, the background of the project, and the purpose of the report.

**Section 2.0** documents the geologic and hydrogeologic conceptual model of the unconfined flow system, which provides the basis for the development of the numerical model of the Hanford Site. The conceptual models are the result of the efforts of many professional scientists and engineers who have made contributions in defining these natural systems. These sections are extensively referenced.

**Section 3.0** describes the model setup, site-specific information (facility effluents) assumptions, calibration process, and initial calibration results. Every numerical model is a

---

<sup>1</sup>The Variably Saturated Analysis Model in 3-Dimensions with Preconditioned Conjugate Gradient Matrix Solvers (VAM3DCG) code (developed by HydroGeoLogic, Inc. of Herndon, Virginia) was selected for the following reasons: (1) the solution algorithms were robust and the original developer, an internationally known expert, was available; (2) the VAM3DCG code efficiently simulates a fluctuating free-water surface, which makes it especially attractive for Hanford Site applications; (3) the code has the ability to deal with transitional elements, which permits the grid to be refined in regions of interest or steep gradients; and (4) it has the capability for dealing with partially saturated flow, a feature that enables it to be used for vadose zone analyses. Support for use of this proprietary code is available from HydroGeoLogic, Inc.

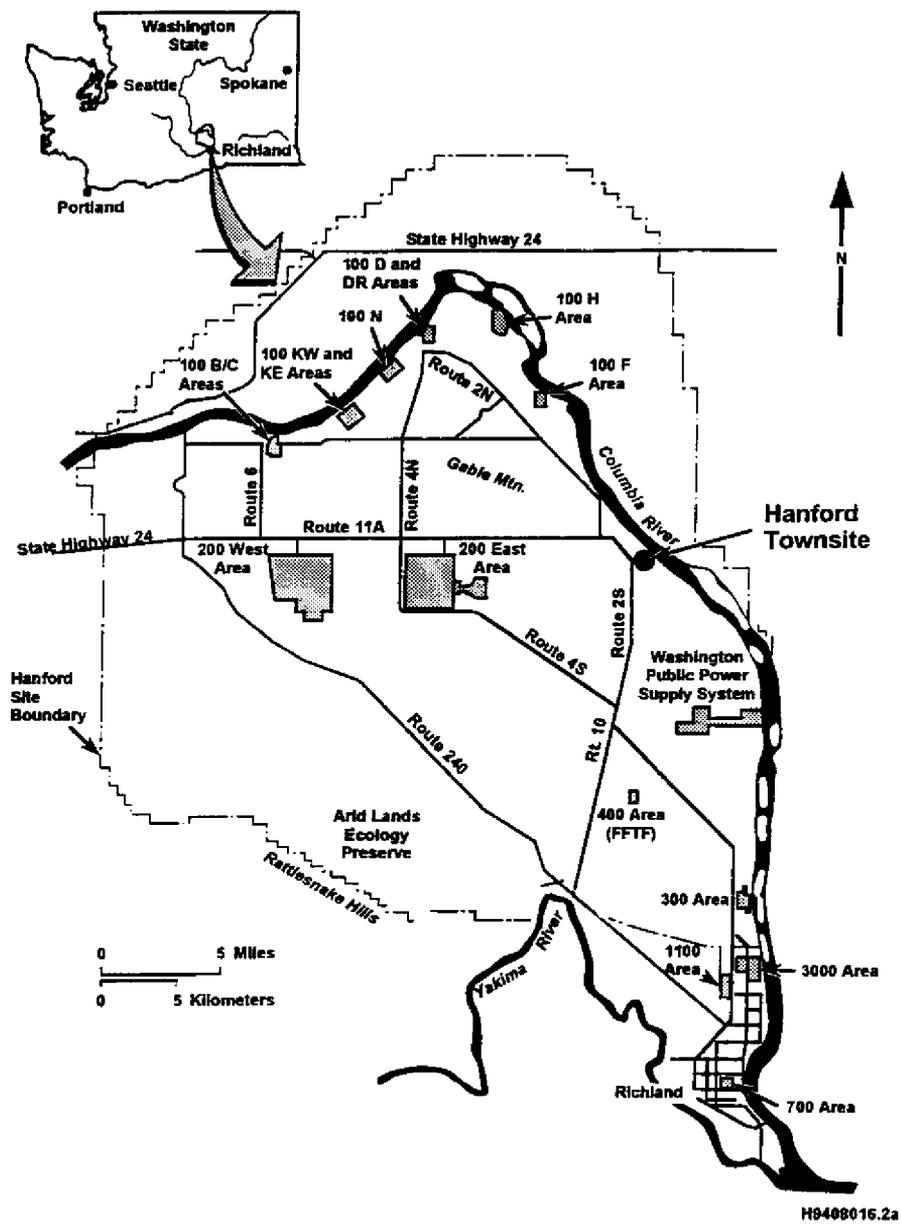
simplification of the technical understanding and knowledge of what is important to solve a problem. The major assumptions made to simplify the conceptual models and allow them to be quantified within the VAM3DCG code are documented along with Hanford site-specific information needed for flow and transport calibration.

**Section 4.0** presents a summary of conclusions and recommendations for future work.

**Appendix A** provides a technical description of the VAM3DCG model for the specific numerical approach and solution algorithms incorporated into this work.

**Appendix B** presents a sensitivity analysis quantifying the major factors affecting predictions of the movement of groundwater plumes.

Figure 1-1. Location Map of the Hanford Site.



## 2.0 CONCEPTUAL MODEL

The conceptual geologic and hydrogeologic models provide the basis for the inputs to the numerical groundwater flow model. The descriptions of the conceptual models are based on numerous technical reports that describe the Hanford Site subsurface environment. This section discusses the salient features of the subsurface environment as they relate to the Sitewide groundwater model.

The subsurface geologic conceptual model is a synthesis of data collected from the analyses of many samples from boreholes over the life of the Hanford Project. Interpretation of these data sets the stage for the conceptualized geohydrologic system, which defines the presence and movement of groundwater beneath the Hanford Site and the geohydrologic properties controlling the movement. This section provides: the geologic model development; stratigraphic descriptions; hydrogeologic system description; hydrogeologic properties; and liquid waste disposal facilities effecting the groundwater flow system.

### 2.1 GEOLOGIC MODEL DEVELOPMENT

Extensive geohydrologic investigations have been conducted at the Hanford Site since initial site construction in 1943. These investigations supported siting and construction of nuclear facilities, operating waste management storage and disposal facilities, monitoring and assessing environmental impacts, environmental remediation, and site restoration. Geohydrologic investigations were designed to support specific projects and often were conducted independently of other investigations. Thus, geohydrologic units were not uniformly defined and described. As a result, stratigraphic nomenclature was consistent only at the geologic formational level. Geologic descriptions at the formational level do not provide sufficient detail to develop a Sitewide conceptual geologic or hydrogeologic model to support remedial action decisions. Therefore, a uniform stratigraphic nomenclature along with consistent geologic unit descriptions and distributions needed to be developed that were applicable to all areas of the Hanford Site.

An integrated plan was formulated to develop the information necessary for a site geologic model. The primary emphasis was to define the major geologic units beneath the Hanford Site with emphasis on the saturated suprabasalt sediments. The plan included the following tasks.

- Define the stratigraphy of major geologic units including unit subdivisions, descriptions, and distributions (Section 2.1.1).
- Create a surface geologic map of the Hanford Site for use in constraining the surface distribution of geologic units and to identify potential exposures/outcrops for measuring detailed geologic sections (Section 2.1.2).

- Define the base of the suprabasalt sediments and determine the structural fabric that may trend upward into the overlying sediments (Section 2.1.3).
- Create a geologic conceptual model consisting of geologic cross sections and structural contour maps that depict unit elevations and lateral continuities. The characteristics of each geologic unit are described in Section 2.2.

The plan included an evaluation of the extensive existing information base as well as collecting new field information.

### **2.1.1 Development of Site Suprabasalt Stratigraphy**

The initial step in developing a site stratigraphic nomenclature was to define and document the major geohydrologic units of the suprabasalt sediments below the formational level with emphasis on the uppermost part of the suprabasalt groundwater flow system. A coordinated effort was established among several on-going projects to collect the information necessary to define and describe the major geologic units beneath the Hanford Site. These major geologic units would provide the framework for establishing geohydrologic units to be used in the Sitewide groundwater model. The coordinated effort consisted of two tasks: (1) subdivide the Hanford formation and Ringold Formation/pre-Missoula gravels into major geologic units and describe each, and (2) determine the spacial distribution of the major geologic units across the Hanford Site.

The Ringold Formation is the oldest of the suprabasalt geologic units beneath the Hanford Site. The Ringold Formation traditionally has been divided into several informal units including: (1) basal gravel and sand unit with associated silty paleosols, (2) lower silt and clay unit, (3) middle gravel unit, (4) upper sand, silt, and clay unit, and (5) basaltic fanglomerate unit (Newcomb 1958; Brown 1959 and 1962; Newcomb et al. 1972; Myers et al. 1979; Tallman et al. 1979; Bjornstad 1984 and 1985; and DOE 1988). The Ringold Formation has also been subdivided into facies (Tallman et al. 1979) and fining upward sequences (PSPL 1982).

In 1989, a project was initiated to develop a sitewide stratigraphic framework for the Ringold Formation for use in waste management and environmental restoration projects. The project included an evaluation of borehole logs, core samples, and geologic exposures. Borehole geophysics, age dates, volcanic ash analyses, remnant magnetism, and surface geologic mapping were included in the evaluation. The results of the evaluation indicated that the Ringold Formation is best subdivided on the basis of sediment facies associations (Lindsey and Gaylord 1990; Lindsey 1991a and 1991b) (see Section 2.2).

Since 1991, additional geologic studies were conducted to confirm and refine sediment facies associations and descriptions in the Ringold Formation. Sitewide and site-specific geologic studies were integrated among waste management and environmental restoration projects to ensure a consistent approach in stratigraphic nomenclature and geologic unit descriptions

(Lindsey 1991a, 1991b, 1992; Lindsey et al. 1994a). The sitewide studies focused on a Hanford Site geologic conceptual model that forms the geohydrologic framework for the site groundwater model (Connelly et al. 1992a and 1992b). The site-specific studies supported development of geohydrologic conceptual models for *Resource Conservation and Recovery Act of 1976* (RCRA) storage and disposal facilities (Lindsey et al. 1994b), remedial investigations of *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) operable units (DOE-RL 1994; Lindsey et al. 1991 and 1992; Lindsey and Jaeger 1993; Raidl 1994; Rohay 1994; Weekes et al. 1995), groundwater impact assessments of operating disposal facilities (Geosciences 1992; Alexander 1993; Alexander and Johnson 1993; Alexander et al. 1993 and 1995; Johnson 1993a and 1995; Johnson et al. 1995; Singleton and Lindsey 1994; and Sweeney et al. 1995) and environmental monitoring programs (Johnson 1993b and 1995; Weekes et al. 1995).

Lindsey (1995) summarized Ringold Formation investigations conducted since 1989. The primary data used to define the sediment facies associations and their distribution include the following:

- 29 measured sections from exposures along the White Bluffs
- Lithologic logs of core samples from 28 coreholes on the Hanford Site
- Driller and geologist logs from hundreds of boreholes on the Hanford Site
- Thousands of grab samples from hundreds of boreholes on the Hanford Site.

Measured sections and core samples were used as control points for subdividing the Ringold Formation into sediment facies associations and to define analogues for use with borehole log and borehole sample data sets. Analogues were used as a basis of comparison with borehole grab samples and borehole logs to be evaluated against in order to determine probable subsurface geologic conditions. The use of analogues is critical to making interpretations of subsurface physical properties of the sediment facies associations. Drilling generates desegregated, disrupted, and/or abraded samples that are not representative of the geologic conditions. The analogues were used as aids (Lindsey 1995) to interpret the following:

- Facies type
- Probable mud content
- Extent of interstratified lithologies
- Cementation and compaction
- Grain-size range.

Lindsey (1995) divided the Ringold Formation into five sediment facies associations based on work by Miall (1977, 1978, 1985) and Rust (1978) (see Section 2.2). The Ringold Formation is divided into three informal members (Figure 2-1). The informal Ringold members are subdivided into units on the basis of the dominate sediment facies associations. A discussion of the Ringold Formation stratigraphy is presented in Section 2.2.

The pre-Missoula gravels originally were recognized as the upper uncemented gravels of the Ringold Formation that contained a higher content of 'felsic' clasts giving the unit a 'bleached' appearance. The pre-Missoula gravels were defined as a separate and distinct geologic unit by PSPL (1981) based on an extensive coring and drilling program used to site a nuclear power plant in the east-central Hanford Site. These gravels were further described and mapped in the subsurface by Lindsey (1995) (see Section 2.2).

The Hanford formation is the youngest formation underlying the Hanford Site (Figure 2-1). The Hanford formation consists of glaciofluvial gravel, fine- to coarse-grained sand, and silt derived from cataclysmic flooding. Surface mapping (Reidel and Fecht 1994a and 1994b) and subsurface investigations (Price and Fecht 1976; Last and Marratt 1978a and 1978b; Smith 1988; WPPSS 1981 and 1986) indicate that the Hanford formation can be described on the basis of three glaciofluvial textured facies: (1) gravel-dominated, (2) sand-dominated, and (3) silt/sand-dominated (Figure 2-2). The Hanford formation also can be subdivided based on age using pedogenitic alteration, ash chronology, and remnant magnetism (Fecht et al. 1987; Baker et al. 1991; Reidel and Fecht 1994a and 1994b). However, these subdivisions have proven only to be useful in surface mapping (Reidel and Fecht 1994a and 1994b) and mapping walls of large excavations (Baker et al. 1991). Many geologic descriptions and unit interpretations must be based solely on grab samples from drill cuttings in which the characteristics necessary to determine age relationships are destroyed during drilling. Therefore, the three textural facies are the only consistently reliable criteria that can be used to define major stratigraphic subdivisions of the Hanford formation beneath the site.

### **2.1.2 Surface Geologic Map of Hanford Environs**

The surface geology of the Hanford environs was mapped to describe and determine the distribution of geologic units at the land surface and to identify potential exposures/outcrops for measuring detailed geologic sections. A secondary purpose of the mapping was to coordinate the geologic studies on the Hanford Site with the Washington Division Geology and Earth Resources state mapping project.

The geologic mapping was conducted at a variety of scales with the most common 1:24,000 U.S. Geological Survey (USGS) topographic maps. The mapping was compiled on 1:100,000-scale Priest Rapids and Richland quadrangles (Reidel and Fecht 1994a and 1994b). The geologic maps incorporated new geologic mapping since the publication of Myers et al. (1979). The mapping by Reidel and Fecht (1994a and 1994b) has been incorporated into the Hanford Geographic Information System (HGIS).

The geologic maps were used to constrain the distribution of major geologic units/facies of the Ringold Formation, pre-Missoula gravels, and Hanford formation.

### 2.1.3 Definition of Base of Suprabasalt Sediment Sequence

The base of the suprabasalt sequence is defined as the top of the bedrock (basalt) sequence. Basalt of the Columbia River Basalt Group is an extensive rock unit throughout the Columbia Basin (Waters 1961; Swanson et al. 1979a; Reidel and Hooper 1989). Maps depicting the top of the basalt sequence beneath Hanford were published earlier (ARHCO 1976; Brown 1959, 1962, and 1971; Myers et al. 1979; Myers 1981). Each subsequent top-of-basalt map was built on the interpretations and data from earlier maps. A new top-of-basalt map was developed for the sitewide groundwater project. The map was developed by integrating an extensive base of geological and geophysical data including the following:

- New surface geologic maps of the Hanford Site (Reidel and Fecht 1994a and 1994b) (see Section 2.1.2)
- Corehole data (core samples and geologic/geophysical logs) (including Bjornstad 1984; PSPL 1982; WPPSS 1974, 1981, and 1986; and various onsite well files/geological sample library)
- Borehole data (chip/grab samples and drillers, geologic/geophysical logs) (including Bjornstad 1984; Blume 1971; Crowley and Ledgerwood 1987; Fecht and Lillie 1982; Graham et al. 1984; Jackson et al. 1984; Ledgerwood 1986; PSPL 1982; Summers and Schwab 1977; Summers and Weber 1978; WPPSS 1974, 1981, and 1986; and various onsite well files/geological sample library)
- Surface-based geophysics (seismic reflection, gravity, magnetics) (including Ault 1981; Berkman 1984 and 1986; Donaldson 1963; Holmes and Mitchell 1981; Kunk 1981 and 1986; Odegard and Mitchell 1987; PSPL 1982; Raymond and Ratcliffe 1959; SSC 1978, 1979, and 1980; WPPSS 1974, 1981, and 1986; and various onsite geophysical files)
- Single- and multiple-layer aeromagnetic surveys (including AERO 1980; Swanson et al. 1979b)
- Structural trends, features, and characteristics of Yakima folds based on structural investigations on Umtanum Ridge (Price 1982; Price and Watkinson 1989), Saddle Mountains (Reidel 1984), Rattlesnake Mountain (Fecht et al. 1984, Reidel et al. 1992) and the Columbia Basin (Reidel et al. 1984, 1989 and 1994; WCC 1980) and remote sensing studies (including Glass 1977; Glass and Simmons 1977)
- Regional paleodrainage patterns of the ancestral Columbia, Palouse, Snake/Clearwater-Salmon, and Yakima Rivers (Fecht et al. 1985 and 1987; Reidel et al. 1994)
- X-Ray fluorescence analysis of core and chip samples from various Hanford Site geochemical databases.

Surface exposures based on geologic mapping compiled on 1:24,000 scale USGS topographic maps (published at a scale of 1:100,000) and subsurface corehole data were used to establish control points in developing a contour map on the basalt surface. Borehole data and geophysical data were used to extrapolate between control points and to refine structural trends. X-Ray fluorescence data were used to identify the basalt flow exposed at the top of the basalt sequence, which was necessary to use the top-of-basalt map to assess structural trends in the upper part of the basalt sequence and the suprabasalt sediments.

Figure 2-3 shows the top-of-basalt map and depicts the results of analyzing and interpreting the aforementioned data sets. Only the contours on the basalt surface are presented on the map. The map is in the HGIS database and is available from the Environmental Restoration Contractor (ERC).

#### **2.1.4 Geologic Model**

The geologic conceptual model for the Hanford Site is presented in Lindsey (1995) as a series of geologic cross sections and structure contour maps. The conceptual model was developed using the methods and data discussed in Section 2.1. Figures 2-4 and 2-5 are example cross sections traversing through the Hanford Site south to north and west to east, respectively. The data from the cross sections and other borehole information were tabulated to generate a summary chart of unit contact elevations and thickness for each major suprabasalt sedimentary geologic unit and is included in this report as Table 2-1. In addition, Lindsey (1995) developed six structure contour maps of the five facies groups of the Ringold Formation and the Plio-Pleistocene Unit.

## **2.2 STRATIGRAPHIC DESCRIPTION**

Major stratigraphic units at the Hanford Site are the Columbia River Basalt Group and intercalated Ellensburg Formation, Ringold Formation, pre-Missoula gravels, and Hanford formation. The stratigraphic relationships and ages are presented in Figure 2-1.

The Columbia River Basalt Group is comprised of a thick sequence (>5,000 m) of tholeiite basalts that form the bedrock in the Columbia Basin. Intercalated between flows in the upper part of the basalt sequence are volcanoclastic and epiclastic sediments of the Ellensburg Formation.

The Ringold Formation consists of variably indurated clay, silt, pedogenically altered mud and sand, fine- to coarse-grained sand, and multi-lithologic gravels (Myers et al. 1979; Lindsey 1991a and 1995; Goodwin 1993). Ringold sediments are best described on the basis of sediment facies associations, which are defined on the basis of lithology, stratification, and pedogenic alteration (Lindsey and Gaylord 1990). These facies associations forms the basis for Ringold stratigraphic subdivisions. The Ringold facies associations are (1) fluvial gravel, (2) fluvial

sand, (3) overbank deposits and paleosols, (4) lacustrine deposits, and (5) alluvial-fan deposits (Lindsey 1991a and 1995; Goodwin 1993). Detailed descriptions of these facies can be found in (Lindsey 1991a and 1995; Goodwin 1993).

Sediments comprising the Ringold Formation are divided into three informal members (Figure 2-1). The lowest member, the member of Wooded Island, contains five separate stratigraphic intervals, designated units A, B, C, D, and E, dominated by fluvial gravel (facies 1). These units are separated by intervals containing deposits typical of overbank-paleosol and lacustrine facies associations (facies 3 and 4). The lower most of the fine-grained sequences, overlying unit A, is designated the lower mud unit. The member of the Wooded Island is overlain by the member of Taylor Flat, which is dominated by interbedded fluvial sands and overbank-paleosol deposits (facies 2 and 3). On the edges of the Pasco Basin and in the northern Hanford Site, the member of Wooded Island pinches out, interfingering with the member of Taylor Flat. The third member of the Ringold Formation, the member of Savage Island, consists dominantly of lacustrine deposits (facies 4) that are basin wide in extent (Lindsey 1995).

The pre-Missoula gravels are comprised of quartzose to gneissic clast-supported pebble to cobble gravel with a quartzo-feldspathic sand matrix. These gravels, called the pre-Missoula gravels (PSPL 1982), are up to 25 m thick, contain less basalt than the underlying Ringold gravels and the overlying Hanford deposits, have a distinctive white or bleached color, and sharply truncate underlying strata. The pre-Missoula gravels are approximately time equivalent to the early "Palouse" soil and the Plio-Pleistocene alluvium. The gravels are interpreted as mainstream deposits of the Columbia River.

The Hanford formation consists of gravel, fine- to coarse-grained sand, and silt. These deposits are divided into three facies: (1) gravel-dominated; (2) sand-dominated; and (3) silt/sand-dominated. The Hanford formation was deposited as a result of cataclysmic flooding of the Pasco Basin during three different episodes Pleistocene glaciation (Fecht et al. 1987). The Hanford Formation is commonly divided into two informal members: Pasco gravels and the Touchet Beds (Myers et al 1979; Tallman et al 1981; Fecht et al 1987; DOE 1988). The Pasco gravels generally correspond to the gravel-dominated facies and the Touchet Beds to the sand-dominated and silt/sand dominated facies. The Hanford formation is absent on the ridges more than 385 m above sea level, the highest level of cataclysmic flooding in the Pasco Basin (Baker et al. 1991).

Stratigraphic relationships (Figure 2-1) across the Hanford Site have been based on observations in intact core and outcrops. Sediment facies and basalt flows were identified from more than 40 measured sections (Myers et al. 1979; Baker et al. 1991; Lindsey 1995). Sedimentary and basalt data also were collected from more than 60 coreholes and from drilling cuttings and borehole logs from several thousand wells. The stratigraphic relationships were used to construct geologic structure contour maps of various stratigraphic horizons (Myers et al. 1979; Lindsey 1995). Key geologic maps to the geologic model are found in Figure 2-3 (top of basalt).

The top of basalt is based on surface geologic maps of the Pasco Basin (Reidel and Fecht 1994a and 1994b) and over 300 boreholes spudded in or drilled into the basalt sequence.

## **2.3 HYDROGEOLOGIC SYSTEM**

### **2.3.1 Aquifers**

Approximately 518 km<sup>2</sup> (200 mi<sup>2</sup>) of confined aquifer is contaminated at the Hanford Site. Beneath this unconfined aquifer is a series of confined aquifers that may interact with the unconfined aquifer to limited but unknown degree (Spang and Webber 1995).

The confined aquifers consist of sedimentary interbeds and basalt intraflow zones of the Ellensburg Formation within the Grande Ronde, Wanapum, and Saddle Mountain basalts. These aquifers are aerially extensive, covering much of the Columbia River plateau in Washington State and Idaho. When the potentiometric surfaces of one of the aquifers is above or below that of the adjoining aquifer, the potential exists for water to move from one aquifer to the other (termed "aquifer intercommunication") depending on the vertical hydraulic conductivity of the confining basalt unit. Figure 2-6 illustrates this upward flow potential by comparing head values for the upper basalt aquifer with those of the unconfined aquifer (Spang and Webber 1995). The direction of any leakage is determined by the relative position of the potentiometric surfaces. The confined aquifer systems were the focus of the Basalt Waste Isolation Project (BWIP) conducted during the period 1977 to 1987; and a detailed discussion of these aquifers is contained in DOE (1988).

The unconfined aquifer is contained within the Ringold Formation and the Hanford formation of the Pasco Basin. This basin is bounded by Umtanum Ridge, Yakima Ridge, and the Rattlesnake Hills on the west; Rattlesnake Mountain on the southwest; Saddle Mountains to the north; and Palouse Slope on the east. The Columbia River traverses through the basin and forms the northern and eastern boundary of the unconfined aquifer for the Hanford Site. The top of the Columbia River basalts generally is considered to form the bottom of the unconfined aquifer. However, for the purpose of the sitewide groundwater model, the bottom of the aquifer is taken to be the top of the lower mud unit of the Ringold Formation where it exists; otherwise it is the top of the basalt. This is because the lower mud acts as an impermeable layer above the basalt (Figure 2-7). This portion of the aquifer is minimally contaminated by Hanford operations. Therefore, the saturated portion of the Ringold Formation and Hanford formation above the top of basalt/top of lower mud is most appropriate for dealing with the Hanford unconfined aquifer system.

Figure 2-8 shows the saturated thickness of the unconfined aquifer varies, based on the 1979 water table configuration, from over 150 m (500 ft) to < 3 m (10 ft). Of particular interest is the portion of the aquifer where the pre-Missoula/Hanford formation exists in the uppermost portion

of the aquifer (Figure 2-9). The portion of the aquifer is of high conductivity and permits contaminants to travel faster than the portions of the aquifer in the Ringold Formation.

### 2.3.2 Unconfined Aquifer Recharge and Discharge

Groundwater flows from regions of recharge to regions of discharge. The geohydrologic properties of the aquifer materials within the system control the magnitude of flow and determine the configuration of the water table, or upper limit of the saturated zone. Direction of flow is controlled by the aquifer properties along with the locations of recharge and discharge. Recharge may be either natural (e.g., streams, precipitation) or artificial (e.g., wastewater disposal) irrigation.

Migration of contaminants in a groundwater system depend on the flow of the groundwater, and also on the properties of the aquifer materials, the chemistry of the contaminant and aquifer material, and the natural degradation of some contaminants.

A first step in the development of a conceptual model of a groundwater system is the identification and evaluation or quantification of recharge and discharge to the system.

**2.3.2.1 Groundwater Recharge.** The primary recharge source for the unconfined aquifer system at the Hanford Site is the higher lands west of the Site: the Cold Creek and Dry Creek drainage basins. These streams are ephemeral on the Hanford Site. The drainage basins receive an annual average precipitation of about 40.6 cm (16 in.) compared to 16.5 cm (6.5 in.) of precipitation at the Hanford Site. Much of this precipitation falls as snow in the upper elevations. Other potential sources of recharge are precipitation and leakage from the underlying confined aquifers.

During a geology and hydrology investigation of the Hanford Site, Newcomb et al. (1972) estimated that subsequent to the cessation of irrigation in the Cold Creek and Dry Creek valleys in 1954, about 500 acre-ft/yr  $0.002 \text{ m}^3/\text{sec}$  ( $0.7 \text{ ft}^3/\text{sec}$ ) recharged the unconfined aquifer at Hanford from the two valleys. The investigation also indicated an unknown amount of recharge to the unconfined aquifer by leakage of unconfined aquifer water at what has become known as the Cold Creek barrier. Newcomb et al. (1972) suggested that this leakage could contribute several hundred acre-feet of water per year (100 acre-ft/yr is equivalent to  $0.004 \text{ m}^3/\text{sec}$  [ $0.14 \text{ ft}^3/\text{sec}$ ]).

As part of a recharge evaluation to the confined aquifer system, Livesay (1986) estimated the surface runoff from the Cold Creek valley on the basis of a regression analysis of small watersheds in eastern Washington. For the Cold Creek watershed, an estimate of  $0.23 \text{ m}^3/\text{sec}$  ( $8 \text{ ft}^3/\text{sec}$ ) was obtained, with an area of  $174 \text{ km}^2$  ( $67 \text{ mi}^2$ ), with an average annual precipitation of 25.4 cm (10 in.). For a combined Cold Creek/Dry Creek drainage area of about  $259 \text{ km}^2$  ( $100 \text{ mi}^2$ ), this would be approximately  $0.34 \text{ m}^3/\text{sec}$  ( $12 \text{ ft}^3/\text{sec}$ ). However, Livesay correctly

pointed out that the regression study was based on watersheds having a perennial base flow component and, therefore, may overestimate runoff from Cold Creek and Dry Creek.

Using a Darcian approach, Graham et al. (1981) estimated the groundwater recharge to Hanford from the Cold Creek valley as  $0.06 \text{ m}^3/\text{sec}$  ( $2 \text{ ft}^3/\text{sec}$ ). The parameter estimates used in this analysis were: hydraulic conductivity =  $12.2 \text{ m/day}$  ( $40 \text{ ft/day}$ ); saturated thickness =  $61 \text{ ft}$  ( $200 \text{ ft}$ ); length of  $3,049 \text{ m}$  ( $10,000 \text{ ft}$ ); and hydraulic gradient =  $0.002$ . No estimate was given for the Dry Creek valley. Graham et al. (1981) also noted that irrigation in the Cold Creek valley resumed in approximately 1969.

Other estimates of recharge are based on model calibrations. Jacobson and Freshley (1990), in performing an inverse calibration of the CFEST model, arrived at a boundary flux of  $0.102 \text{ m}^3/\text{sec}$  ( $3.6 \text{ ft}^3/\text{sec}$ ) from Cold Creek valley, which they noted was in agreement with the estimated flux of  $0.105 \text{ m}^3/\text{sec}$  ( $3.7 \text{ ft}^3/\text{sec}$ ) in the previous calibration of the VTT model. The VTT calibration indicated a boundary flux of  $1.4 \times 10^{-2} \text{ m}^3/\text{sec}$  ( $0.5 \text{ ft}^3/\text{sec}$ ) for the Dry Creek valley.

Bennett (1992) approximated the runoff from the two valleys, based on limited information, as slightly over  $0.23 \text{ m}^3/\text{sec}$  ( $8 \text{ ft}^3/\text{sec}$ ). His estimate was based on an approximate water balance and was factored in an increase in irrigation from 1954 quantities.

Two additional potential sources of recharge to the unconfined aquifer are (1) recharge from the confined aquifer systems beneath the unconfined aquifer, and (2) recharge from precipitation on the Hanford Site that percolates to the water table.

During the BWIP, considerable emphasis was focused on the confined aquifer system at Hanford. Attention was also given to springs in the Cold Creek and Dry Creek basins that might provide recharge to one or more of the confined aquifer systems. In turn, the confined systems may provide recharge to the unconfined system, either as widespread upwelling over a broad area or at specific locations, such as the Cold Creek barrier noted by Newcomb et al. (1972). While limited data are available to determine or quantify if leakage exists between the confined aquifer systems and the unconfined aquifer, the potential is recognized to exist. However, for the Sitewide model, it is assumed that there is no recharge or discharge from the confined aquifer to the unconfined aquifer due to insufficient data.

Newcomb et al. (1972) also considered recharge to the unconfined aquifer via the precipitation route. Their review of well hydrographs suggested annual recharge was zero or at least negligible. Graham et al. (1981) also suggested little, if any, recharge to groundwater from precipitation due to the high rate of evapotranspiration. Review of other pertinent Hanford literature indicates that there is general agreement that the recharge from precipitation is negligible when soils are fine-grained with a vegetative cover, especially if it is deep-rooted vegetation. When soils are coarse-grained and there is no vegetative cover, then recharge can occur during years of high precipitation, especially when it occurs as snow with rapid melting and heavy rainfall. (Rockhold et al. 1990; Routson and Johnson 1988; Gee et al. 1992:

Prych 1995; Fayer and Walters 1995; and Rockhold et al. 1995.) For the purpose of the Sitewide model, the recharge from precipitation is assumed to be negligible because almost all of the non-operating areas are vegetated, and in the operational areas the quantity of any natural recharge is quite small compared to the artificial recharge resulting from waste disposal operations that is input to the model.

Along the southeast portion of the Hanford Site, the Yakima River contributes some flow into the unconfined aquifer.

**2.3.2.2 Aquifer Discharge.** Estimates of groundwater discharge to the Columbia River, from the unconfined aquifer have been made in previous studies (Luttrell et al 1992) estimated  $6.6 \times 10^6$  m<sup>3</sup>/yr (7.4 cfs) of groundwater discharged to the river along a 1 km (0.6 mi) section near the old Hanford Townsite. Prater et al (1984) estimated groundwater discharge to the river at  $2.7 \times 10^6$  m<sup>3</sup>/yr (3.0 cfs) along the same section at Luttrell (1992) using a groundwater flow model.

**2.3.2.3 Aquifer Intercommunication.** The Cold Creek fault (Johnson 1993b) has been interpreted to allow water from lower confined aquifers to move up into the upper confined aquifer. However, it is thought that no water moves up into the unconfined aquifer. Intercommunication exists between the uppermost confined aquifer and the unconfined aquifer in the area south of Gable Gap, which is the gap between Gable Mountain and Gable Butte. This intercommunication has been investigated by Ledgerwood and Deju 1976, Strait and Moore (1982), and Graham et al. (1984). The studies show that water from the unconfined aquifer migrates down into the uppermost confined aquifer, but within the constraints of the area of the study, water from the confined aquifer then flows back into the unconfined aquifer. No quantification or estimate of such aquifer intercommunication has been made. The sitewide model does not attempt to take this intercommunication into account.

## 2.4 HYDROGEOLOGIC PROPERTIES

The movement and storage of groundwater in an aquifer is controlled by the hydrogeologic properties of the aquifer. The hydraulic conductivity (or transmissivity, which is the product of the hydraulic conductivity and the saturated thickness) is a measure of how the water moves in the aquifer. The storativity and specific yield are measures of the aquifer's ability to store water. Estimates of these parameters are obtained from aquifer tests conducted in one or preferably several wells. These tests can provide good estimates for near well aquifer characteristics. The success of the model simulation depends on the representation of these tests to provide a numerical description of the model domain.

Table 2-2 is a listing of the wells for which aquifer test data are available. Figure 2-10 shows the locations of these wells. Hydraulic conductivities for the 200 East and 200 West Areas were obtained from Connelly et al. (1992a and 1992b). Hydraulic conductivities for the 600 Area were obtained from Thorne and Newcomer (1992). Data obtained from slug tests were

discarded as they represent only very near well characteristics. For each well, the test results were reviewed for reasonableness with respect to the hydrogeologic unit tested.

Almost all the aquifer tests were single-well tests (i.e., there was no observation well for measuring drawdown). This results in hydraulic conductivity and transmissivity only being estimated and no estimate for storage properties of the formation. In addition, water-level measurements in the pumped well due to energy losses at the well-formation interface were not assessed.

The aquifer test results then were extended from the point measurements to areal values with the application of Earth Vision, a software program of Dynamic Graphics, Inc.

## **2.5 HANFORD OPERATIONS AND EFFLUENT DISPOSAL**

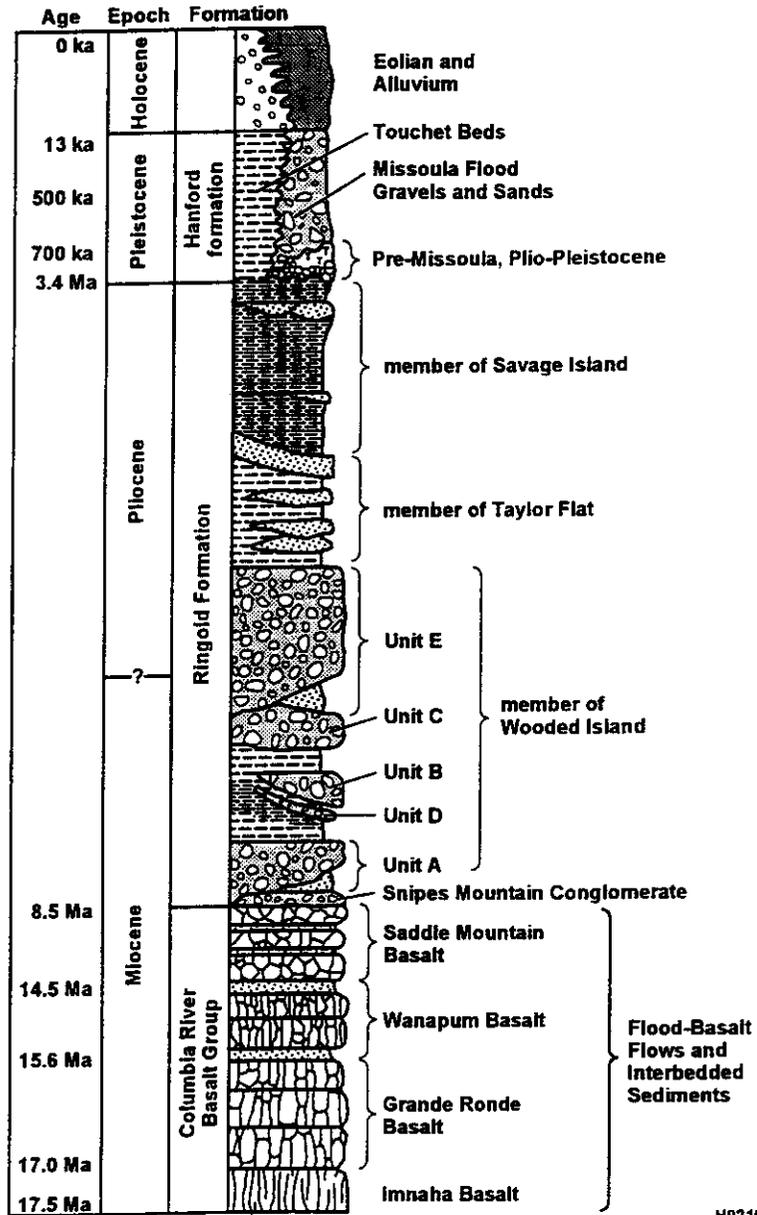
Since operations started in 1943, large quantities of wastewater were disposed of to the soil column at Hanford, some of it contaminated with radioactive and/or hazardous waste. Low-level radioactive waste, primarily cooling water, was disposed of to surface ponds for infiltration into the soil. Intermediate-level radioactive waste, such as process condensates and steam condensates, was disposed of to subsurface facilities termed cribs. These facilities isolated contaminants from animals and plants while allowing the water to percolate through the soil. Figure 2-11 shows the volumes of wastewater disposed of to the ground from the processing facilities in the 200 Area plateau. Disposal of this wastewater raised the water table as much as 24.4 m (80 ft) in 200 West Area and 9.1 m (30 ft) near 200 East Area.

Process discharges from each facility are tabulated in annual waste volume reports for all cribs, ditches, and ponds. The sitewide model incorporated the major liquid waste disposal facilities located in the 200 East and West Areas. Table 2-3 identifies each facility and provides the volume of liquids discharged over the period between 1980 and 1993. Locations of these facilities are shown on Figure 2-12. Discharges from these facilities account for over 90% of the total facility discharge. Total discharge over this period from all facilities was  $2.31 \times 10^{11}$ L ( $6.10 \times 10^{10}$ gal) and  $1.88 \times 10^{10}$ L ( $4.96 \times 10^9$ gal) from the 200 East and West Areas, respectively. Only one of the liquid waste disposal facilities currently are operating (B Pond).

Similarly, tritium was introduced into the groundwater from a number of liquid waste disposal facilities found in both 200 East and West areas. Table 2-4 identifies those facilities and the quantity of tritium discharged from each over the period 1980 to 1993, which are included in the model. No significant discharges of tritium during this period are found in the 200 West Area. Total tritium discharged in the 200 East and 200 West Areas was 31,700 and 323 curies, respectively.

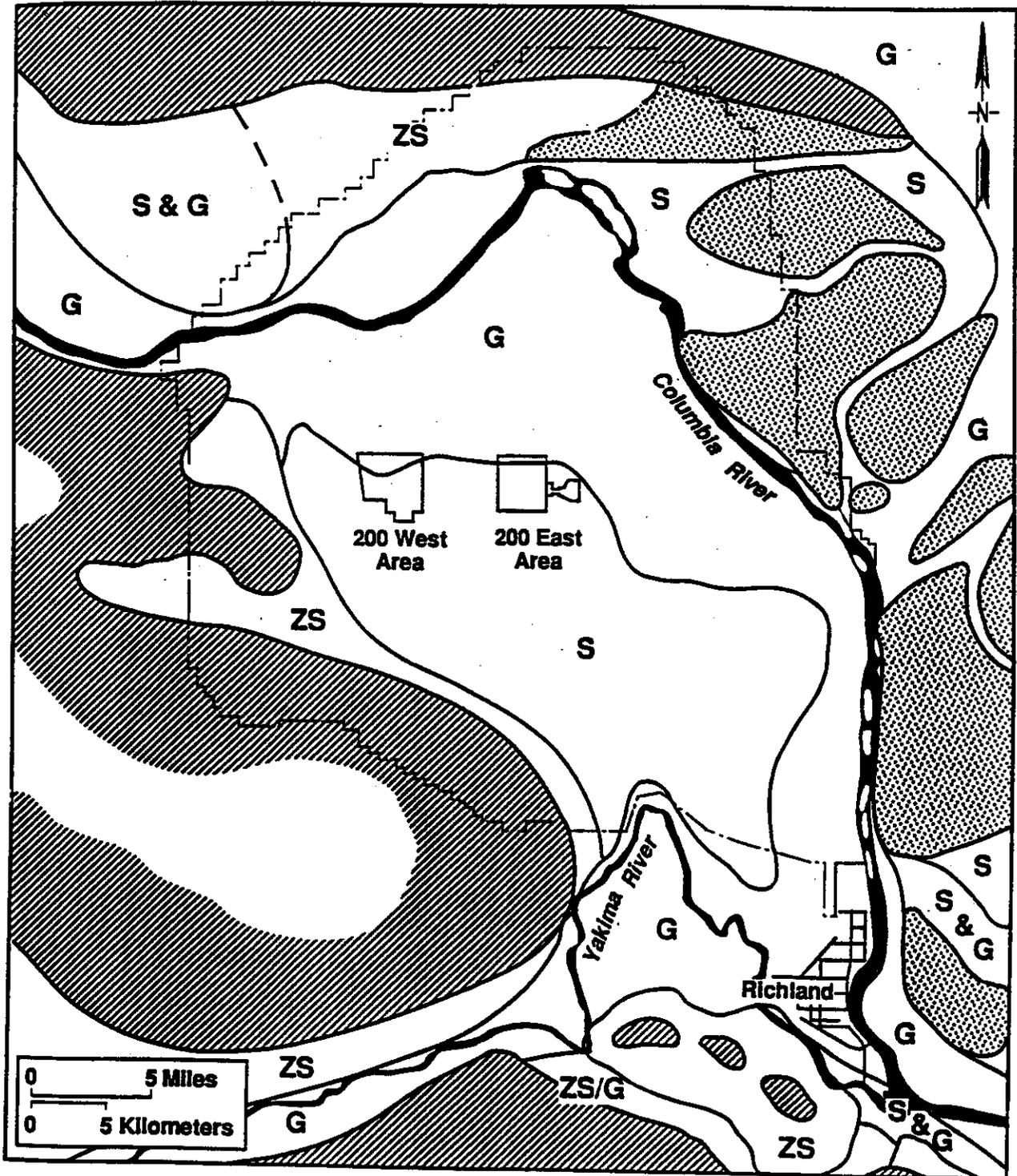
The sitewide model assumes flow from sanitary systems is minimal. There are approximately 86 individual septic systems known to exist on the Hanford Site. The estimated flow from each is highly variable and aerielly distributed. (Correspondence J. J. Luke, Westinghouse Hanford Company, to J. E. Rasmussen, DOE dated Dec. 19, 1995, Correspondence Control No. 9504951B R1).

Figure 2-1. Idealized Suprabasalt Stratigraphy of the Hanford Site and Stratigraphic Nomenclature.



H9210011.1b

Figure 2-2. Distribution of Glaciofluvial Facies of Hanford Formation on the Hanford Site.



<b>Touchet Beds</b>	<b>Pasco Gravels</b>	 Columbia River Basalt
<b>S = Sand Facies</b>	<b>G = Gravel</b>	 Ringold Formation
<b>ZS = Silty Sand Facies</b>	<b>S&amp;G = Sand and Gravel</b>	

H040012.6

Figure 2-3. Top-of-Basalt Map.

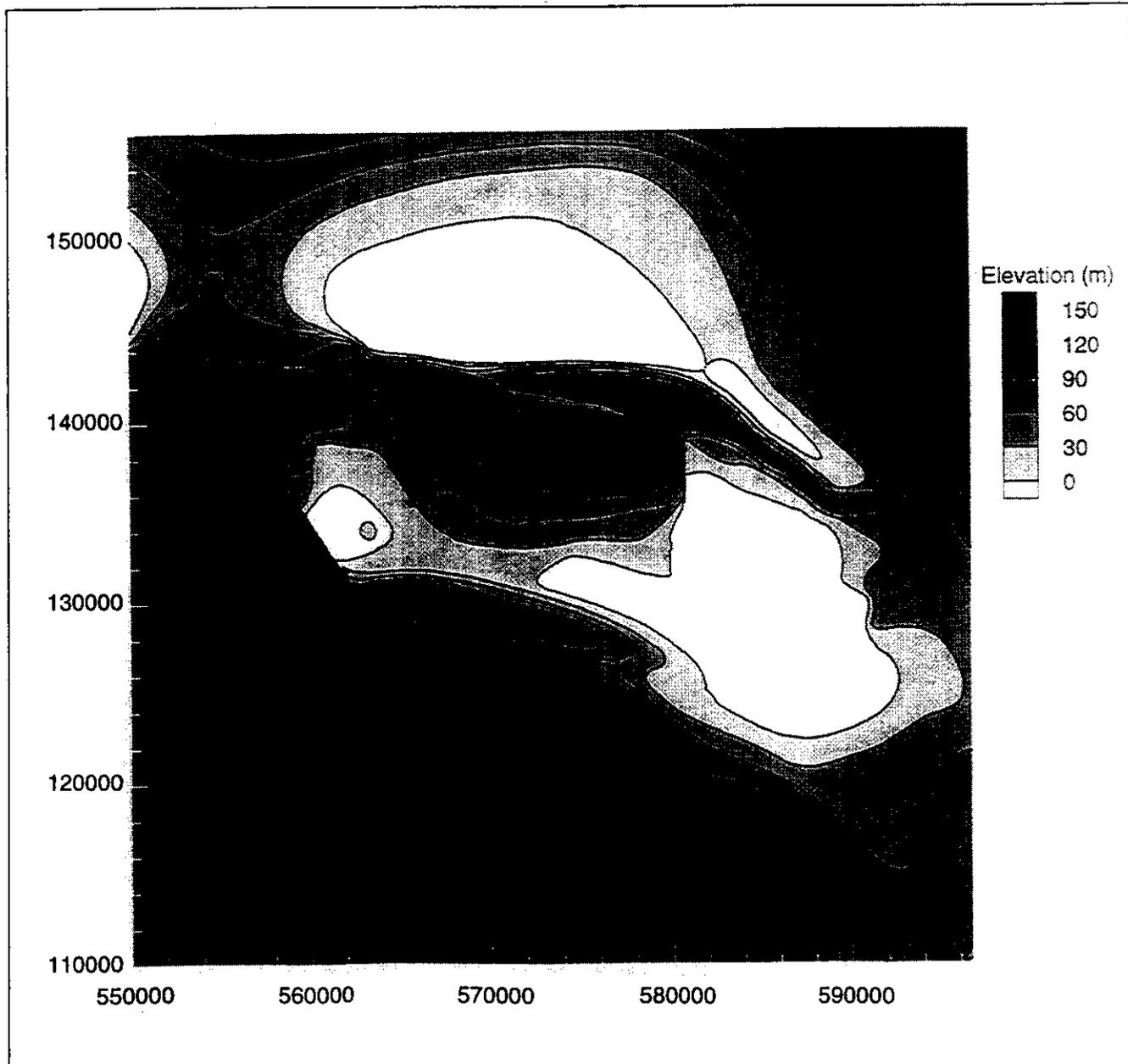


Figure 2-4. Miocene to Pliocene-Aged Suprabasalt Sediments of the Hanford Site-Cross Section H (from Lindsey 1995).

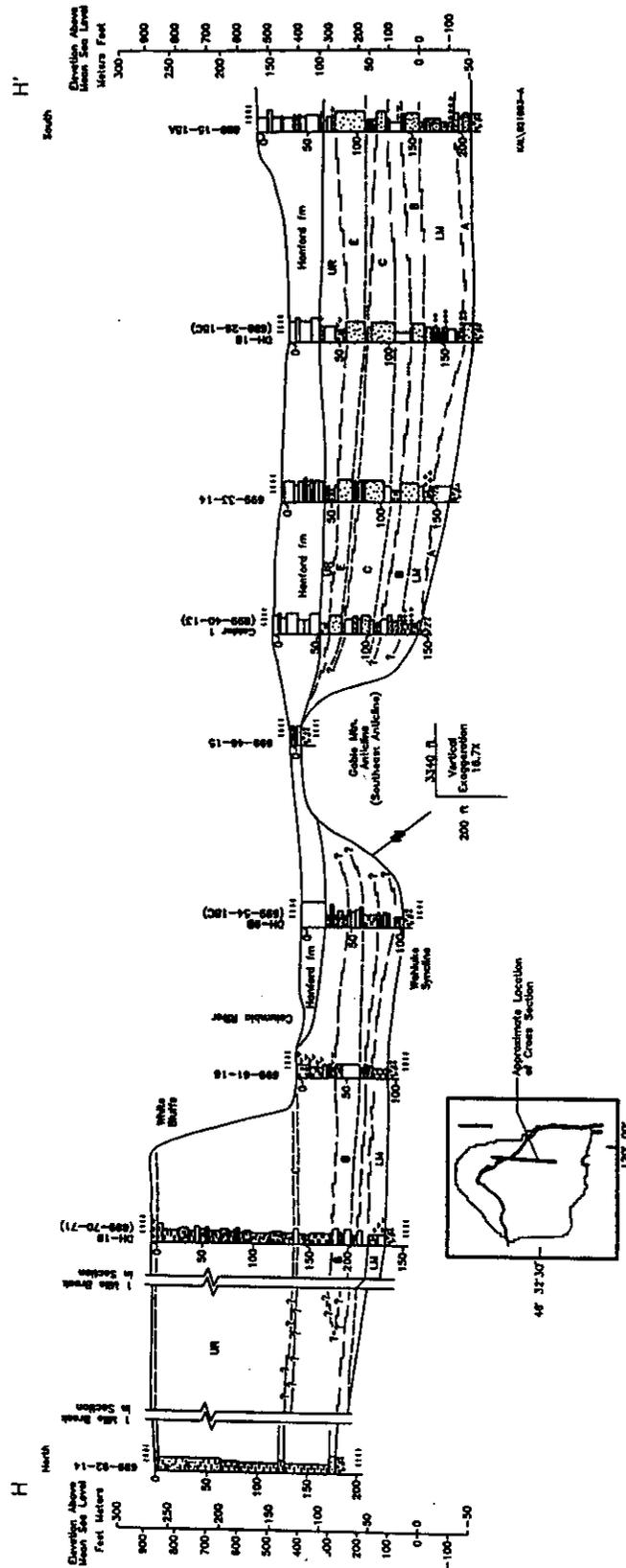


Figure 2-5. Miocene to Pliocene-Aged Suprabasalt Sediments of the Hanford Site-Cross Section N (from Lindsey 1995).

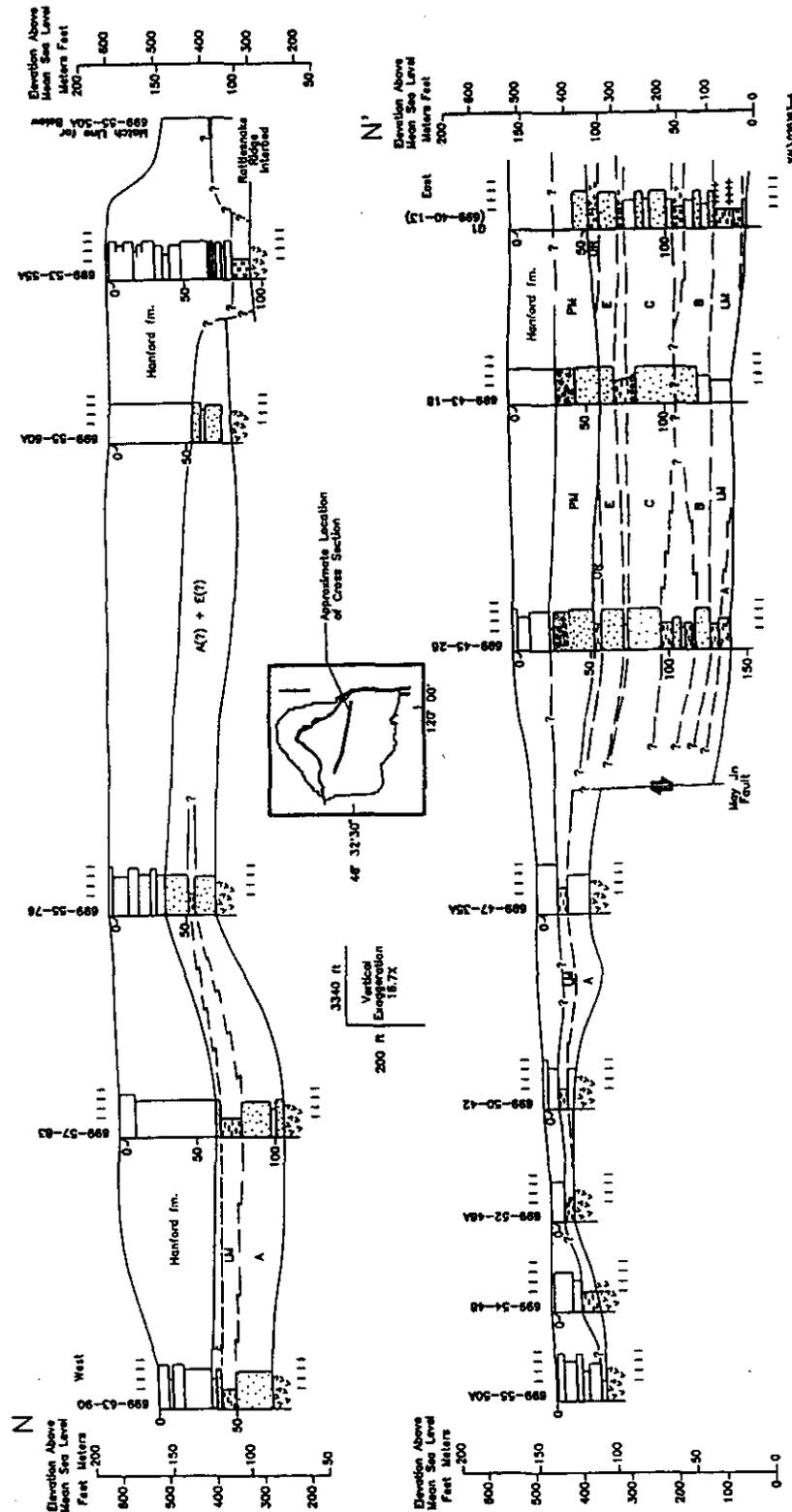




Figure 2-7. Bottom of the Modeled Aquifer.

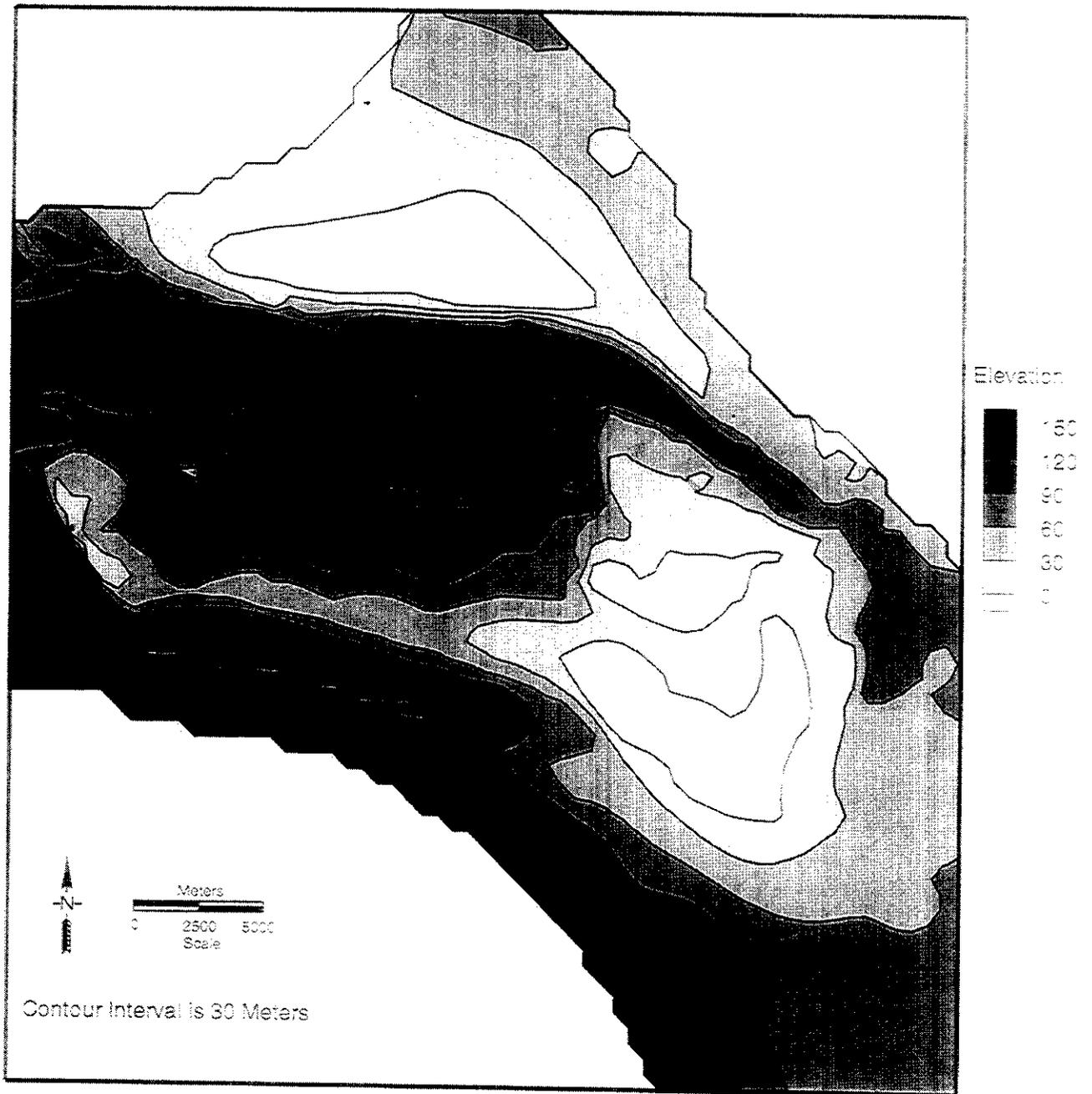


Figure 2-8. Saturated Thickness of the Unconfined Aquifer.

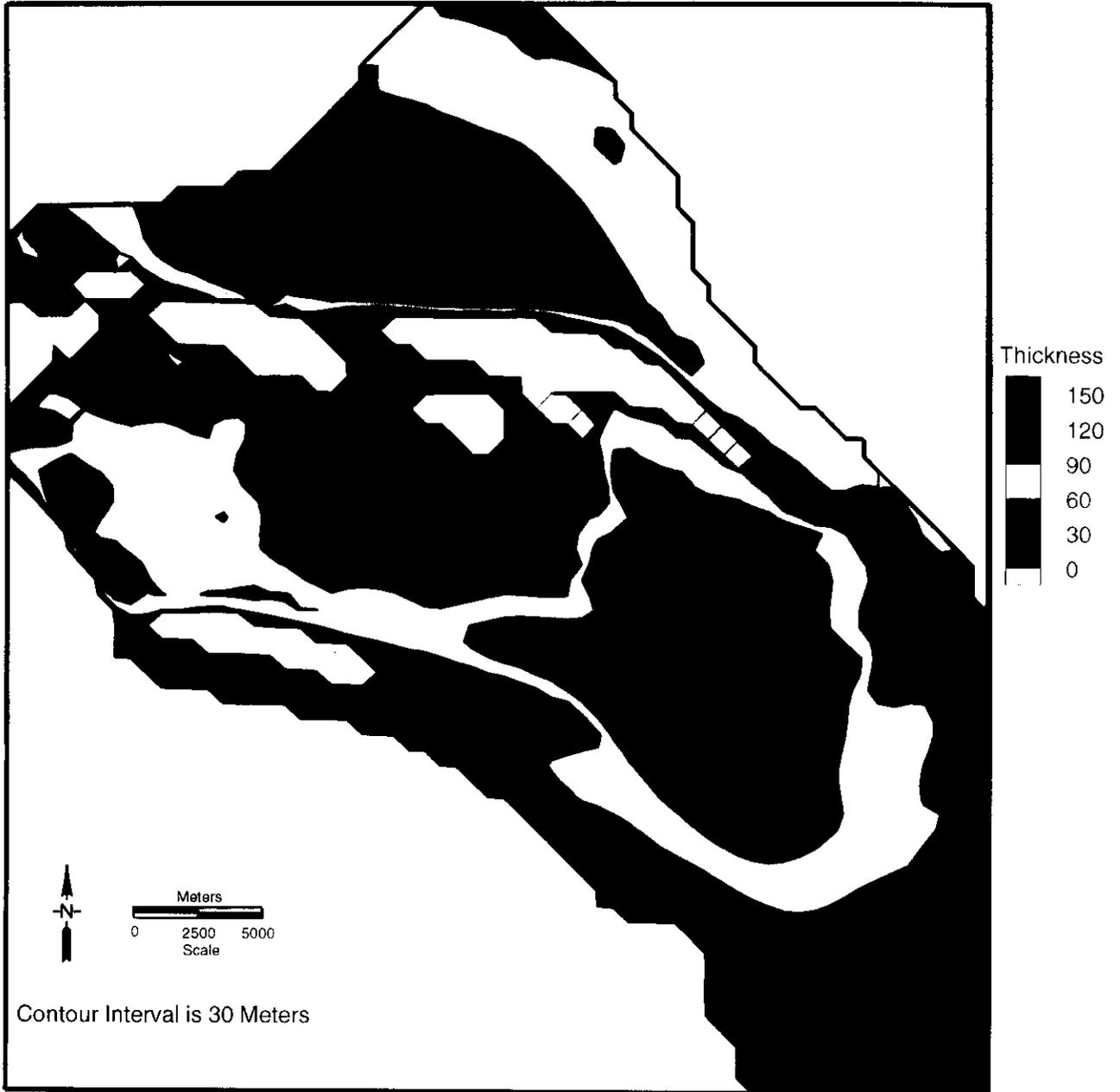


Figure 2-9. Saturated Thickness of the Pre-Missoula/Hanford Formation.

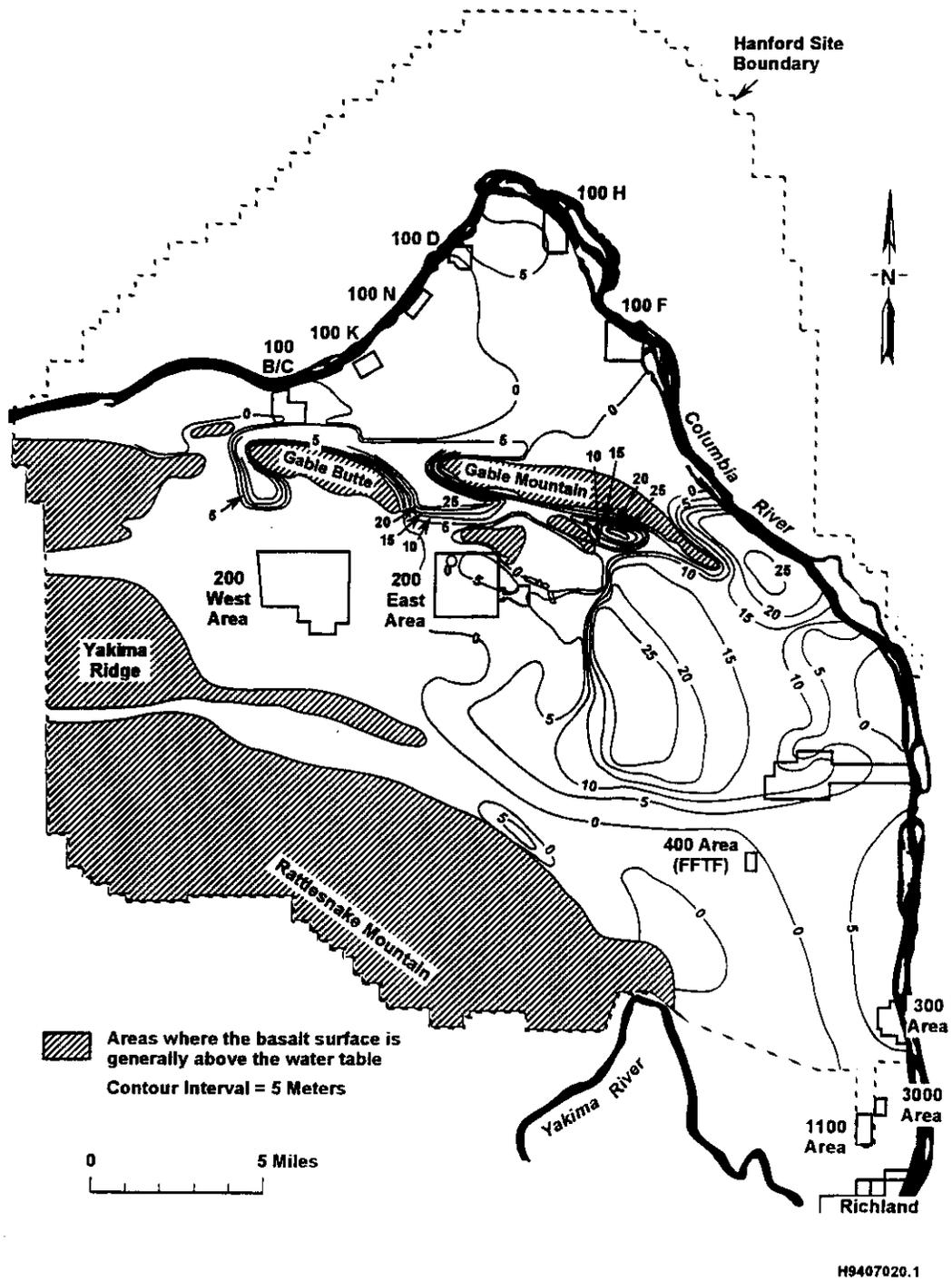


Figure 2-10. Location Map for Wells Used in Estimating Model Hydraulic Conductivities.

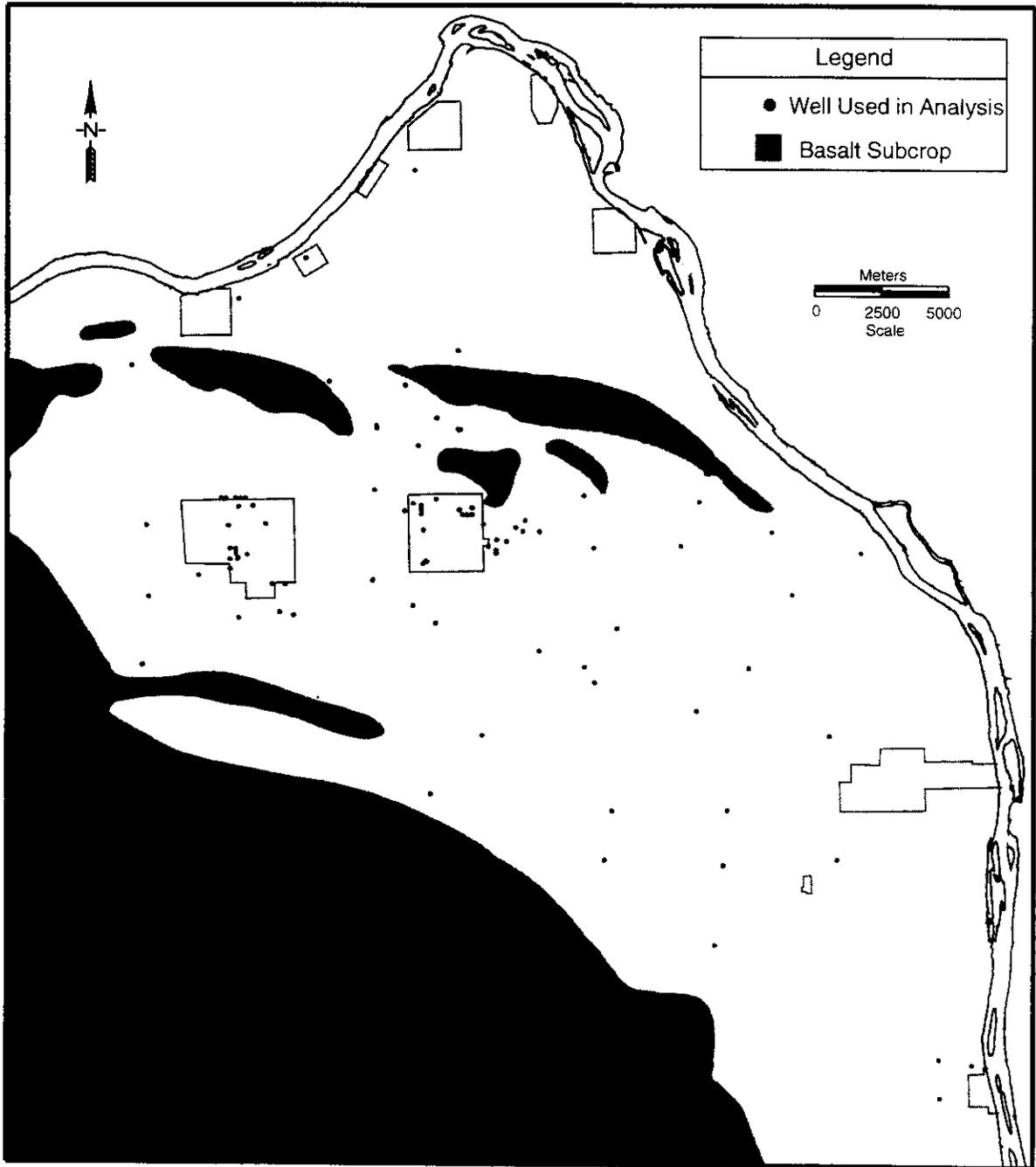


Figure 2-11. Liquid Effluents Discharged to the Soil Column.

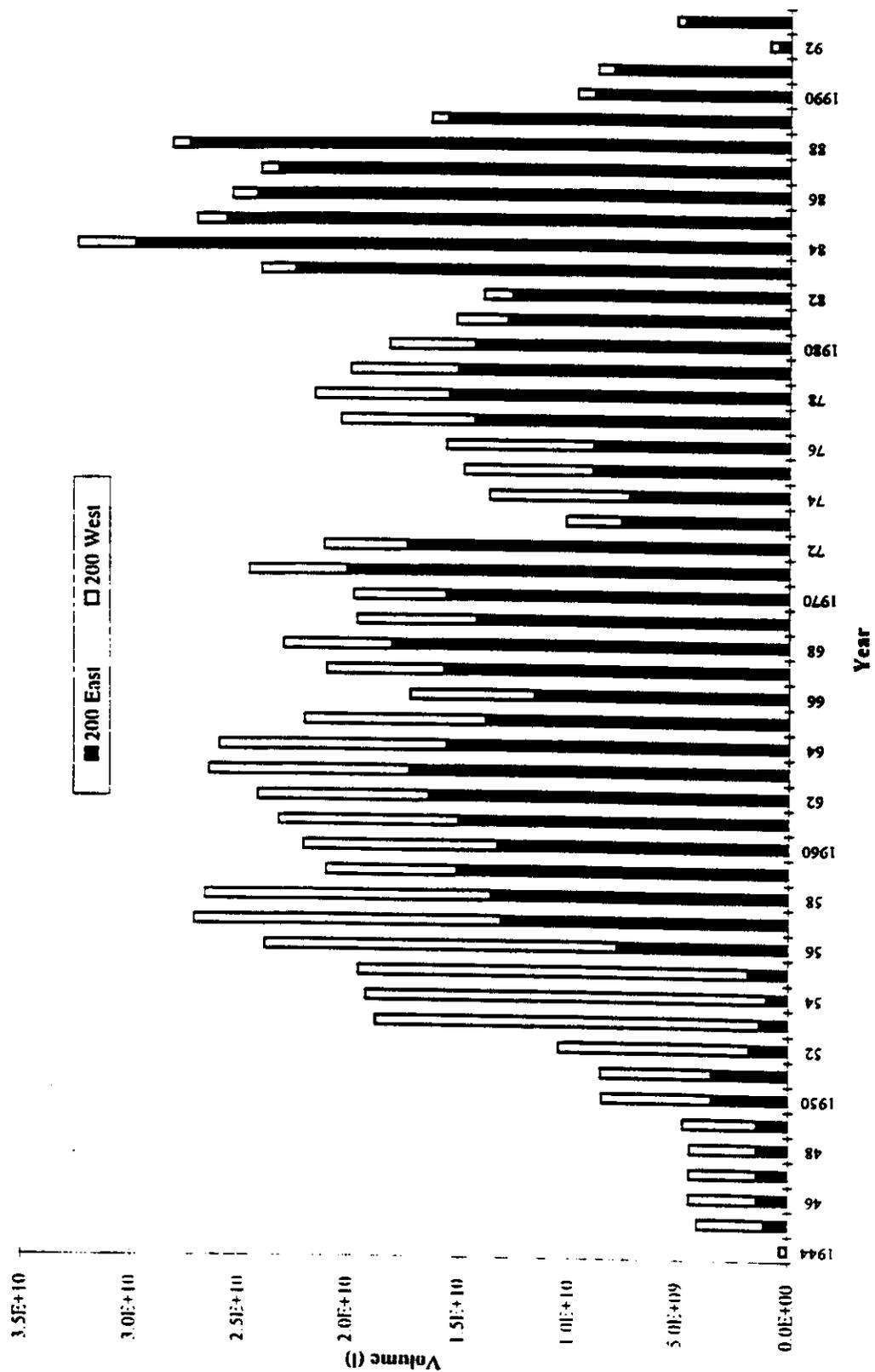


Figure 2-12. Location Map of Major Liquid Waste Disposal Facilities in the 200 East and 200 West Areas.

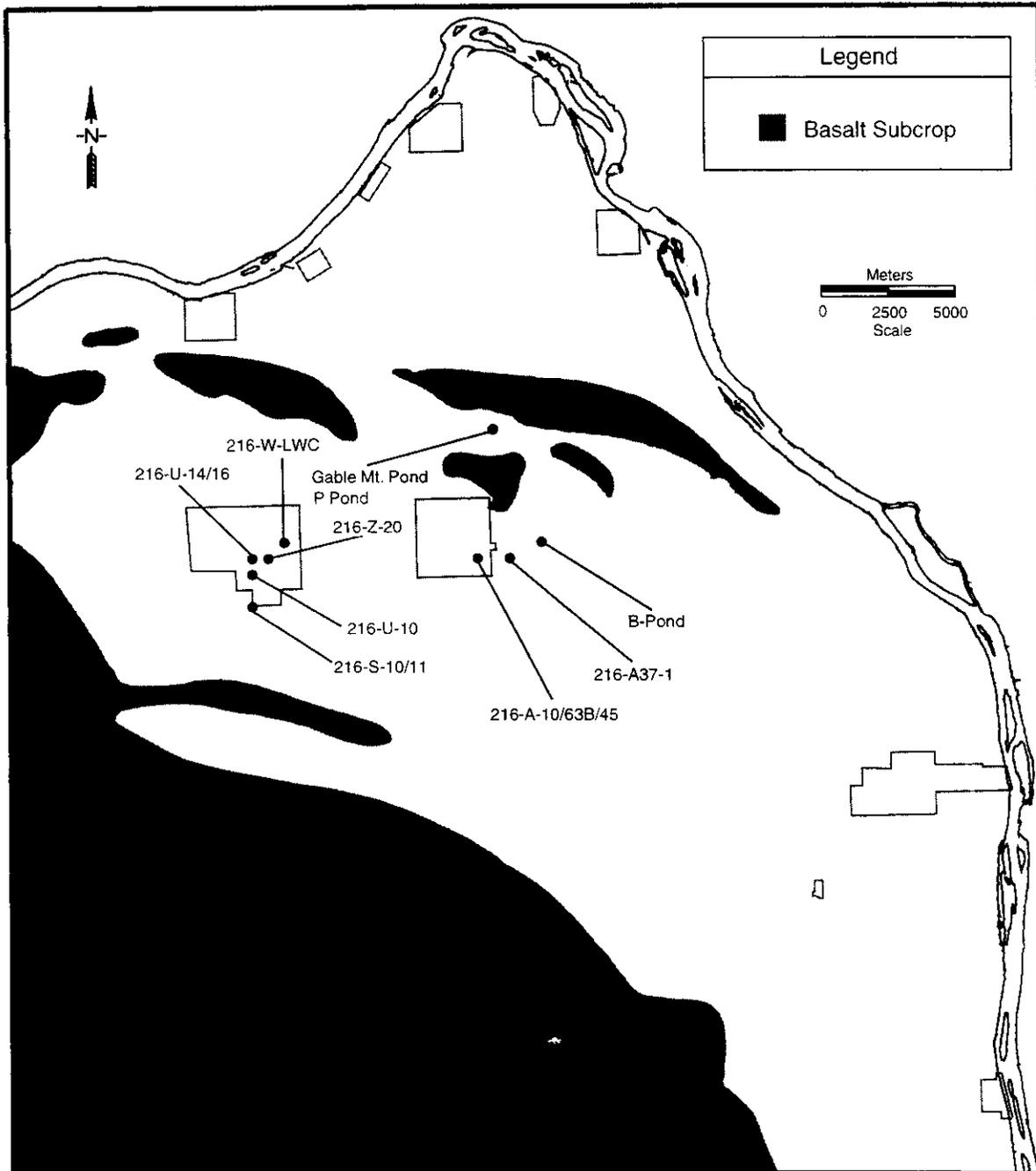


Table 2-1. Structure Contour and Isopach Data for the Ringold Formation at Selected Boreholes at the Hanford Site (from Lindsey 1995). Page 1 of 7

Borehole #	Easting	Northing	Top Bas	Top Sub A	Iso Sub A	Top A	Iso A	Top LM	Iso LM	Top BD	Iso BO	Top Sub C	Iso Sub C	Top C	Iso C	Top Sub E	Iso Sub E	Top E	Iso E	Iso C+E	Top UR	Iso UR	Top PMPP	Iso PMPP	Top HI	Iso HI	Iso Eo	Elev
101-48C	575222.89	154411.01																			338 >28	338	0		387	49	0	387
103-25	582315.80	155095.00	312																									
107-79	565779.00	156071.00	305																									
107-83	564484.70	156306.90	340																									
109-80	565525.40	156928.30	430																									
10-3	588880.00	126580.00	-84																									
10-30	580747.30	126573.40	43																									
10-54A	573597.40	126572.00	360																									
10-E12	593575.00	126577.00	72		0	90	19	170	80	205	35	220	15	260	40	343 >27	35	420	77	77	420	0	420	0	507	87	9	516
111-24	582528.00	157331.00	490																									
112-37	578693.00	157549.00	453																									
113-38	578388.40	158105.20	457																									
114-60	571842.00	158340.00	552																									
115-61	571378.00	158413.00	494																									
115-7	587630.00	158898.00	880																									
115-77	568281.00	158642.00	590																									
117-11	586518.50	159113.00	892																									
119-11	586483.80	159859.20	981																									
11-29	581154.00	126938.00	-184																									
11-45	578279.00	126808.00	203		0	268	85	353	85	353	0	353	0	353	0	353	0	408	55	55	408	0	408	0	578	170	0	578
11-E4E	590984.65	126738.23	-25	-25	0	25	50	115	90	145	30	145	0	145	0	205	60	330	125	125	330	0	330	0	440	110	0	440
11-E8B	592319.31	126748.12		64	0	89	25	129	40	212	83	212	0	249	37	259	10	344	85	122	344	0	344	0	449	105	0	449
122-11	586436.20	160885.80	1191																									
12-1	589881.80	127038.30	-61																									
12-18	584514.50	127197.50	-188																									
13-28	581994.10	127391.70	-235																									
13-28	589353.85	127338.16		-82	0	-26	38	29	55	149	120	149	0	149	0	179	30	319	140	140	349	30	349	0	439	90	0	439
13-64	570418.00	127309.00		390	0	390	0	390	0	390	0	390	0	390	0	390	0	443	53	53	443	0	443	0	552	109	0	552
14-38	578411.00	127782.00	92																									
14-E3E	590878.18	127637.80		8	0	55	47	125	70	165	40	165	0	165	0	218	51	325	109	109	345	20	345	0	450	105	0	450
14-E8P	591593.89	127703.47			0	98	43	153	55	178	25	178	0	178	0	203	25	323	120	120	323	0	323	0	458	135	0	458
15-15A	585353.58	128023.99		-180	2	-105	55	5	110	60	55	120	60	160	40	190	30	290	100	140	330	40	395	65	545	150	0	545
15-26	581875.98	128254.88																										
15-E13	593789.00	128200.00		104	7	170	58	204	34	243	39	245	2	293	48	341	8	341	48	104	341	0	341	0	404	63	8	410
16-23	582942.00	128372.00	-168																									
16-30A	580620.00	128448.00	-306																									
16-E4A	591005.01	128299.37		155	0	174	19	248	72	298	50	298	0	332	36	342	10	370	28	84	370	0	370	0	459	89	0	459
17-15	585418.80	128548.80	-137																									
17-28	581930.00	128750.00		-178	22	-132	46	-23	109	28	49	94	88	148	54	184	16	255	91	145	320	65	393	73	523	130	0	523
17-47	575490.00	128785.00		243	0	250	7	278	28	295	19	295	0	295	0	358	63	398	40	40	398	0	398	0	571	173	5	578
17-70	568578.00	128647.00		313	18	333	20	353	20	353	0	353	0	353	0	443	90	524	81	81	524	0	524	0	563	39	0	563
17-93	561565.00	128829.00			0	736	0	736	0	736	0	736	0	736	0	736	0	736	0	0	736	0	736	0	765	29	0	765
18-21	583735.70	128785.20	-149																									
18-25	582427.10	128901.40	-244																									
18-23	582985.40	129315.00	-141																									
19-27	581850.80	129220.40	-184																									
19-34	580100.10	129085.10	-172																									
19-58	572153.00	129252.00		368	0	368	0	383	15	383	0	383	0	383	0	383	0	424	41	41	424	0	424	0	573	148	0	573
19-88	583183.30	129255.20	293																									
1-18	584528.90	123948.88														217 >30		412	195	195	412	0	412	0	532	120	5	537
20-18	584484.00	129419.30	-75																									
20-25	582486.40	129680.80	-145																									
20-39	577999.00	129729.00			0	-54	15	58	110	70	14	148	78	155	9	210	55	380	170	179	380	0	430	50	525	95	15	540
20-69	568842.80	129485.80	493																									
20-82	584812.00	129506.00		289	0	269	0	309	40	309	0	309	0	309	0	309	0	548	237	237	548	0	548	0	608	82	8	614
20-E12	593573.00	129718.00		112	15	112	0	182	70	248	84	248	0	287	41	287	0	352	65	108	357	5	372	15	437	85	0	437
20-E2	590685.00	129722.00		-13	0	11	24	91	80	153	82	161	8	201	40	224	23	311	87	127	334	23	398	84	466	68	0	466
20-E5	5																											











Table 2-1. Structure Contour and Isopach Data for the Ringold Formation at Selected Boreholes at the Hanford Site (from Lindsey 1995). Page 7 of 7

Borehole #	Easting	Northing	Top Bas	Top Sub A	Iso Sub A	Top A	Iso A	Top LM	Iso LM	Top BD	Iso BD	Top Sub C	Iso Sub C	Top C	Iso C	Top Sub E	Iso Sub E	Top E	Iso E	Iso C+E	Top UR	Iso UR	Top PMPP	Iso PMPP	Top HI	Iso HI	Iso Eo	Elev	
H3-2C	577632.23	152750.54																			356 >85	356	0	418	60	0	416		
H4-12C	578011.97	152920.10																			352 >160	352	0	411	59	0	406		
H4-15C	577907.86	153060.27	92	92	0	92	0	194	102	200	8	200	0	200	0	200	0	200	0	0	357	157	357	0	408	49	0	406	
H4-2	578094.00	152502.00	84	84	0	84	0	170	86	229	59	229	0	229	0	229	0	229	0	0	356	127	356	0	420	64	0	420	
K-20	569520.52	147667.24																			420	0	420	0	420	0	0	420	
K-24	568833.85	146934.33																			445 >1	445	0	445	0	467	22	0	467
N-2	571476.21	149859.43														351 >27	386	35	386	0	386	0	386	0	451	65	0	451	
N-5	571405.70	149875.17														349 >15	399	50	399	0	399	0	399	0	454	55	0	454	
N-89	571483.89	148804.80														358 >3	415	59	415	0	415	0	415	0	457	42	0	457	
N-80	571477.76	149951.09														357 >29	417	80	417	0	417	0	417	0	455	38	0	455	
S11-E12A	593576.40	120173.85	129	129	0	160	31	195	35	225	30	225	0	225	0	255	30	310	55	55	310	0	310	0	365	55	0	365	
S12-29	580953.00	119932.00	308	308	0	308	0	332	24	352	20	352	0	352	0	382	10	427	65	65	427	0	427	0	487	60	0	487	
S12-3	589113.03	119761.79														326 >2	391	65	391	0	391	0	391	0	430	39	5	430	
S14-20A	583921.00	119087.00			0	347	15	357	10	357	0	357	0	357	0	357	0	392	35	35	392	0	392	0	472	80	20	492	
S16-24	582765.00	118540.00	534																										
S16-E14A	594330.00	118797.00	204																										
S17-24	582523.60	118336.70	500																										
S17-25	582373.60	118332.50	450																										
S17-28	581487.90	118348.10	440																										
S17-30	580932.10	118311.90	430																										
S18-51	574395.00	117994.00	1169																										
S18-E2A	590549.00	117881.00	165	165	0	185	0	229	44	274	45	274	0	274	0	279	5	364	85	85	364	0	364	0	424	60	10	434	
S19-11	586583.82	117799.80																			388	0	388	0	483	95	0	483	
S19-E13	593835.39	117605.38																			316 >5	316	0	316	0	378	60	15	391
S1-7	587778.50	123118.90	-72																										
S1-8H	587524.94	123302.58	-57	-57	0	0	57	70	70	120	50	120	0	120	0	145	25	410	285	285	410	0	410	0	550	140	5	555	
S22-E9C	592689.00	116753.00	201	201	0	201	0	222	21	256	34	281	5	310	49	326	16	341	15	84	341	0	341	0	367	26	4	371	
S24-19	584182.00	116200.00	381	381	0	381	0	381	0	381	0	381	0	381	0	381	0	403	22	22	403	0	403	0	426	23	1	427	
S27-E9C	592721.00	115325.00	189	189	0	189	0	211	22	252	41	288	16	288	20	314	26	341	27	47	341	0	341	0	386	45	2	388	
S28-E0	590205.30	114994.30	225																										
S29-E12	593826.16	114569.88																			339 >35	339	0	339	0	384	45	0	384
S29-E10C	594742.00	114731.00	202	202	0	202	0	258	56	292	34	292	0	292	0	292	0	319	27	27	319	0	319	0	374	55	3	377	
S30-E15C	594368.00	114270.00	201	201	0	201	0	241	40	271	30	271	0	271	0	281	10	331	50	50	331	0	331	0	399	68	2	401	
S31-1	589749.00	114213.00	239	239	0	239	0	274	35	311	37	311	0	311	0	327	16	367	60	60	367	0	367	0	444	57	16	460	
S3-25	582459.96	122587.86																			398 >39	398	0	398	0	493	95	30	523
S3-67	569446.00	122507.00	1160																										
S3-E12	583586.00	122615.00			0	145	0	178	33	225	47	245	20	306	61	313	7	340	27	88	351	11	351	0	378	27	17	385	
S4-E16	594988.00	122405.00	187	187	0	187	0	193	6	236	43	236	0	236	0	270	34	318	48	48	318	0	318	0	343	25	0	343	
S6-E14A	594262.39	121569.74	181	181	0	181	0	202	21	260	78	260	0	260	0	288	6	342	54	54	342	0	342	0	378	36	0	378	
S6-E4C	591083.17	121663.59	84	84	0	102	38	136	34	198	62	234	36	291	57	314	23	378	82	119	376	0	376	0	431	55	0	431	
S7-34	579431.00	121503.00	384	384	0	401	17	435	34	435	0	435	0	435	0	435	0	435	0	0	435	0	435	0	523	88	4	527	
S7-62	571034.00	121248.00	1250																		391 >36	391	0	391	0	484	83	19	503
S8-19	584226.54	120964.55																											
S9-58	572986.00	120672.00	1112																										
S9-63B	570661.00	120745.00	1168																										
W10-14	568018.00	136609.00						248 >11	248																				
W11-2	567407.00	136671.00	199	199	0	272	73	289	17	289	0	289	0	289	0	289	0	559	313	313	559	0	566	7	696	130	0	696	
W11-28	567045.00	136564.00	190	190	0	264	74	281	17	281	0	281	0	281	0	281	0	552	271	271	564	0	601	37	707	108	5	712	
W14-7	567034.00	136554.00	159	159	0	214	55	253	39	253	0	253	0	253	0	253	0	547	294	294	547	0	558	11	672	114	5	677	
W14-8	568073.30	135996.70	186	186	0	265	79	282	17	282	0	282	0	282	0	282	0	547	285	285	547	0	555	8	722	187	0	722	
W15-14	566093.00	135648.00	134	134	0	199	85	240	41	240	0	240	0	240	0	240	0	517	277	277	528	11	540	12	693	153	5	698	
W15-5	566735.00	135512.00	142	142	0	188	48	242	54	242	0	242	0	242	0	242	0	532	290	290	532	0	549	17	652	103	18	670	
W18-22	566089.13	134990.30																			281 >70	281	0	281	0	306	130	0	666
W19-10	566887.00	134925.00	125	125	0	195	70	221	26	221	0	221	0	221	0	221	0	509	288	288	509	0	540	31	680	140	0	680	
W19-4	568003.00	135366.40	178	178	0	191	15	210	19	210	0	210	0	210	0	210	0	451	241	241	470	19	548	76	708	162	5	713	
W19-8	567564.00	135220.00	140	140	0	235	95	267	32	267	0	267	0	267	0	267	0	490	223	223	490	0	525	35	700	175	0	700	
W22-19	567618.44	133981.44																			453 >223	453	0	487	34	678	191	2	680
W22-24	567648.00	134411.00	122	122	39	262	101	293	31	293	0	293	0	293	0	293	0	450	157	157	473	23	500	27	690	180	0	690	
W22-27	567151.00	134497.00	120	120	8	174	45	226	52	226	0	226	0	226	0	226	0	489	263	263	524	35	544	20	678	135	0	679	
W27-2	566906.55	133670.63																			250 >12	250	0	250	0	272	171	2	272
W6-1	567214.00	137510.00	232																										

Table 2-2. Hydraulic Conductivity Used in Model Setup.  
(Page 1 of 2)

Hanford Well Designation	Transmissivity ft <sup>2</sup> /d (m <sup>2</sup> /d)	Hydraulic Conductivity ft/d (m/y)	Hydrogeologic Unit	Source
199-H3-2A	19,000 (1,765)	1,900 (2.11E+05)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
199-H4-10	53,500 (4,970)	5,940 (6.61E+05)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
199-H4-11	1,070 (99)	71 (7.90E+03)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
199-H4-12A	2,670 (248)	213 (2.37E+04)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
199-H4-15A	2,340 (217)	195 (2.17E+04)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
199-K-10	4,500 (418)	53 (5.90E+03)	Ringold	Thorne and Newcomer (1992)
299-E18-1	700 (65)	50 (5.56E+03)	Ringold	Newcomer et al. (1992a)
299-E18-3	3,000 (279)	210 (2.34E+04)	Ringold	Newcomer et al. (1992a)
299-E25-22	150,000 (13,935)	6,200 (6.90E+05)	pre-Missoula/ Hanford	Newcomer et al. (1992a)
299-E25-34	>250,000 (>23,225)	19,000 (2.11E+06)	pre-Missoula/ Hanford	Newcomer et al. (1992a)
299-E25-35	>80,000 (>7,432)	6,500 (7.23E+05)	pre-Missoula/ Hanford	Newcomer et al. (1992a)
299-E27-8	>68,000 (>6,317)	6,800 (7.57E+05)	pre-Missoula/ Hanford	Newcomer et al. (1992a)
299-E27-9	35,000 (3,252)	3,500 (3.89E+05)	pre-Missoula/ Hanford	Newcomer et al. (1992a)
299-E28-27	>48,000 (>4,459)	4,800 (5.34E+05)	Ringold	Newcomer et al. (1992a)
299-E32-4	>9,500 (>883)	950 (1.06E+05)	Ringold	Newcomer et al. (1992a)
299-E33-28	>53,000 (>4,924)	5,300 (5.90E+05)	Ringold	Newcomer et al. (1992a)
299-E33-29	>51,000 (>4,738)	5,100 (5.67E+05)	Ringold	Newcomer et al. (1992a)
299-E33-30	>56,000 (>5,202)	5,600 (6.23E+05)	pre-Missoula/ Hanford	Newcomer et al. (1992a)
299-E34-2	114,000 (10,591)	11,400 (1.27E+06)	pre-Missoula/ Hanford	Newcomer et al. (1992a)
299-E34-3	14,000 (1,301)	1,400 (1.56E+05)	pre-Missoula/ Hanford	Newcomer et al. (1992a)
299-W10-13	7,000 (650)	700 (7.79E+04)	Ringold	Connelly et al. (1992b)
299-W10-14	3,500 (325)	350 (3.89E+04)	Ringold	Connelly et al. (1992b)
299-W15-15	10,000 (929)	1,000 (1.11E+05)	Ringold	Connelly et al. (1992b)
299-W15-16	12,000 (1,115)	1,200 (1.34E+05)	Ringold	Connelly et al. (1992b)
299-W15-17	12,000 (1,115)	1,200 (1.34E+05)	Ringold	Connelly et al. (1992b)
299-W15-18	14,000 (1,301)	1,400 (1.56E+05)	Ringold	Connelly et al. (1992b)
299-W18-21	51,000 (4,738)	5,100 (5.67E+05)	Ringold	Connelly et al. (1992b)
299-W18-22	420 (39)	42 (4.67E+03)	Ringold	Connelly et al. (1992b)
299-W18-23	23,000 (2,137)	2,300 (2.56E+05)	Ringold	Connelly et al. (1992b)
299-W18-24	44,000 (4,088)	4,400 (4.90E+05)	Ringold	Connelly et al. (1992b)
299-W6-2	500 (46)	50 (5.56E+03)	Ringold	Connelly et al. (1992b)
299-W7-1	1,400 (130)	140 (1.56E+04)	Ringold	Connelly et al. (1992b)
299-W7-2	740 (69)	74 (8.23E+03)	Ringold	Connelly et al. (1992b)
299-W7-4	2,800 (260)	95 (1.06E+04)	Ringold	Connelly et al. (1992b)
299-W7-5	170 (16)	9 (1.00E+03)	Ringold	Connelly et al. (1992b)
299-W7-6	40 (4)	4 (4.45E+02)	Ringold	Connelly et al. (1992b)
299-W8-1	80 (7)	8 (8.90E+02)	Ringold	Connelly et al. (1992b)
699-1-18	10,000 (929)	60 (6.68E+03)	Ringold	Bierschenk (1959)
699-10-54A	9,700 (901)	346 (3.85E+04)	Ringold	Thorne and Newcomer (1992)
699-17-47	5,100 (474)	50 (5.56E+03)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
699-17-5	1,100 (102)	25 (2.78E+03)	Ringold	Bierschenk (1959)
699-2-3	25,000 (2,323)	420 (4.67E+04)	Ringold	Kipp and Mudd (1973)
699-2-33A	4,600 (427)	105 (1.17E+04)	Ringold	Thorne and Newcomer (1992)
699-20-20	3,200 (297)	160 (1.78E+04)	pre-Missoula/ Hanford	Bierschenk (1959)
699-24-33	390,000 (36,231)	8,600 (9.57E+05)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
699-26-15	8,400 (780)	175 (1.95E+04)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
699-26-35C	74,000 (6,875)	1,200 (1.34E+05)	pre-Missoula/ Hanford	Weeks et al. (1987)

Table 2-2. Hydraulic Conductivity Used in Model Setup.  
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699-26-89	525 (49)	2 (2.23E+02)	Ringold	Deju (1974), Kipp & Mudd (1973)
699-31-31	250,000 (23,225)	7,100 (7.90E+05)	pre-Missoula/ Hanford	Bierschenk (1959)
699-31-53B	14,000 (1,301)	117 (1.30E+04)	Ringold	Deju (1974), Graham et al. (1981)
699-32-77	4,500 (418)	21 (2.34E+03)	Ringold	Kipp & Mudd (1973), Graham et al. (1981)
699-33-56	1,100 (102)	13 (1.45E+03)	Ringold	Bierschenk (1959); Kipp and Mudd (1974)
699-35-9	14,900 (1,384)	298 (3.32E+04)	pre-Missoula/ Hanford - Ringold	Thorne and Newcomer (1992)
699-36-61A	3,900 (362)	60 (6.68E+03)	Ringold	Deju (1974), Graham et al. (1981)
699-37-82A	270 (25)	9 (1.00E+03)	Ringold	Graham et al. (1981)
699-40-1	30,000 (2,787)	600 (6.68E+04)	pre-Missoula/ Hanford	Luttrell et al. (1989)
699-40-33A	200 (19)	1 (1.45E+02)	Ringold - lower mud	Bierschenk (1959)
699-41-23	28,000 (2,601)	190 (2.11E+04)	pre-Missoula/ Hanford	Bierschenk (1959)
699-42-12A	86,000 (7,989)	660 (7.34E+04)	Ringold	Bierschenk (1959)
699-43-43	37,000 (3,437)	2,100 (2.34E+05)	pre-Missoula/ Hanford	WHC (1990)
699-43-88	970 (90)	10 (1.11E+03)	Ringold	Newcomer et al. (1992a)
699-46-21B	3,900 (362)	29 (3.23E+03)	Ringold	Thorne and Newcomer (1992)
699-47-35C	530 (49)	12 (1.34E+03)	Ringold	Newcomer et al. (1992b)
699-47-60	3300 (307)	80 (8.90E+03)	Ringold	Kipp and Mudd (1973); Deju (1974)
699-53-55A	66,300 (6,159)	660 (7.34E+04)	pre-Missoula/ Hanford	Thorne and Newcomer (1992)
699-55-50B	594,000 (55,183)	6,150 (6.84E+05)	pre-Missoula/ Hanford	Deju (1974); Graham et al. (1981)
699-61-66	>40,000 (>3,716)	500 (5.56E+04)	pre-Missoula/ Hanford	Deju (1974)
699-63-90	63,000 (5,853)	450 (5.01E+04)	pre-Missoula/ Hanford - Ringold	Kipp and Mudd (1973)
699-65-50	64,000 (5,946)	1,800 (2.00E+05)	pre-Missoula/ Hanford	Bierschenk (1959)
699-71-77	44,000 (4,088)	120 (1.34E+04)	Ringold	Kipp and Mudd (1973)
699-8-17	35,000 (3,252)	640 (7.12E+04)	pre-Missoula/ Hanford	Deju (1974)
699-8-32	1,000 (93)	20 (2.23E+03)	Ringold	Kipp and Mudd (1973)
699-87-55	1,950 (181)	55 (6.12E+03)	Ringold	Gilmore et al. (1992)
699-S8-19	11000 (1,022)	270 (3.00E+04)	Ringold	Bierschenk (1959)

ft<sup>2</sup>/d = square feet per day  
m<sup>2</sup>/d = square meters per day  
ft/d = feet per day  
m/y = meters per year

Table 2-3. Liquid Waste Disposal Facilities Included in the Calibration (liters/year).

200 East Area		200 West Area	
Facility	Rate (L/yr x [gal/yr])	Facility	Rate (L/yr [gal/yr])
216-A-10	$3.30 \times 10^8$ ( $8.71 \times 10^7$ )	216-S-10	$1.59 \times 10^9$ ( $4.20 \times 10^8$ )
216-A-36B	$2.20 \times 10^8$ ( $5.80 \times 10^7$ )	216-U10	$7.47 \times 10^9$ ( $1.97 \times 10^9$ )
216-A37-1	$3.09 \times 10^8$ ( $8.16 \times 10^7$ )	216-U-14	$3.08 \times 10^9$ ( $8.13 \times 10^8$ )
216-A-45	$1.03 \times 10^8$ ( $2.72 \times 10^7$ )	216-U-16	$4.09 \times 10^8$ ( $1.08 \times 10^8$ )
Gable Mtn Pond	$7.98 \times 10^{10}$ ( $2.11 \times 10^{10}$ )	6-W-LWC	$1.04 \times 10^9$ ( $2.75 \times 10^8$ )
B Pond	$1.41 \times 10^{11}$ ( $3.72 \times 10^{10}$ )	216-Z-20	$4.07 \times 10^9$ ( $1.07 \times 10^9$ )

Table 2-4. Tritium Discharged from Liquid Waste Disposal Facilities (curies/year).

200 East Area	
216-A-10	$2.37 \times 10^4$
216-A36B	$6.47 \times 10^2$
216-A-37	$1.85 \times 10^3$
216-A-45	$4.20 \times 10^3$
B Pond	3.08

### 3.0 VAM3DCG MODEL APPLICATION

#### 3.1 MODEL SETUP

The modeled region covers approximately 971 km<sup>2</sup> (375 mi<sup>2</sup>) and is bounded by Rattlesnake Mountain to the southwest, Cold and Dry Creeks to the west, and the Columbia River to the north and east. The domain consists of the unconfined aquifer system with the bottom of the Ringold Formation at the base, and the pre-Missoula/Hanford formation on the top where it exists. The general trend for water in the unconfined modeled system is from west to east, with water entering the domain from Cold Creek and Dry Creek, and discharge occurring into the Columbia River. The system also receives artificial recharge of wastewater generated by the Hanford operations, primarily from surface ponds, ditches, and cribs located in the 200 West and 200 East Areas. Communication between the modeled unconfined aquifer and the underlying confined systems is assumed negligible, as is areal recharge over the site due to precipitation.

Water table levels across the simulation domain were observed to remain fairly constant from 1976 to 1979 and the model first was calibrated for steady-state conditions to these water levels. Transient simulations were performed for a 14-yr period to represent model system behavior from January 1980 through December 1993. Recharge of water from the cribs and ponds was varied to reflect the changing wastewater disposal trends at the site. Wastewater disposal volumes have been declining since the mid to late 1980's.

#### 3.2 GRID

The model grid size is dependent on the domain area of interest and the problem to be solved. Small grid spacing provides for greater accuracy but requires increased computer time and a larger grid spacing provides for less computer time but provides for less accuracy. Therefore a compromise must be established. A horizontal finite element grid size of 600 m by 600 m (1,970 ft by 1,970 ft) (Figure 3-1) was selected as it provided the needed accuracy and with a reasonable amount of computer computational time. The Hanford Site unconfined groundwater flow system was simulated using a six-layer model with 2,474 elements and 2,611 nodes per layer. The vertical grid spacing was established considering the saturated thickness of the aquifer in total and the individual saturated thicknesses of the two geohydrologic units. Vertical discretization was performed using six elemental layers; the top three represent the pre-Missoula/Hanford formation and the bottom three the underlying Ringold Formation. Application of "pseudo-soil" model functions, used to deal with unconfined groundwater conditions, requires that the water table be located between two grid nodes (see Appendix A for a discussion of "pseudo-soil" model functions). Thus, at least two layers of elements are required. In addition, during contaminant transport modeling, it was determined that multiple layers were required for vertical segregation of contaminants. In consideration of the above modeling needs and requirements, a model using six layers was selected. A six-layer model represented an appropriate compromise between numerical issues and the project needs. The six

layers are not intended to present individual geohydrologic layers but are used to allow for model computational requirements. Thus, only geohydrologic units are represented in the model.

A vertically deformed grid was used to allow the model geometry to conform to the topography of the top and bottom of the modeled formation. Vertical discretization varied from 0.5 m (1.6 ft) to 20 m (65.6 ft) depending on formation thicknesses.

### **3.3 INITIAL ELEMENT PROPERTIES**

The hydrogeologic units of interest consist of the Ringold Formation overlain (in eastern portions of the domain) by the highly conductive pre-Missoula/Hanford formation. The domain is separated into two distinct hydrogeologic units, the Ringold and the pre-Missoula/Hanford formations. Each of the units is represented by three elemental layers with material properties assigned to each model element. For groundwater flow, horizontal and vertical hydraulic conductivity, specific storage, storativity, and porosity values are assigned. Eighteen distinct elemental zones were identified, which covered the expected aquifer parameter range for the site. For initial conditions, these distinct material zones were assigned to each element of the finite-element grid such that the hydraulic conductivities approximated the observed value at each location. Material properties were distributed homogeneously in the vertical direction for each hydrogeologic unit.

Model calibration was conducted by adjusting the element or zone conductivity values such that the modeled behavior mimics the observed water levels and recharge/discharge values. The elemental zones and material properties for the final calibrated groundwater flow model are listed in Table 3-1. Figures 3-2 and 3-3 show the calibrated model material zone distribution across the modeled area for the Ringold and pre-Missoula/Hanford units. Specific storage values were varied to represent observed condition and storativity was held constant. Porosity was varied in a few of the element zones to represent observed conditions.

### **3.4 BOUNDARY CONDITIONS**

Boundary conditions were applied to the model as conceptualized in Chapter 2.0. Inflow boundaries along Cold Creek, Dry Creek, and the Yakima River initially were treated as prescribed head conditions, with the head values supplied from observed water table elevations in the region. Holding heads constant allows the model to calculate recharge into the system so that the reasonableness of model recharge can be assessed. After the model was calibrated to satisfactorily emulate field conditions, the upstream boundaries for Cold and Dry Creeks were changed to flux boundaries, using flux values obtained from the simulations using constant head. The change to flux boundaries was warranted due to the likelihood of declining water levels for simulations of future groundwater flow conditions. Boundary conditions for the Yakima River remained as constant head. Model boundaries are shown on Figure 3-4.

The southwest model boundary, along the front of Rattlesnake Ridge, is set at no flow as the recharge along Rattlesnake ridge is assumed to be negligible. If recharge does occur along this boundary, the effects on the overall model would be minimal, as this portion of the model domain is separated from the main portion by the subsurface extension of Yakima Ridge.

The model boundary along the Columbia River is constant head with head values determined from the average annual stage from five river-stage gages. Because of river gradient, the head values are constant with time but variable in distance. The stage values were noted to be fairly stable through time, and therefore individual element values were not varied during the model simulation period. The Yakima River, on the southern boundary of the model, is treated as a constant head boundary.

Boundaries to flow also were set in the domain interior at Gable Mountain, Gable Butte, associated subcrops, and the subcrop associated with the subsurface extension of Yakima Ridge. For these features, the hydraulic properties were set to zero to establish no flow in these elements. The bottom model boundary is assumed to have a no-normal-flow condition.

Recharge to the model primarily is from natural sources Dry and Cold Creeks and from artificial sources resulting from Hanford Site operations. Recharge from precipitation generally is agreed to be negligible in areas with vegetation and fine-grained sediments (see discussion in Section 2.3.2.1) and was set to zero in the model domain.

The model assumes that there is no interchange of water between the underlying confined aquifer system and the unconfined system. Potentiometric data indicate the possibility for vertical leakage as discussed in Section 2.3.2.1. However, there is inadequate data on which to quantify leakage. In addition, the vertical conductivity of the underlying basalt is very low, which would indicate low leakage rates.

Artificial recharge resulting from Hanford operations, discussed in Section 2.5, was input at nodes coincident with the disposal site location. Table 2-3 provides a listing of the volumes disposed of to the various disposal facilities represented in the model. The estimated average fluxes from 1976 to 1979 were used to calibrate steady-state model flow conditions. Annual estimated fluxes for each disposal facility were input for the years 1980 through 1993. Recharge from facilities contributing only negligible volumes were not included. Artificial recharge volumes from included facilities representing approximately 90 percent of the total volume disposed of across the site.

### **3.5 INITIAL CONDITIONS AND PLAN FOR MODEL CALIBRATION**

The groundwater flow portion of model was calibrated to both steady-state and transient groundwater flow conditions. The steady-state flow was calibrated to 1979 conditions, and the transient period was run for 14 yr from 1980 through 1993. The transient calibration was evaluated for 1988 and 1993. 1979 was chosen for the steady-state calibration point because

water levels and waste water discharges between 1976 and 1979 remained relatively constant. Figure 3-5 is a west-to-east cross section through the central modeled domain. The figure shows the vertical distribution of the calibrated material properties. Figure 3-6 shows the contoured elevations of the pre-Missoula/Hanford formation - Ringold Formation Contact.

The calibration of groundwater flow was confirmed by simulating tritium transport. Tritium was selected because it has been discharged to the ground in large quantities at numerous locations across the site and is the most aerially distributed contaminant onsite, as other radioisotopes and hazardous chemicals are not as widespread in the groundwater. Tritium also is ideal for confirming groundwater movement because it is a chemically unretarded contaminant moving at the same rate as the groundwater.

Groundwater flow calibration confirmation using tritium transport began by including the observed 1979 tritium distribution with the calibrated steady-state flow model. Transient simulations were run for the period 1979 through 1993, with actual versus simulated plumes checks made for 1988 and 1993.

### **3.6 FLOW CALIBRATION AND VALIDATION**

Several groundwater flow simulations were first performed to calibrate the model to where it reasonably emulates observed water levels. Each simulation series was comprised of a steady-state flow simulation followed by a transient simulation. The steady-state simulation was calibrated to water levels observed in December 1979, and the transient simulations were run for 14 yr to December 1993. During the steady-state calibration process, the various material properties are adjusted to better simulate groundwater levels during December 1979. The final material values for the calibrated model are listed in Table 3-1. The distribution of these values throughout the modeled domain are shown in Figures 3-2 and 3-3. Figure 3-7 shows a comparison between observed water table elevations and the calibrated model results for the steady-state conditions of December 1979. In general, observed water table and modeled elevations are in agreement when observed from a sitewide perspective. Water levels throughout most of the modeled domain are within a few feet of observed values. There are however, local areas where modeled values are different than observed values. These areas are associated with groundwater flow gaps where groundwater flows between no-flow zones near basalt ridges and immediately north of the ridges. Summary statistics comparing model predictions to observed water table values are presented in Appendix C. Groundwater flux through the water gaps is uncertain as well as hydraulic properties of the units, which results in a poorer match between actual and simulated water levels. In addition, there is an approximately 3m (10 ft) difference between observed and simulated water levels along the Columbia River Boundary.

Recharge to the system from Cold Creek was 0.12 m<sup>3</sup>/sec (4.3 cfs) and Dry Creek 0.51 m<sup>3</sup>/sec (18.1 cfs), which is in agreement with field estimates of 0.028 to 0.28 m<sup>3</sup>/sec (1 to 10 cfs) discussed in Section 2.3.2. The model simulated an average of 1.47 m<sup>3</sup>/sec (51.9 cfs) was

discharged to the Columbia River during the modeled year 1979. This results in approximately 0.022 m<sup>3</sup>/sec (0.80 cfs) of groundwater discharged per km of river. This value is within an order of magnitude of the discharge estimates of Luttrell et al (1992) and Prater et al (1984) who estimated 0.21 m<sup>3</sup>/sec (7.4 cfs) and 0.085 m<sup>3</sup>/sec (3.0 cfs), is reasonable when considering the uncertainty of these estimates.

The calibrated steady-state simulation next was used as the starting point for a transient simulation of 14 yr. Flux boundary conditions over the ponds and cribs were varied annually in a stepwise fashion to represent the annual recharge at the respective locations. Figures 3-8 and 3-9 compare observed water table conditions with those modeled for 1988 and 1993. These modeled water levels are in agreement with observed. However, as with the steady-state simulation flow, there are differences near the water gaps associated with basalt ridges and along the boundary of the Columbia River. Features to note in these figures are: 1) the groundwater mound in 200 West Area declines during the 14-yr modeled period; and 2) the groundwater mound associated with 200 East Area and B Pond can be seen to increase between December 1979 and 1988, due to increased recharge to B Pond, and then decline with decreased discharge through 1993. Both of these are in agreement with observed water levels.

Figures 3-10, 3-11 and 3-12 illustrate the groundwater flow directions for the Hanford Site by using steady state velocity streamlines for 1979, 1988, and 1993. Each streamline represents the path that a single non-retarded, non-degraded particle would take if the groundwater flow was at steady state. Each solid dot represents 5 yr of travel time. Comparison of the three plots illustrates the following:

- The decline of the groundwater mound in the 200 West Area, which results in changing the groundwater flow from being split between flowing north through Gable Gap and easterly south of the 200 East Area towards the 300 Area, to all flow being directed through Gable Gap
- Flow in the central portion of the 200 East Area from flow south out of the 200 East Area then east towards the 300 Area to flowing north through Gable Gap and due east to the Columbia River just south of Gable Mountain.

These flow directions are consistent with observed tritium concentrations in and near Gable Gap between 1979, 1988, and 1993 (tritium concentrations are low in the Gable Gap area in 1979, then increase in 1988). The increased tritium concentrations in Gable Gap area are due to increased discharges of tritium contaminated water in 200 East Area and due to the change in flow directions with time.

### **3.7 TRANSPORT MODEL FOR FATE OF TRITIUM**

The objective of the transport simulations is to start with the tritium plume identified for 1979 conditions, and model the fate of tritium for 14 yr, through 1993. Transport of tritium is subject

to the calibrated transient flow field obtained for the same time period in earlier sections. Mechanisms that govern the fate of the tritium plume include advection, dispersion, and decay with adsorption being assumed negligible.

### 3.7.1 Tritium Numerical Model Development

The fate of tritium at the Hanford Site from January 1980 to January 1994 is examined under the flow field generated by the transient calibrated flow model over the same time period. The same material zones that were used for the flow model are provided to the transport model. Uniform transport properties are provided to all material zones in the Ringold and in the pre-Missoula/Hanford formations. Transport properties of the material zones are provided in Table 3-2. The dispersivities and porosities are representative of the soil at the site, and diffusion and decay constants are typical for tritium. The decay constant of  $0.0564 \text{ yr}^{-1}$  is based on the 12.3 yr half-life of tritium. The tritium plume configuration shown in Figure 3-13 is the observed averaged 1979-1981 conditions and provides initial conditions for the simulation. It should be noted that tritium concentrations along the 100 Areas were not input as part of the calibration process. The plume is known to not penetrate the Ringold Formation in the east, and modeled contaminant distributions were provided only on the top four layers of nodes, as initial conditions representative of January 1980. Boundary conditions for transport include a zero concentration for inflow at Cold and Dry Creeks and the Yakima River, and a zero normal concentration gradient condition at the discharge nodes along the Columbia River, which allows advective flux out to the river. Transient mass flux conditions are provided at inflow locations in the cribs and ponds. Observed annual average tritium mass inflows are supplied to the model as stepped annual variations in accordance with the flux conditions for the flow model.

Figures 3-14 and 3-15 provide 1979 simulated tritium concentrations and a comparison of simulations and measured initial conditions.

### 3.7.2 Simulation Results

The transport model was simulated through 14 yr (through December 1993) with the groundwater flow velocities supplied from the corresponding flow simulation. This ensures that the water table levels of the flow simulation are honored so that the combined flow and transport behavior of the model emulates site conditions. The transport simulation is performed and tritium distributions through the fifth nodal plane (2nd layer from the top) are presented. Figures 3-16, 3-17, and 3-18 present measured, simulated, and comparative plots 1988 conditions, respectively. Similarly, Figures 3-19, 3-20, and 3-21 present measured, simulated, and comparative plots for 1993 conditions, respectively. The tritium plumes compare fairly well with observed conditions, with slightly higher simulated concentrations noted in the east of the domain, than is observed. The domain lost a net  $2.16 \times 10^{14}$  pCi of tritium in the 14-yr simulation period, with  $1.75 \times 10^{13}$  pCi being discharged across the boundary into the Columbia River, and  $2.09 \times 10^{14}$  pCi having decayed. This results in over 81% of the tritium, lost to

decay, during the 14-yr simulation. These numbers include the continual operation of B Pond tritium releases.

The transport calibration process requires a recalibration of the flow field under which advection occurs. The entire model, for flow and transport, is noted to emulate field conditions fairly well from all parameters known, including Cold and Dry Creek recharge, water-table levels, and tritium plume distribution for 1979 and through 1988 and 1994.

Figure 3-1. VAM3DCG Finite Element Grid.

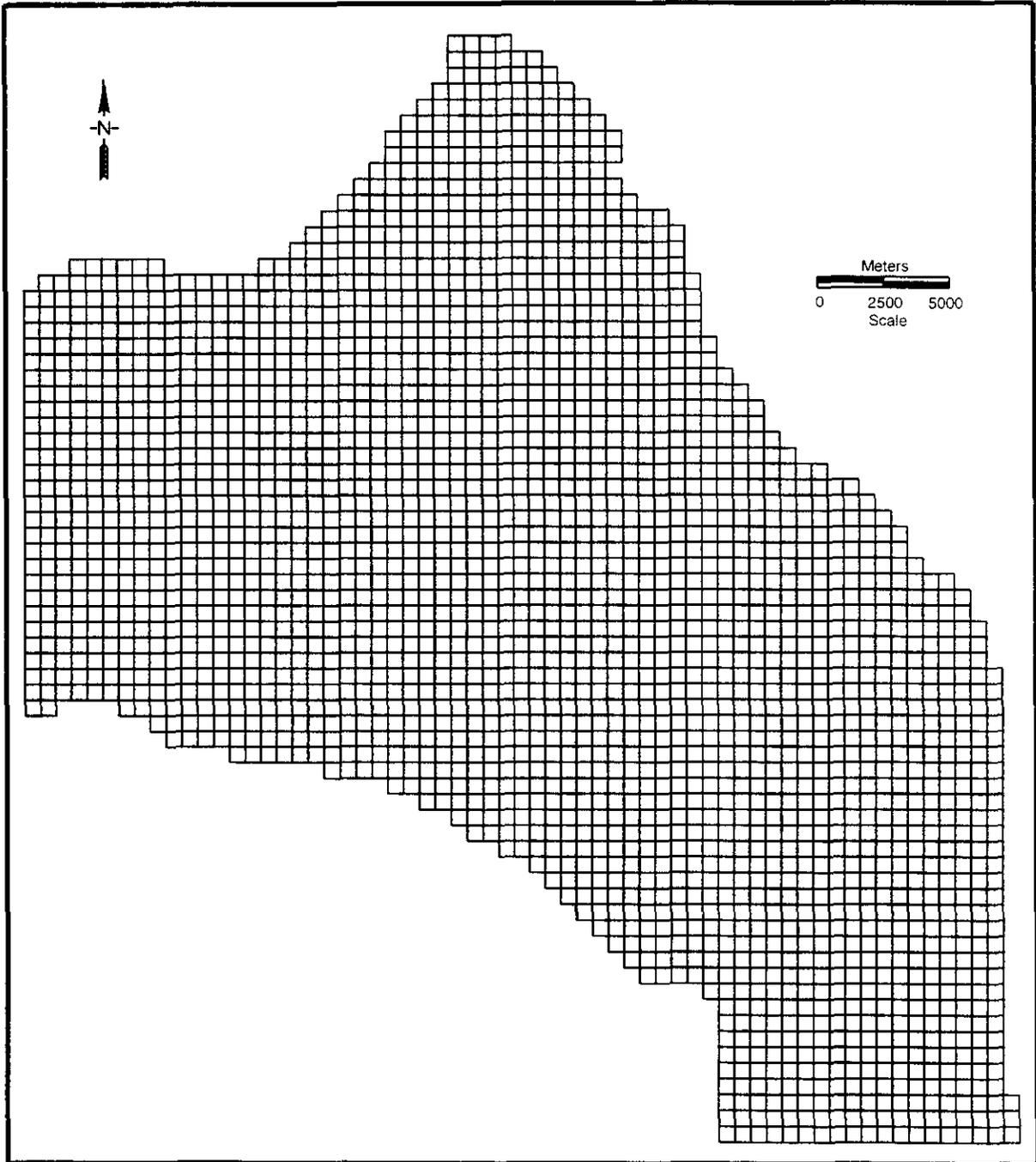


Figure 3-2. Material Property Distribution for the Lower Three Elemental Layers within the Domain.  
(See Table 3-1 or key to material properties.)



Figure 3-3. Material Property Distribution for the Upper Three Elemental Layers within the Domain.  
(See Table 3-1 for key to material properties )



Figure 3-4. Model Boundary Conditions.

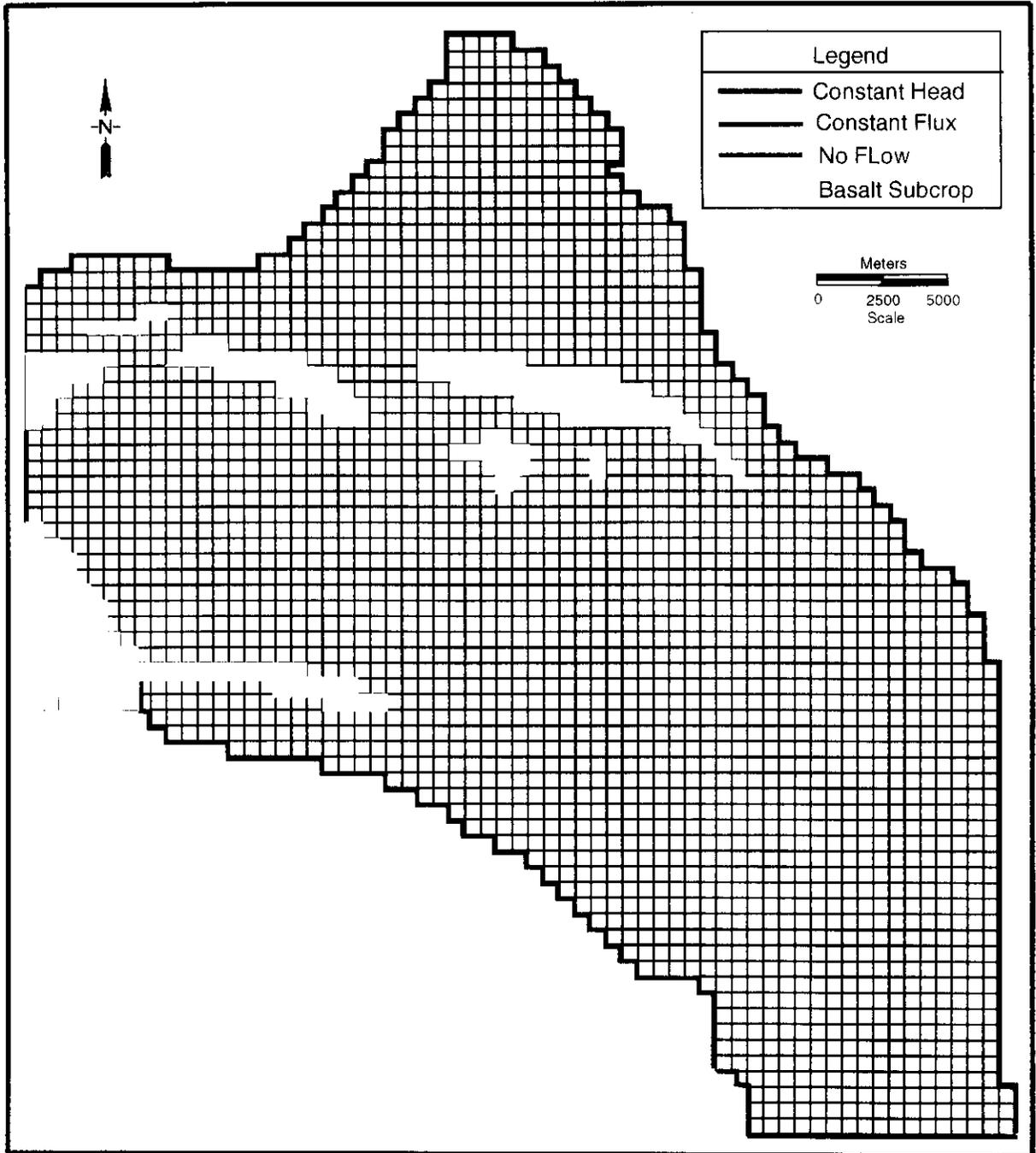


Figure 3-5. West-East Material Property Cross Section through Center of Modeled Domain.

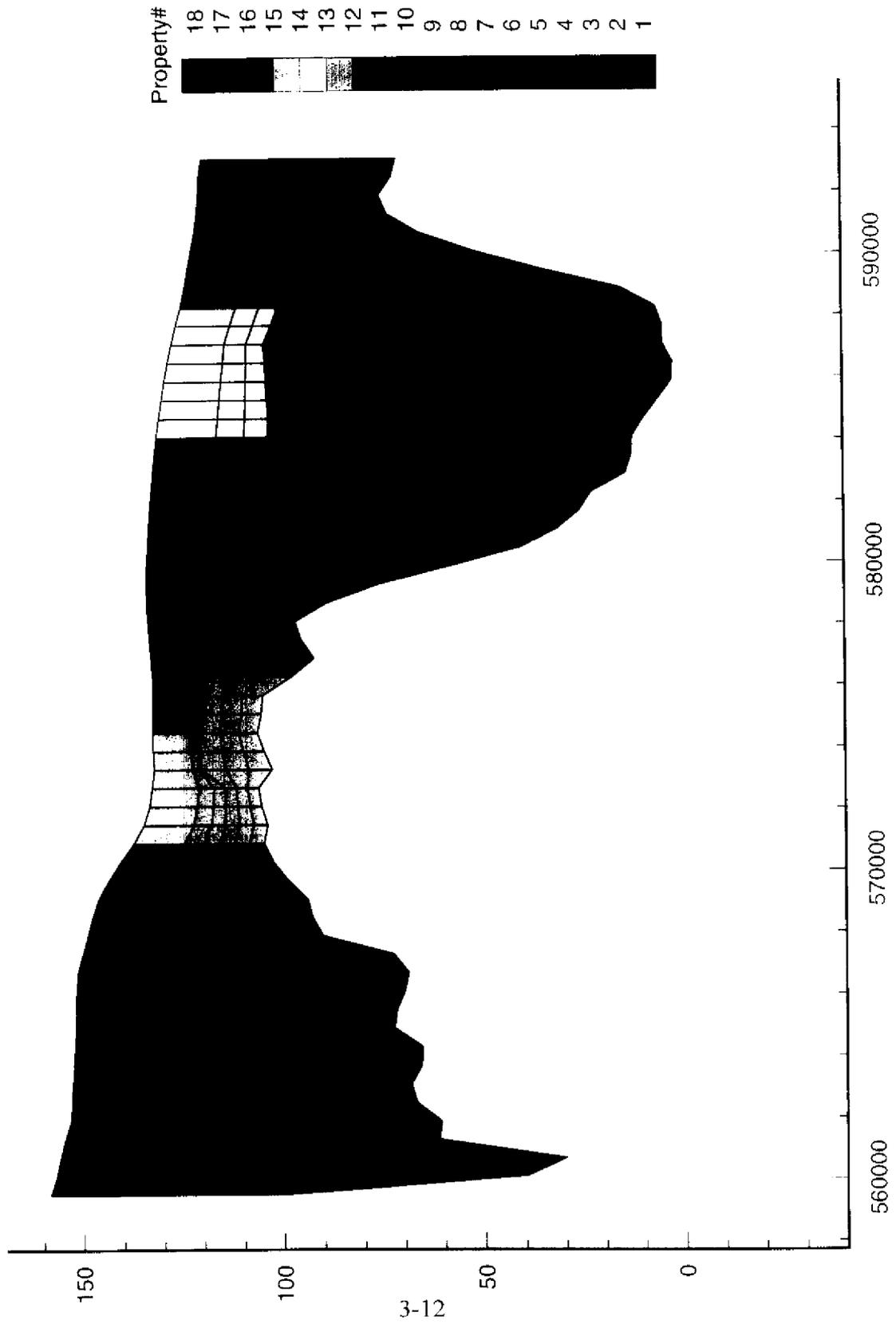


Figure 3-6. Elevation of pre-Missoula/Hanford Formation - Ringold Formation Contact.

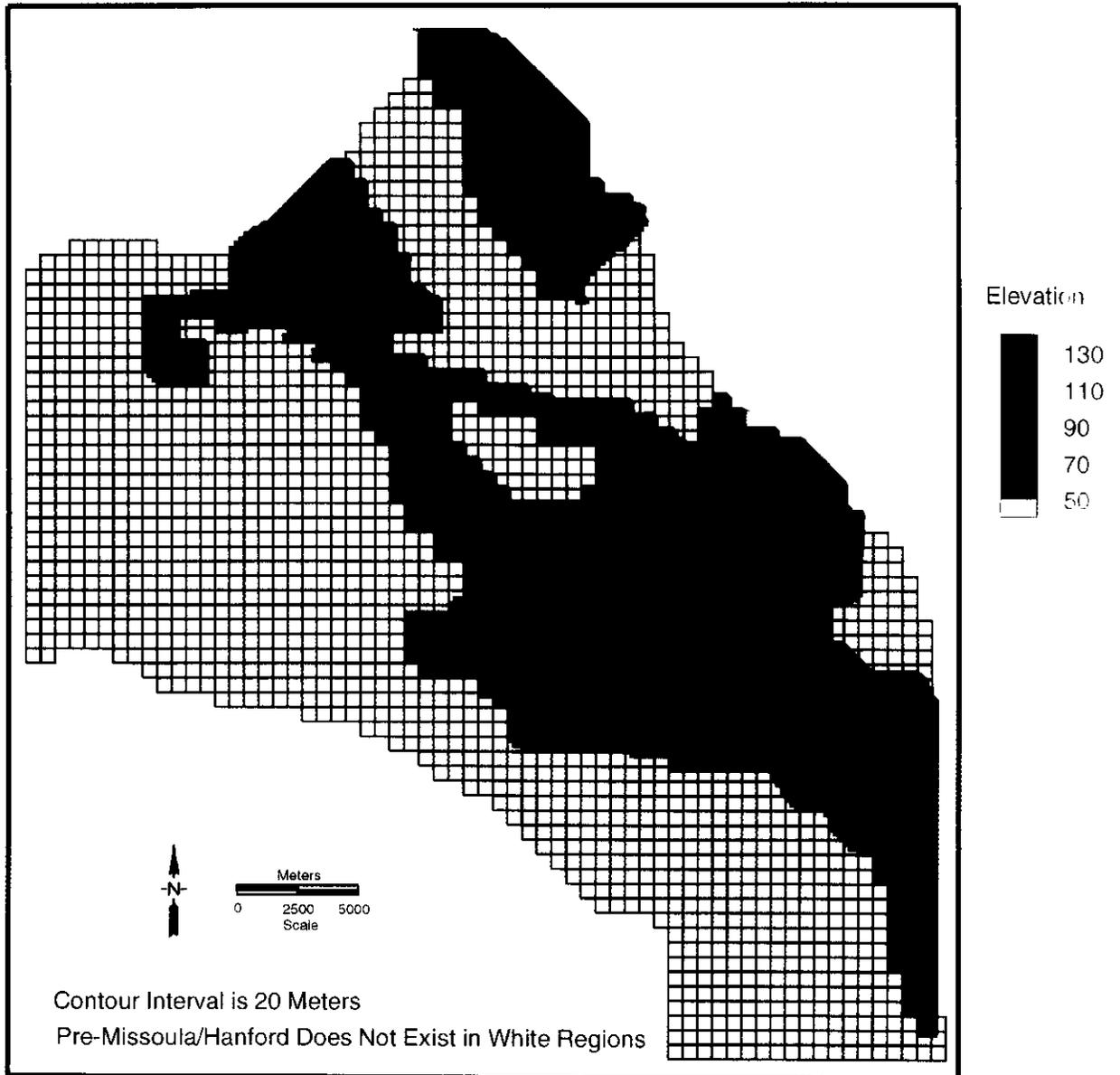


Figure 3-7. Comparison of Steady-State Simulated Water Table Elevations  
Representing December 1979 Conditions.

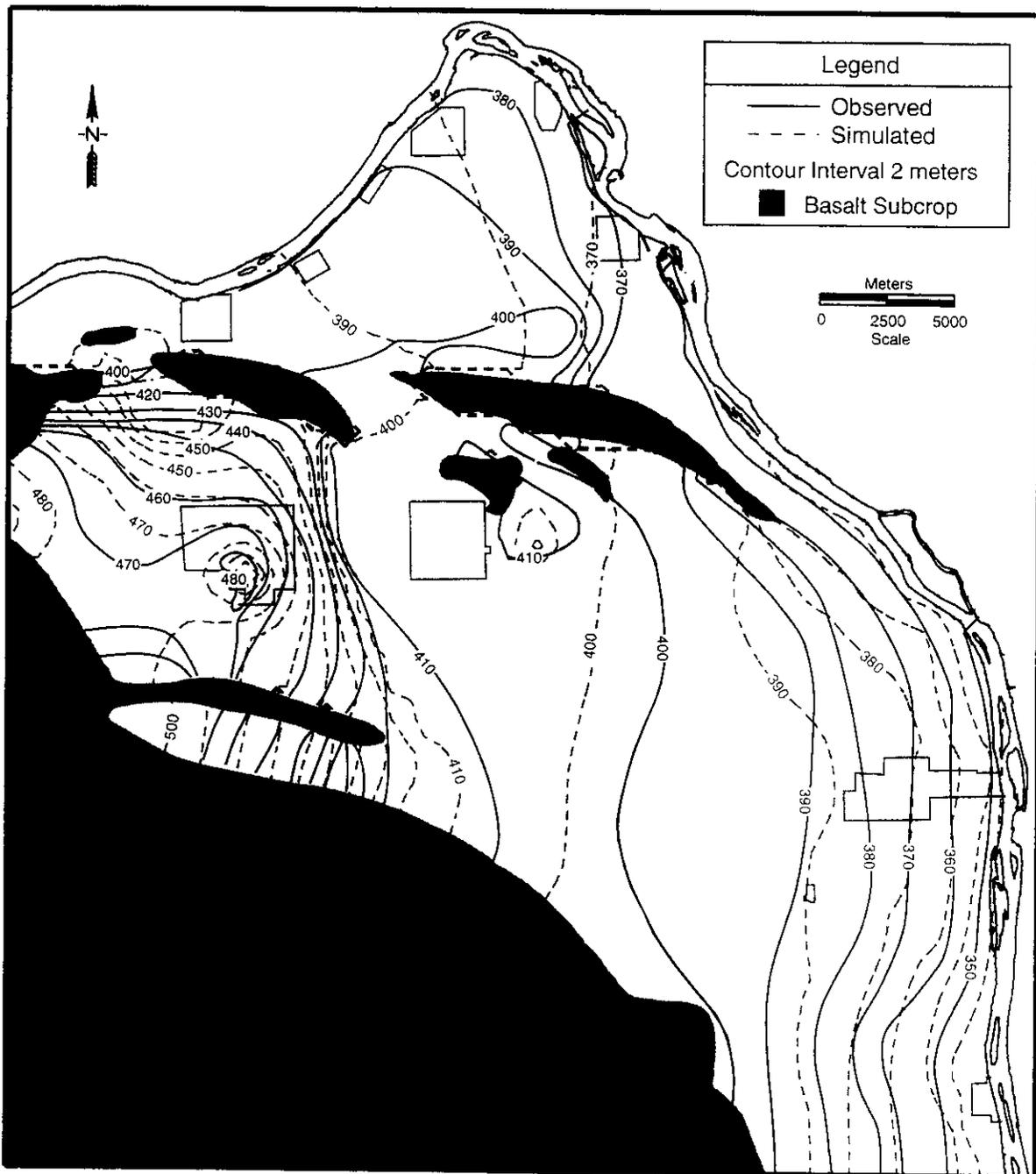


Figure 3-8. Water Table Comparison After 9 Years of Transient Simulation Representing 1988 Conditions.

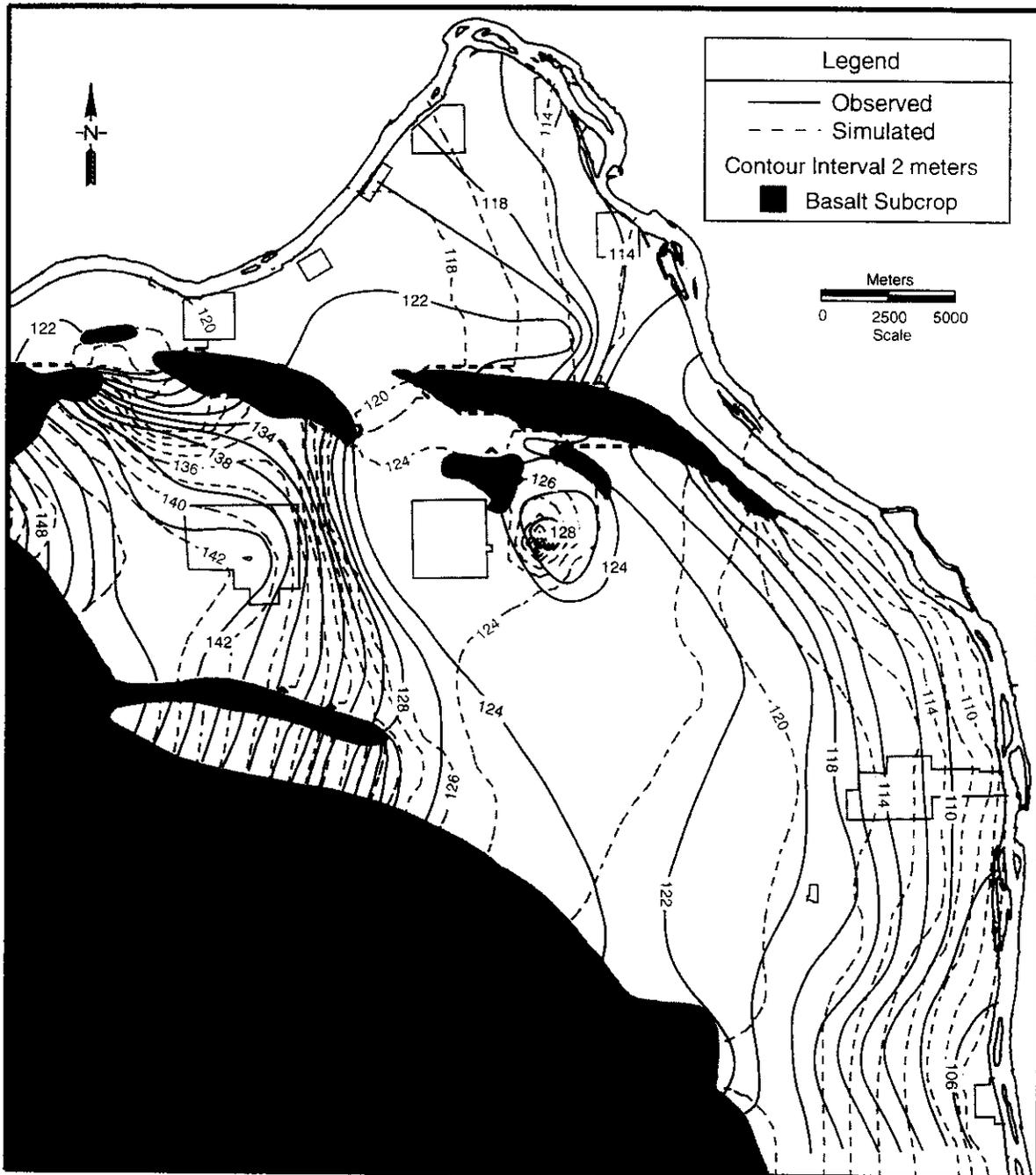


Figure 3-9. Water Table Comparison After 14 Years of Transient Simulation  
Representing 1993 Conditions.

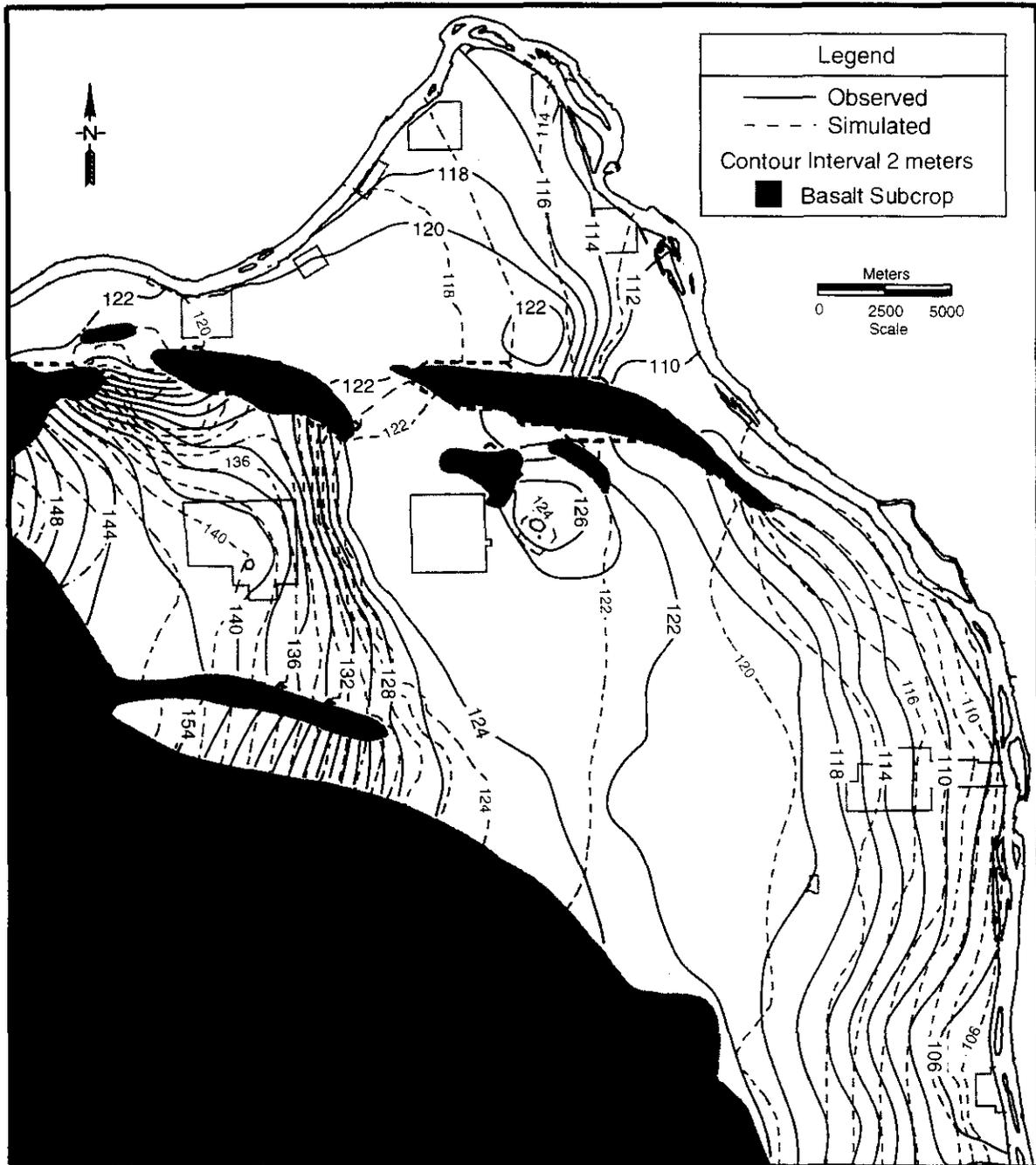


Figure 3-10. Simulated Steady State Pore Velocity Streamlines - 1979.

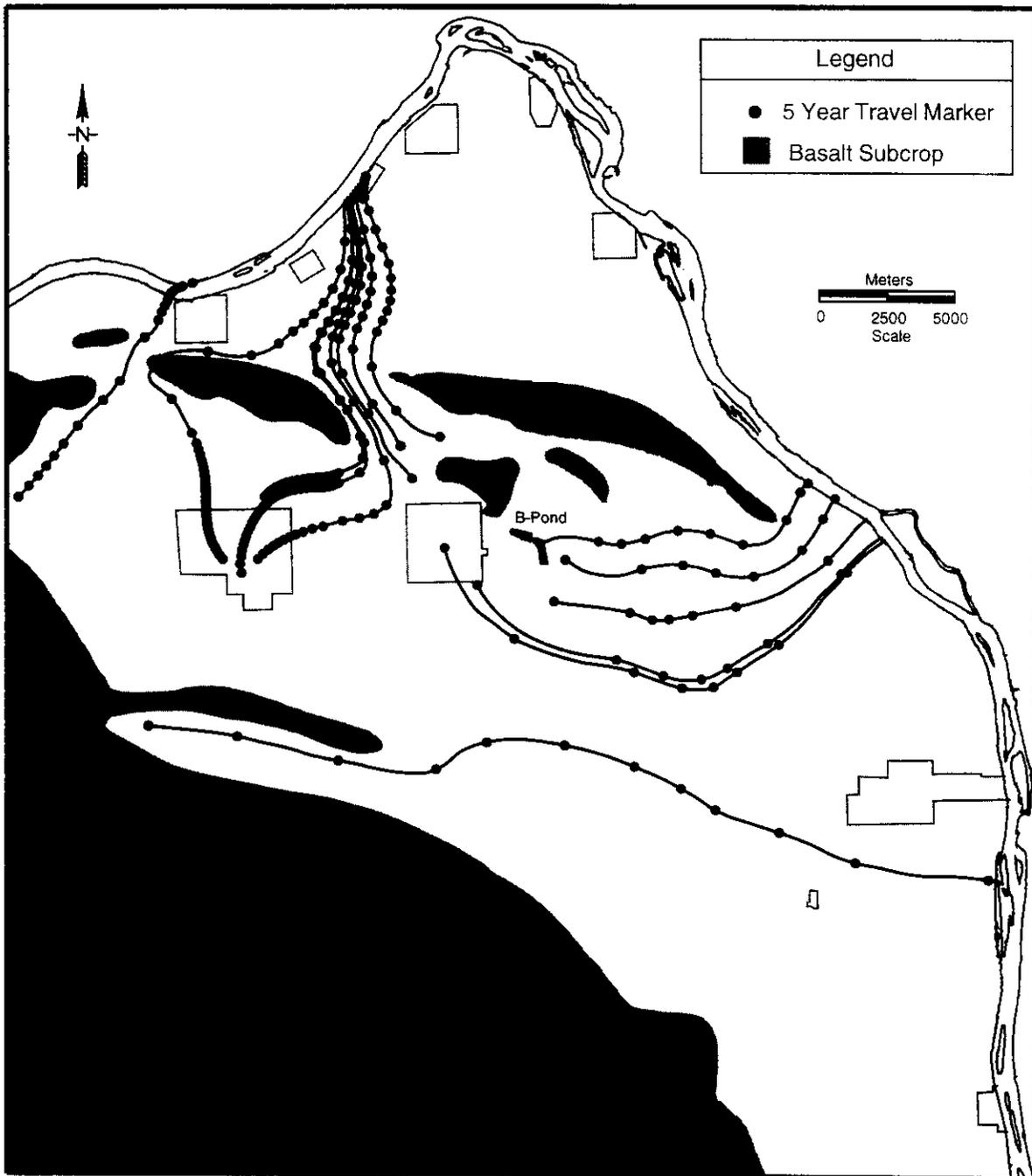


Figure 3-11. Simulated Steady State Velocity Streamlines - 1988.

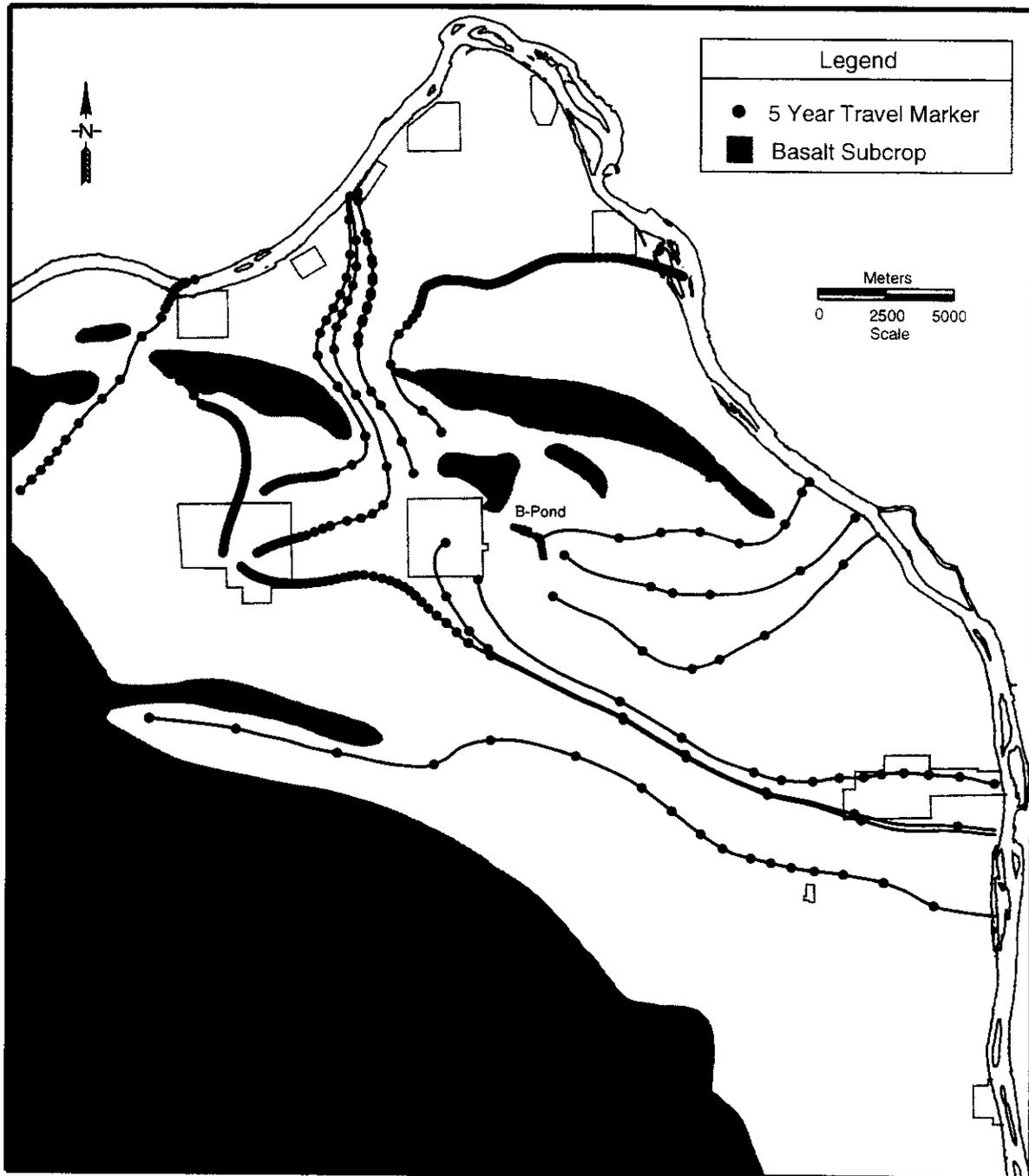


Figure 3-12. Simulated Steady State Velocity Streamlines - 1993.

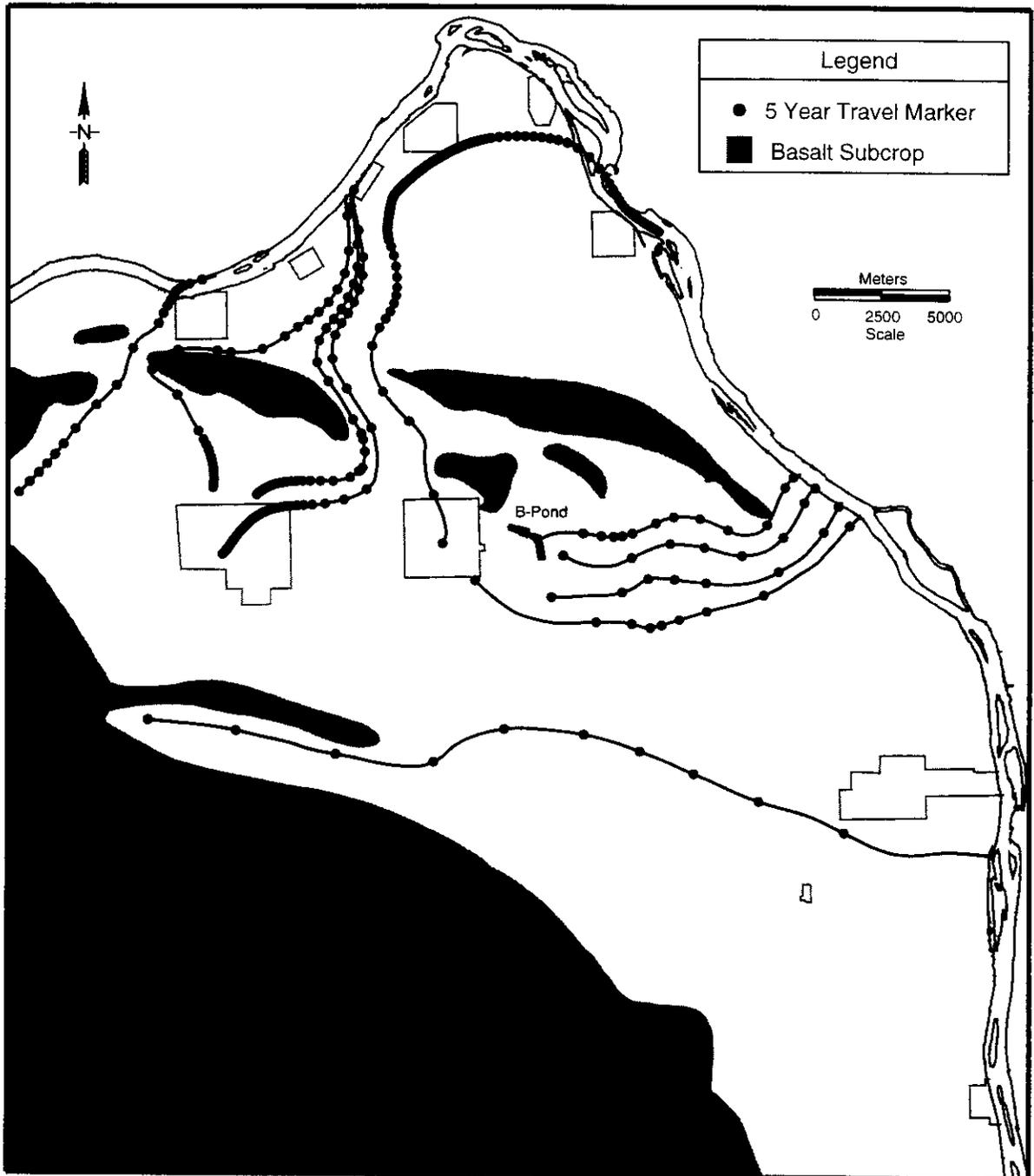


Figure 3-13. Averaged 1979-1981 Distribution of Tritium Under the Hanford Site.

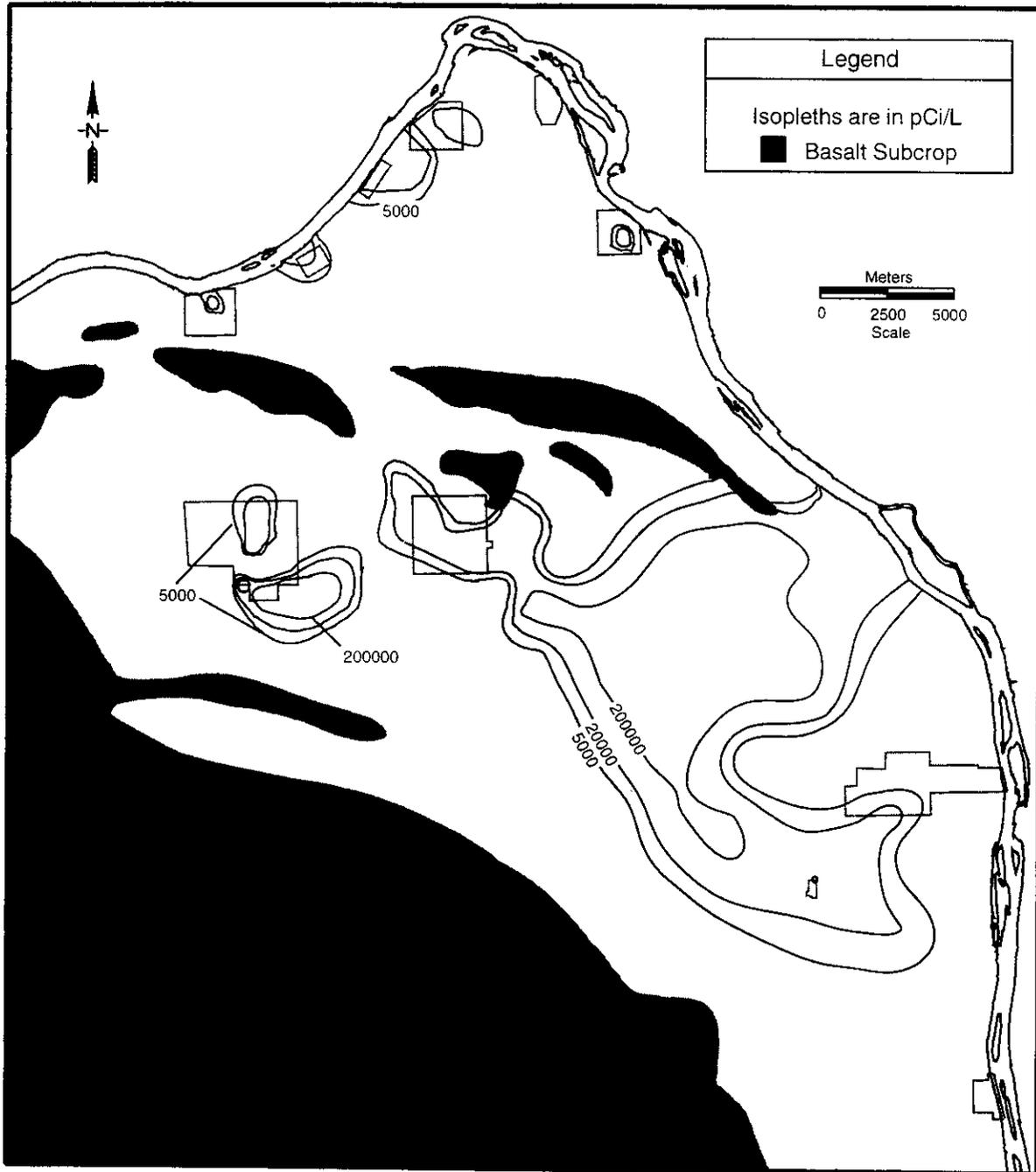


Figure 3-14. Simulated Tritium Plume - 1979.

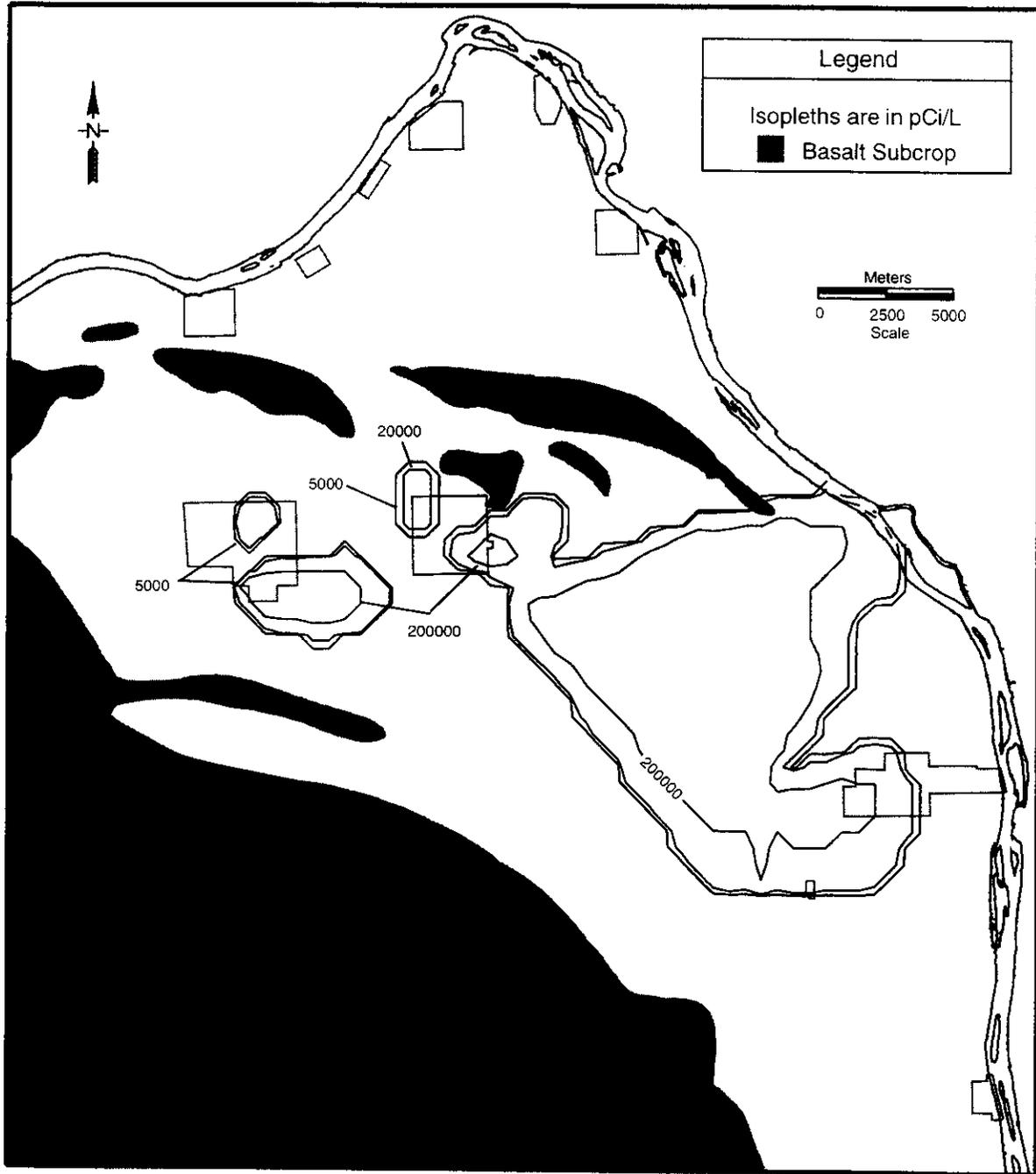


Figure 3-15. Comparison of Initial Conditions versus Simulated Results - 1979.

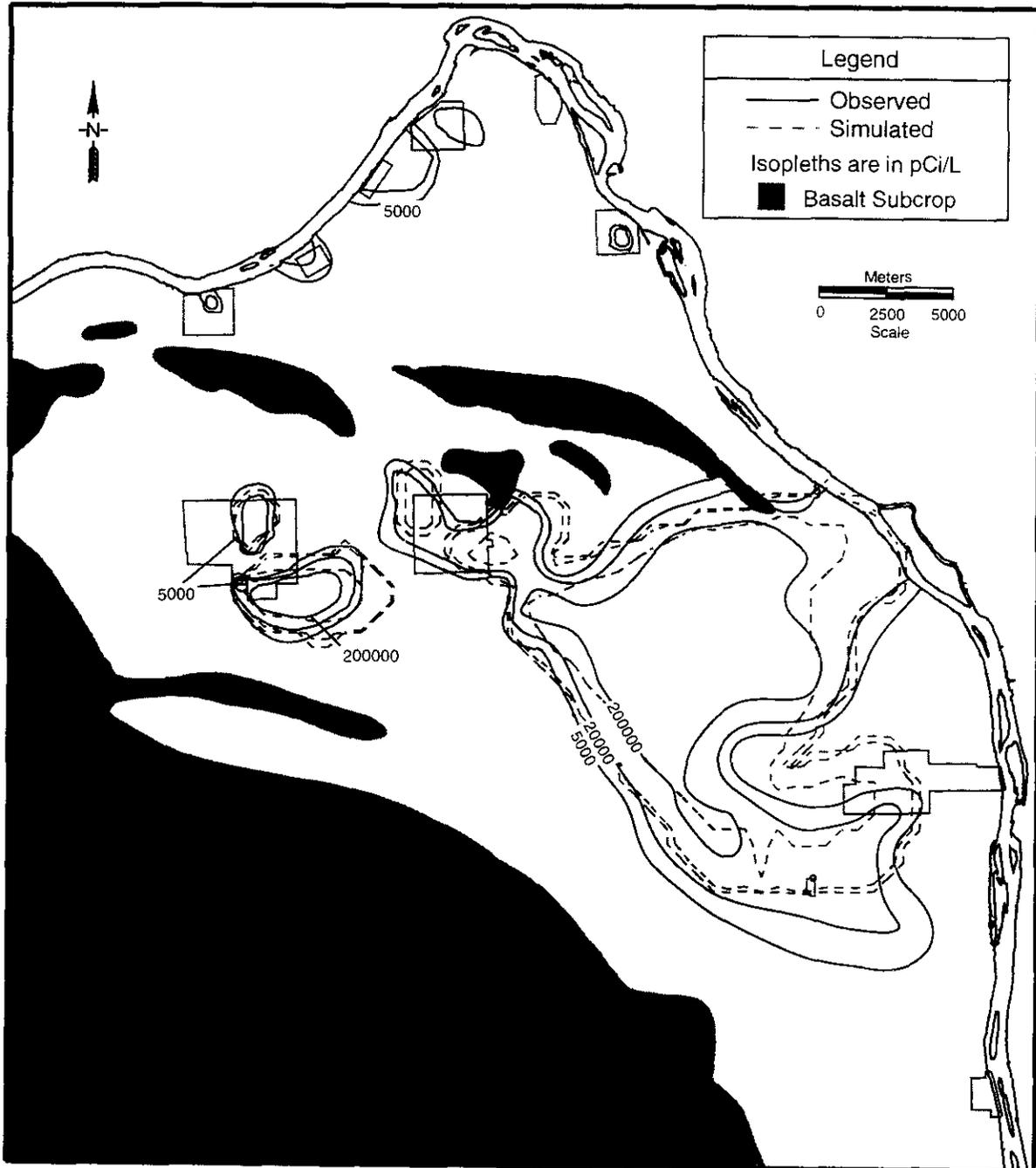


Figure 3-16. Observed Tritium Plume - 1988.

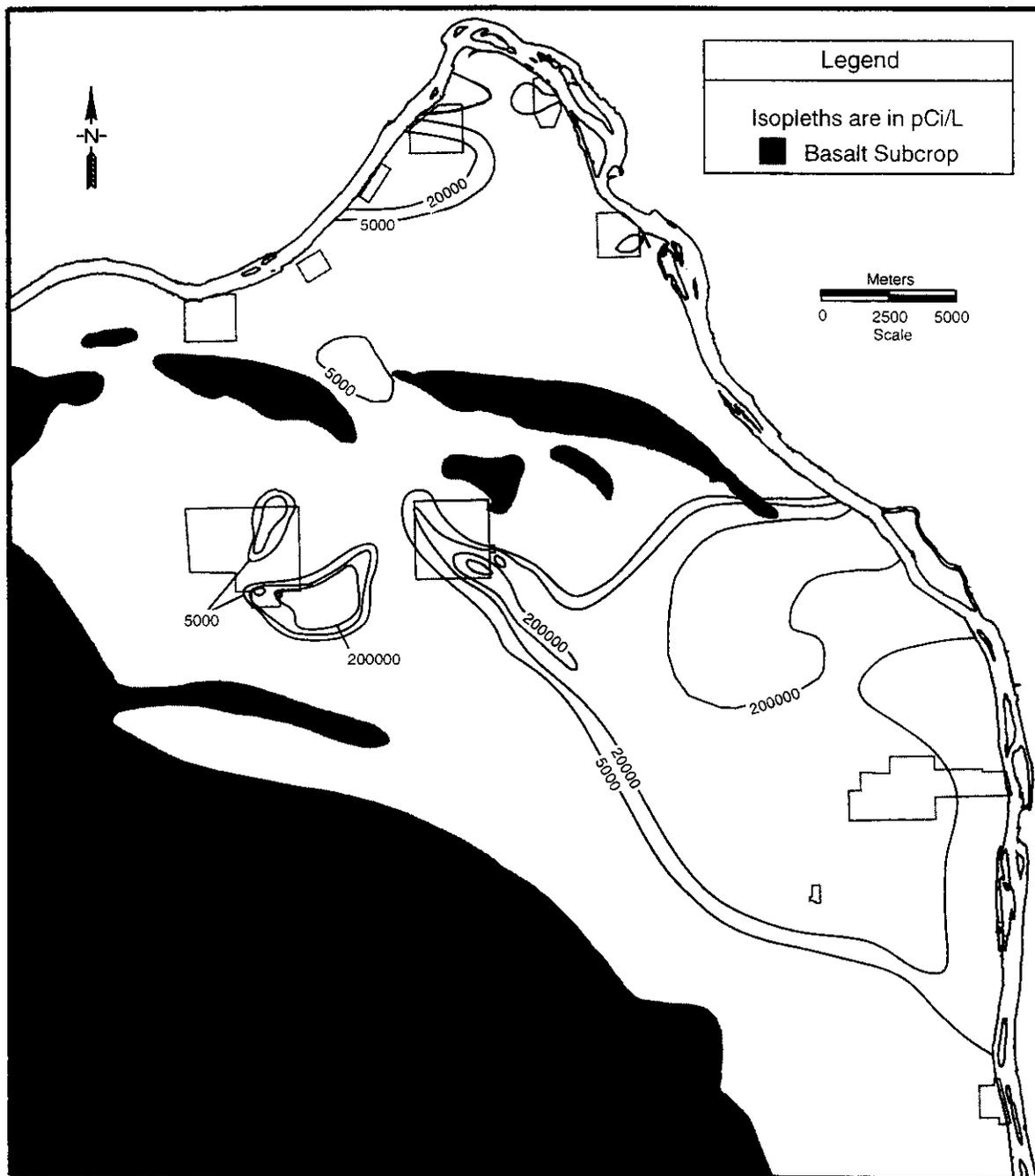


Figure 3-17. Simulated Tritium Plume - 1988.

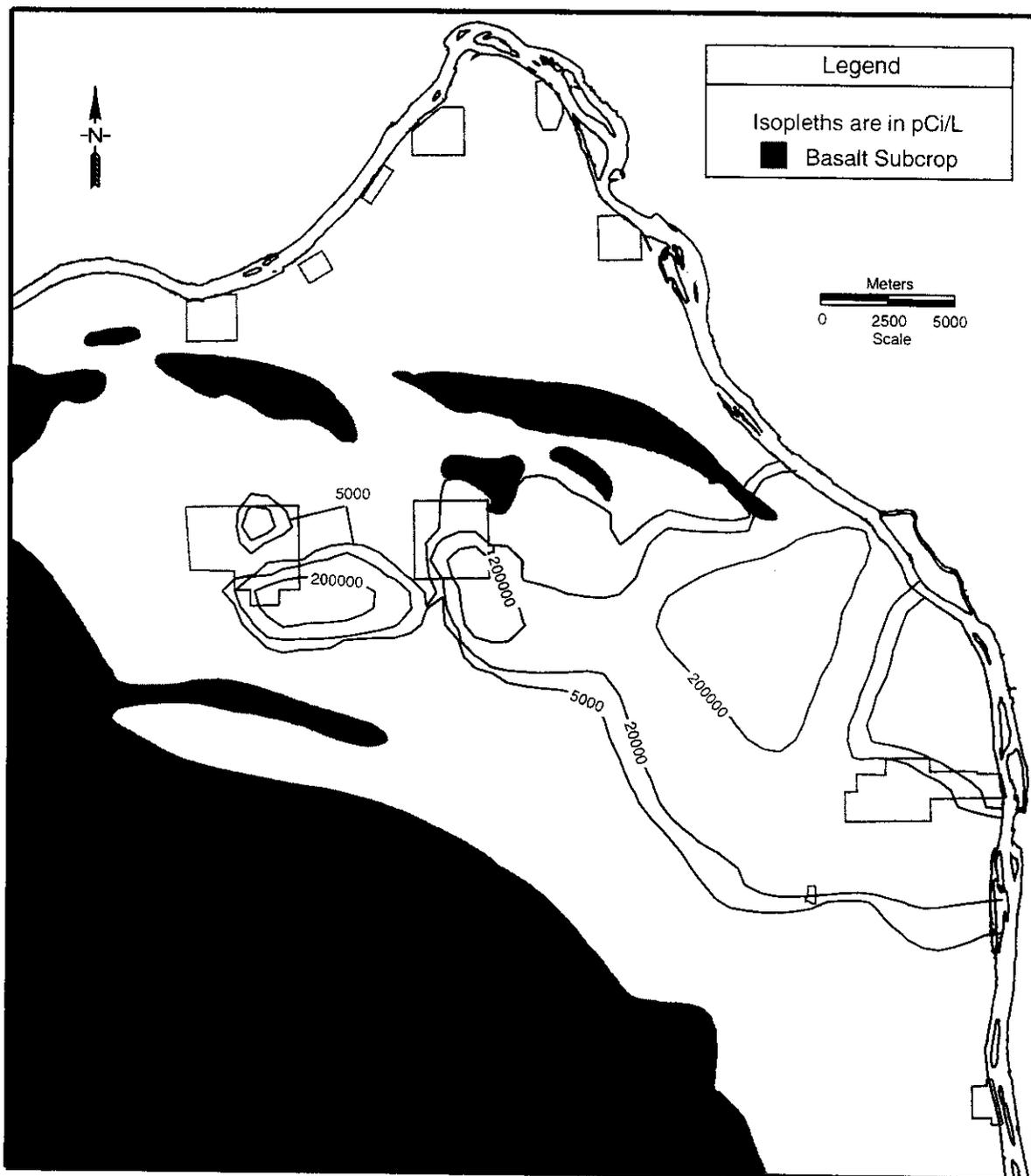


Figure 3-18. Observed versus Simulated Tritium Results - 1988.

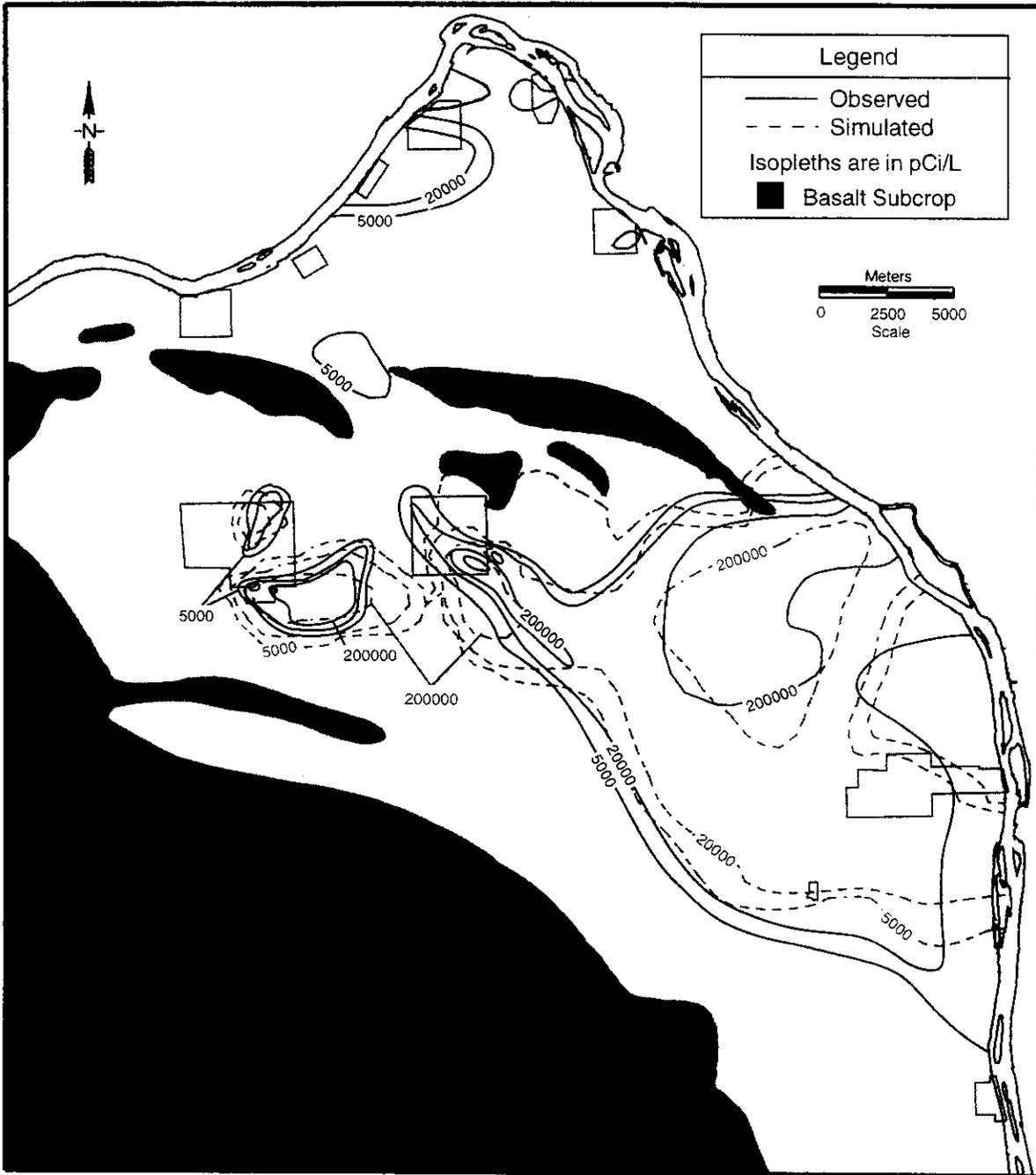


Figure 3-19. Observed Tritium Plume - 1993.

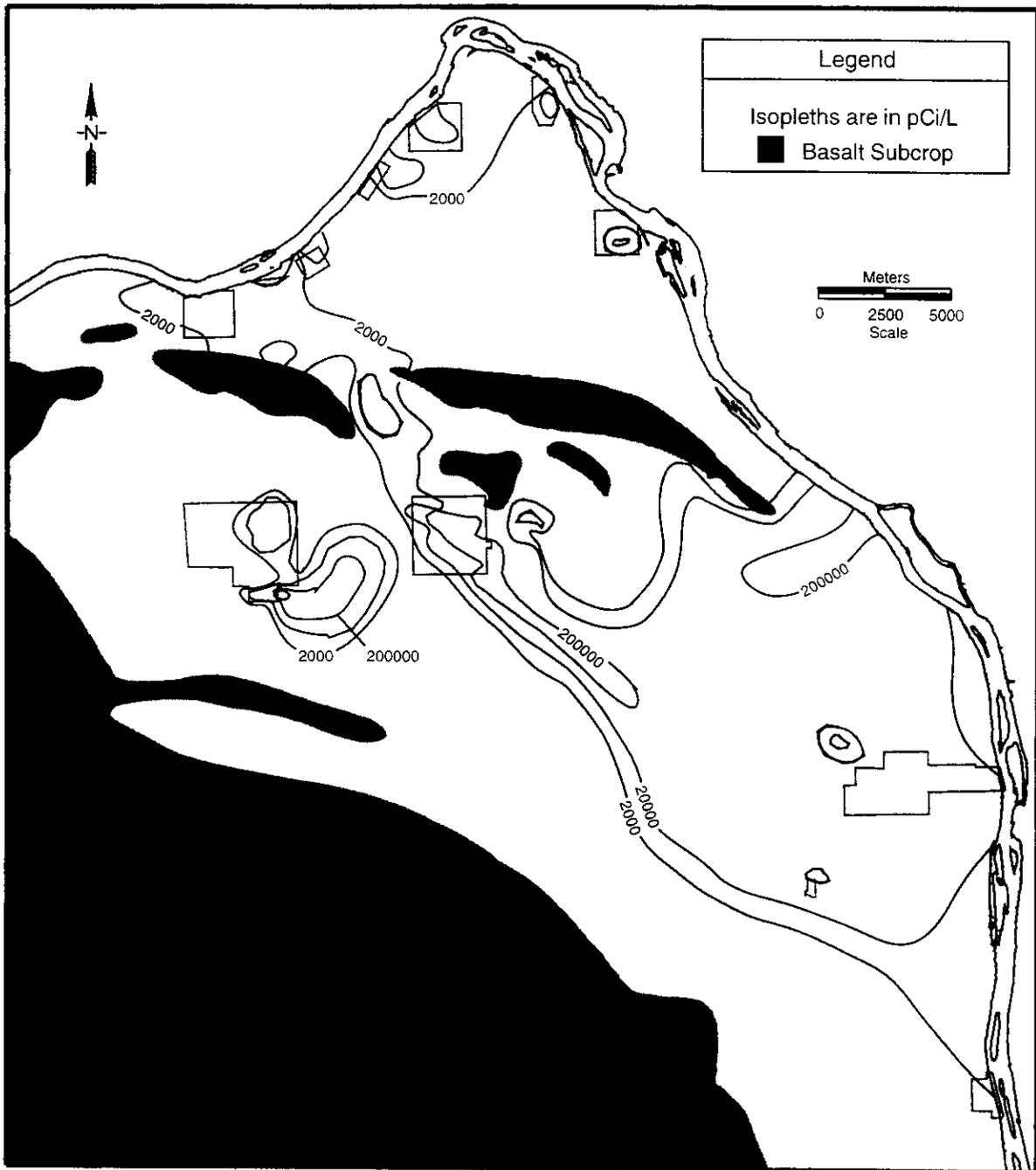


Figure 3-20. Simulated Tritium Plume - 1993.

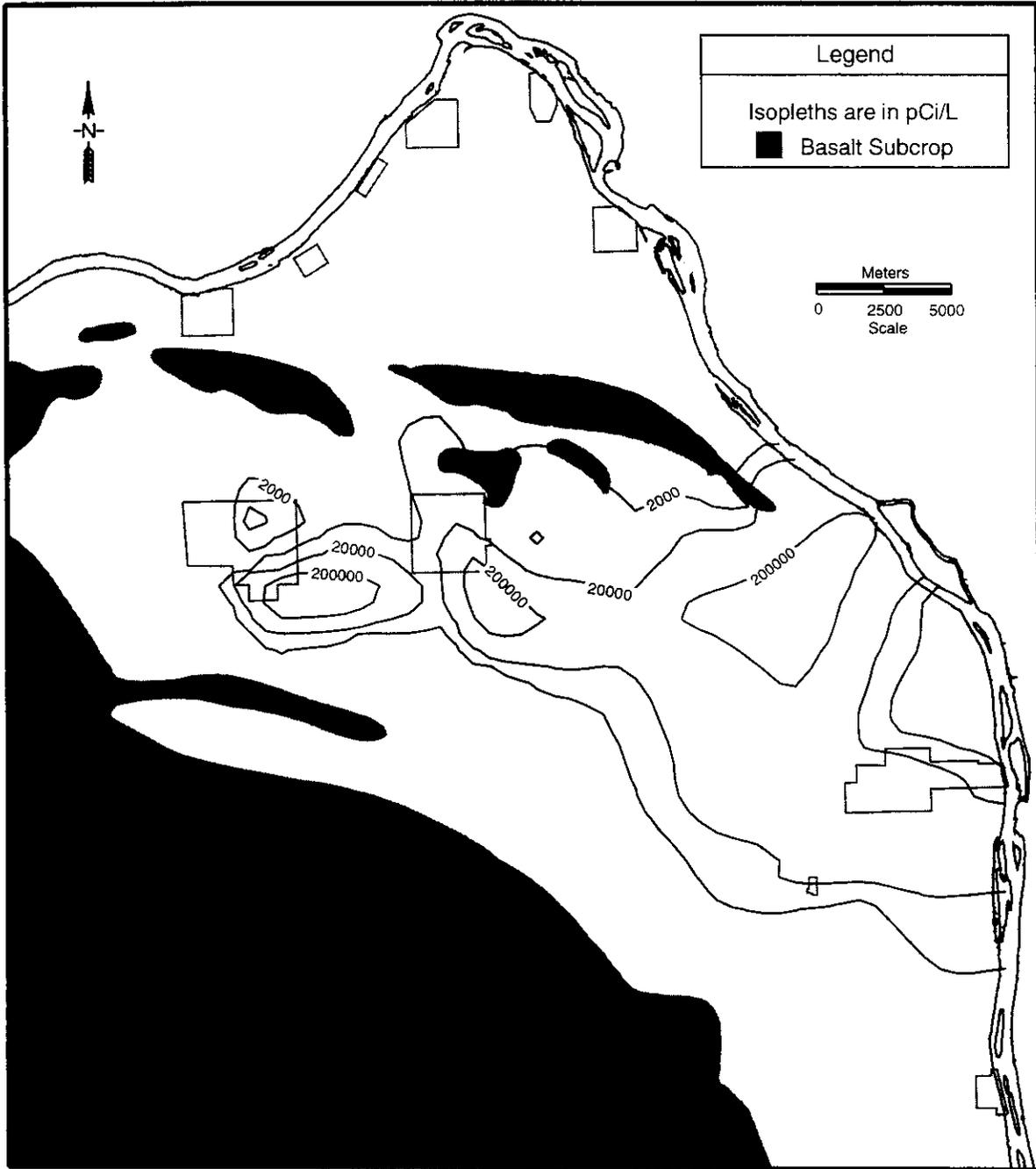


Figure 3-21. Observed versus Simulated Tritium Results - 1993

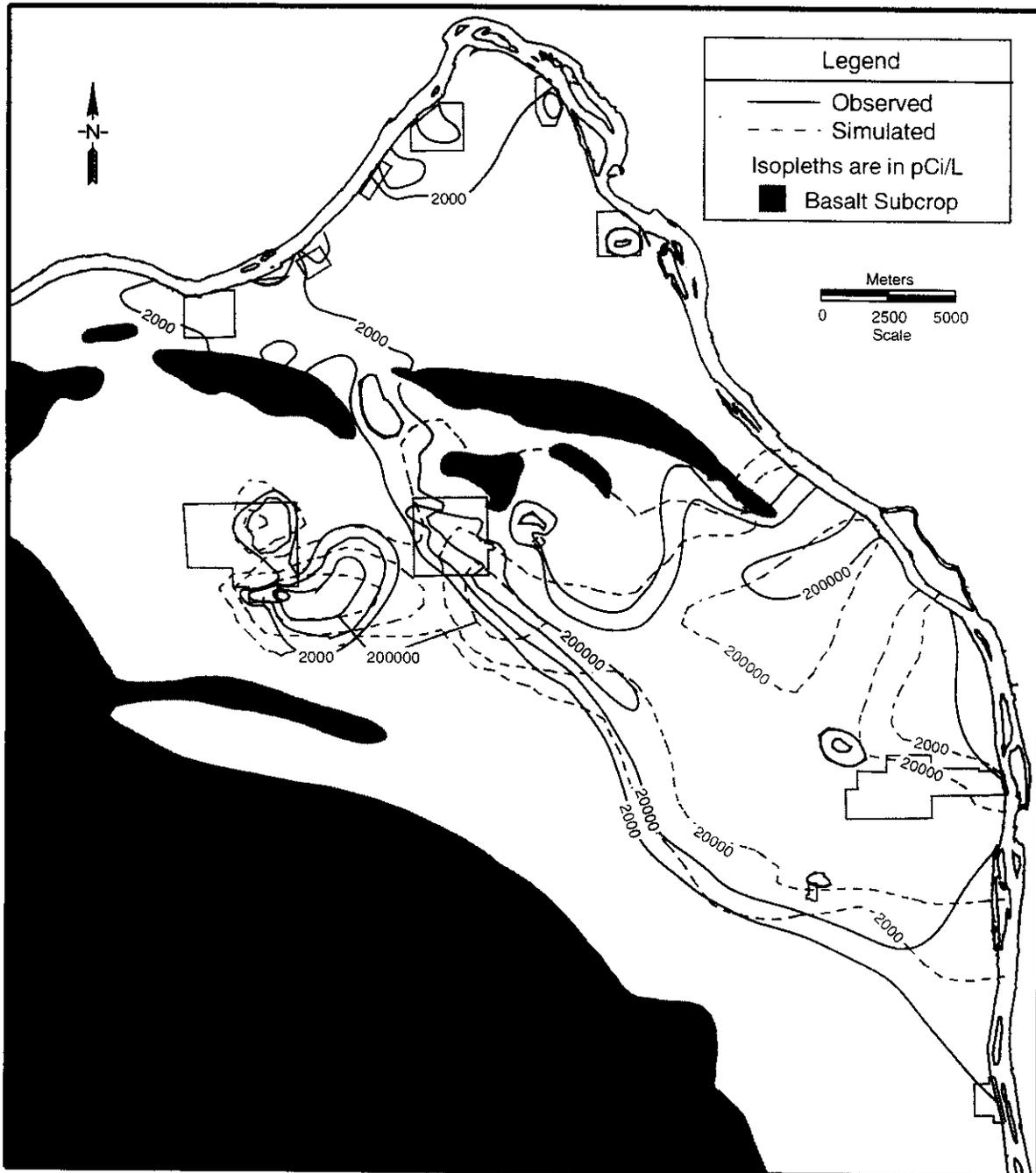


Table 3-1. Element Material-Zone Flow Properties.

Zone	$K_{xx}$ (m/y)	$K_{yy}$ (m/y)	$K_{zz}$ (m/y)	$S_s$ (1/m)	Porosity (Percent)
1	.800E+03	.800E+03	.800E+02	.100E-05	10
2	.190E+04	.190E+04	.190E+03	.100E-05	25
3	.500E+04	.500E+04	.500E+03	.100E-05	10
4	.650E+04	.650E+04	.650E+03	.100E-05	10
5	.140E+05	.140E+05	.140E+04	.100E-05	25
6	.720E+05	.720E+05	.720E+04	.100E-05	25
7	.260E+05	.260E+05	.260E+04	.100E-05	10
8	.300E+05	.300E+05	.300E+04	.100E-05	25
9	.430E+05	.430E+05	.430E+04	.100E-05	25
10	.055E+06	.055E+06	.055E+05	.100E-05	25
11	.770E+05	.770E+05	.770E+04	.100E-05	25
12	.899E+05	.899E+05	.899E+04	.100E-05	25
13	.140E+06	.140E+06	.140E+05	.100E-05	25
14	.300E+06	.300E+06	.300E+05	.100E-05	25
15	.750E+06	.750E+06	.750E+05	.100E-05	25
16	.113E+07	.113E+07	.113E+06	.100E-05	25
17	.183E+07	.183E+07	.183E+06	.100E-05	25
18	.213E+07	.213E+07	.213E+06	.100E-05	25

 $K_{xx}$  = Hydraulic conductivity in the North-South direction $K_{yy}$  = Hydraulic conductivity in the East-West direction $K_{zz}$  = Hydraulic conductivity in the vertical direction $S_s$  = Specific storage

m/y = meters per year

1/m = 1 per meter

Table 3-2. Transport Properties for Tritium.

Longitudinal dispersivity	$\alpha_L = 30.5 \text{ m}$
Transverse dispersivity	$\alpha_T = 3 \text{ m}$
Decay coefficient	$\lambda = 0.0564 \text{ year}^{-1}$
Adsorption coefficient	$\kappa_d = 0$
NOTE: Porosities of the material zones are the same as for the flow run shown in Table 3-1.	

m = meters

#### 4.0 SUMMARY OF CONCLUSIONS

The development of a new model of groundwater flow in the unconfined aquifer represents an important step in remediating Hanford groundwater contamination. This model allows large-scale groundwater remediation alternatives to be evaluated and allows their impacts to be visualized on a sitewide basis. This calibrated model also offers many opportunities for programs outside of the remediation program to estimate the impacts they may have on groundwater flow conditions and thus the cleanup program. Conclusions of the model calibration are:

- The VAM3DCG model has the capability and flexibility to simulate the major features needed to evaluate the effectiveness of alternative groundwater remediation approaches currently under consideration.
- Input to the VAM3DCG model effectively incorporates the most updated geologic and hydrogeologic conceptualization of the groundwater flow and transport system available on the Hanford Site.
- The reduction in liquid effluent discharges to the soil column is causing significant alterations to the groundwater flow system that can best be considered on a sitewide basis using a sitewide model.
- The combined steady-state and transient simulations used in the calibration approach provide an evaluation that indicates the model is calibrated.
- Quantification of the ability of the model to predict groundwater travel time is a significant feature needed for effective use by the groundwater remediation program.
- Comparison of simulated and measured tritium plume concentrations indicates local geologic/lithologic control of transport not currently incorporated into the model
- Sensitivity of modeled results to input assumptions varies throughout the modeled domain. Interpretations of results must incorporate information gained under the sensitivity studies performed.



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**APPENDIX A**  
**DESCRIPTION OF VAM3DCG**



## **A1.0 DESCRIPTION OF VAM3DCG**

### **A1.1 INTRODUCTION**

VAM3DCG is a three-dimensional, finite element code developed to simulate moisture movement and solute transport in variably saturated porous media. The code is capable of simulating a wide range of conditions commonly encountered in the field. Simulations can be performed efficiently for fully three-dimensional, two-dimensional, or axisymmetric problems. Both flow and transport simulations can be handled concurrently or sequentially. Material heterogeneities and anisotropy are handled by taking advantage of the finite element approach. Efficient matrix computational and solution schemes are employed in conjunction with simple rectangular prism elements or hexahedral orthogonal curvilinear elements, to analyze problems involving highly nonlinear, hysteretic/nonhysteretic soil moisture characteristics. Many types of boundary conditions can be accommodated:

- Water table conditions
- Atmospheric conditions associated with seepage faces (i.e., evaporation, and nonponding infiltration)
- Water uptake by plant roots
- Vertical recharge of the water table
- Pumping and injection wells.

The model formulation used in VAM3DCG is a descendant of the formulation used in the FLAMINCO and VAM3DCG code presented by Huyakorn et al. (1986, 1987), and has been published by Panday et al. (1993). Where possible, the VAM3DCG code has been rigorously checked against available analytical or semianalytical solutions and similar numerical codes including UNSAT2, FEMWATER/FEMWASTE, SATURN, FLAMINCO and VAM3DCG. A variety of field simulation problems described in the works of Huyakorn et al. (1984, 1985, 1987), Enfield et al. (1983), and Carsel et al. (1985) have been used to validate VAM3DCG and demonstrate its utility.

### **A1.2 OVERVIEW OF CODE CAPABILITIES AND SALIENT FEATURES**

Multidimensional modeling of water flow and waste migration in variably saturated subsurface systems is a formidable task. Recognizing this point, VAM3DCG was developed to have not only

essential modeling capabilities but also salient features that facilitate practical use. The following is an overview of these code aspects:

- VAM3DCG can perform transient analyses or single step, steady-state analyses of both variably saturated water flow and solute transport problems. If the flow and transport problems are associated, a dual simulation can be performed by solving the problems concurrently or sequentially in a single computer run. (Feature used in model.)
- The finite element formulation and nonlinear solution procedures in VAM3DCG are based on the state-of-the-art technology designed to accommodate a wide range of field conditions, including highly nonlinear moisture characteristics, material heterogeneity and anisotropy, and rapidly fluctuating transient boundary conditions. (Feature used in model with the exception of transient boundary condition.)
- VAM3DCG uses highly efficient matrix computational and matrix solution techniques. The code is directly interfaced with iterative ORTHOMIN and Preconditioned Conjugate Gradient matrix solvers designed to efficiently handle large, sparse problems. (Feature used in model.)
- An orthogonal curvilinear mesh can be used with this version of VAM3DCG, which makes the code attractive for undulating layered systems, and is more capable of handling irregular boundaries, geometry, and material properties. (Feature used in model.)
- Transition elements have been provided with VAM3DCG for finer gradation of the grid in regions of interest with coarser gridding elsewhere. This allows for significant savings in grid points and the resulting computational memory and time. (Feature used in model.)
- Various matrix connectivity options are provided with this version of VAM3DCG which comprise the accuracy of the simulation for computational speed and storage. (Feature used in model.)
- The flow simulator of VAM3DCG can handle various boundary conditions and physical processes including infiltration, evaporation, plant root uptake, well pumping recharge, and varying water table conditions. Temporal variations of head and flux boundary conditions can be handled conveniently using either continuous piecewise linear representations or discontinuous (stepped) representations. Further, the pseudo-soil moisture relations are incorporated for use when the unsaturated zone moisture relations are unknown and moisture behavior above the water table is unimportant. (Pseudo-soil functions and changing head and flux boundary conditions used in model.)
- The transport simulator of VAM3DCG is designed to handle both conservative and nonconservative solutes. Its formulation is designed to have an upstream weighting capability as an option to circumvent numerical oscillations. Both steady and time-varying release of contaminants from each source can be simulated. (Feature used in model.)

### A1.3 GOVERNING AND SUPPLEMENTARY EQUATIONS FOR VARIABLELY SATURATED FLOW

To perform a variably saturated flow analysis, the VAM3DCG code uses the pressure head or the hydraulic head as the dependent variable if a rectangular grid is used. For an orthogonal curvilinear grid, the dependent variable is the hydraulic head. This is advantageous because it precludes the necessity of computing gradients in the elevation potential term. The governing mass balance for water flow in a variably saturated soil is calculated by Equation 1:

$$\frac{\partial}{\partial x_i} \left[ \rho_w K_{ij} k_{rw} \left( \frac{\partial \Psi}{\partial x_j} + e_j \right) \right] - \frac{\partial}{\partial t} (\rho_w \phi S_w) - \rho_w q \quad (1)$$

where

$\rho_w$  = density of water.

$\Psi$  = pressure head.

$K_{ij}$  = saturated hydraulic conductivity tensor.

$k_{rw}$  = relative permeability with respect to the water phase.

$x_i$  ( $i = 1, 2, 3$ ) are a set of orthogonal spatial coordinates.

$t$  = time.

$e_j$  = unit vector assumed to be vertically upward.

$S_w$  = water phase saturation.

$\phi$  = effective porosity.

$q$  = volumetric flow rate via sources (or sinks) per unit volume of the porous medium.

The pressure head and hydraulic head  $h$  are related as  $h = \Psi + z$ , where  $z$  is the vertically upward direction.

For a slightly compressible fluid, Equation 1 can be written in the form of Equations 2, 3, or 4 (Cooley 1971):

$$\frac{\partial}{\partial x_i} \left[ K_{ij} k_{rw} \left( \frac{\partial \Psi}{\partial x_j} + e_j \right) \right] - S_w S_s \frac{d\Psi}{dt} - \frac{\phi dS_w}{dt} - q \quad (2)$$

or

$$\frac{\partial}{\partial x_i} \left[ K_{ij} k_{rw} \left( \frac{\partial \Psi}{\partial x_j} + e_j \right) \right] - \eta \frac{\partial \Psi}{\partial t} - q \quad (3)$$

where  $\eta$  is a coefficient defined as

$$\eta = S_w S_s + \phi \frac{dS_w}{d\psi} \quad (4)$$

the coefficient  $S_s$  is defined as the specific storage in Equation 5 (Bear 1979)

$$S_s = \rho_w g (\phi \beta + \alpha) \quad (5)$$

Where

$g$  = the gravitational constant.

$\alpha$  and  $\beta$  = coefficients of compressibility of the porous medium and water, respectively.

The off-diagonal components of the saturated conductivity tensor will be zero if the coordinate system coincides with the principal axes of anisotropy of the hydraulic conductivity (e.g., the  $x_1$  and  $x_3$  directions are parallel to the plane of stratification, and  $x_2$  direction is normal to the plane of stratification). The initial and boundary conditions of the variably saturated flow problem are shown in Equations 6, 7, and 8:

$$\Psi(x_i, 0) = \Psi_o(x_i) \quad (6)$$

$$\Psi(x_i, t) = \tilde{\Psi} \text{ on } B_1 \quad (7)$$

and

$$V_i n_i = -V_n \text{ on } B_2 \quad (8)$$

Where

$\Psi_o$  = initial head value.

$B_1$  = portion of the flow boundary where  $\Psi$  is prescribed as  $\tilde{\Psi}$ .

$V_i$  = Darcy velocity vector.

$B_2$  = portion of the flow boundary where the outward normal velocity is prescribed as  $-V_n$ .

$n_i$  = outward unit normal vector.

The boundary and initial conditions are provided in terms of hydraulic head  $h$  instead of the pressure head  $\psi$  when the hydraulic head is the dependent variable.

The relationships of relative permeability versus water phase saturation are given by two alternative functional expressions in Equation 9 (Brooks and Corey 1966):

$$k_{rw} = S_e^n \quad (9)$$

and Equation 10 (van Genuchten 1976):

$$k_{rw} = S_e^{1/2} [1 - (1 - S_e^{1/\gamma})^\gamma]^2 \quad (10)$$

Where

$n$  and  $\gamma$  = empirical parameters.

$S_e$  = effective water saturation defined as  $S_e = (S_w - S_{wr}) / (1 - S_{wr})$  with  $S_{wr}$  being referred to as the residual water saturation.

The relationship of pressure head versus water saturation is described by Equation 11 (van Genuchten 1976; Mualem 1976):

$$\frac{S_w - S_{wr}}{1 - S_{wr}} = \begin{cases} \frac{1}{[1 + (\alpha |\Psi - \Psi_a|)^\beta]^\gamma} & \text{for } \Psi < \Psi_a \\ 1 & \text{for } \Psi \geq \Psi_a \end{cases} \quad (11)$$

Where

$\alpha$  and  $\beta$  = empirical parameters.

$\Psi_a$  = air entry pressure head value.

$S_{wr}$  = residual water phase saturation.

The parameters  $\beta$  and  $\gamma$  are usually related by  $\gamma = 1 - 1/\beta$ .

Moisture retention and relative permeability characteristics for a given soil can be measured in the laboratory using Equations 9 and 10.

Equation 3 is solved numerically using the Galerkin finite element method subject to the initial and boundary conditions given in Equations 5 through 7. After the distributions of  $\Psi$  (or  $h$ ) and  $S_w$  have been determined, Darcy velocity components are calculated from Equation 12.

$$V_i = -K_{ij} k_{rw} \left( \frac{\partial \Psi}{\partial x_j} + e_j \right) = -K_{ij} k_{rw} \frac{\partial h}{\partial x_j} \quad (12)$$

#### A1.4 TREATMENT OF HYSTERESIS AND ANISOTROPY

To simulate the effect of hysteresis in soil moisture properties in a variably saturated flow simulation, VAM3DCG incorporates the procedure described by Kool and Parker (1987). This procedure requires that the boundary wetting and drying curves in the  $S_w(\psi)$  relation are known. In VAM3DCG it is assumed that these boundary curves are described by expressions that have the same form as Equation 11 but with different parameter values for the wetting and drying boundary curves.

Using superscripts  $w$  and  $d$  to distinguish between wetting and drying, respectively, the boundary  $S_w(\psi)$  curves are described by the following relationships in Equations 13 and 14:

$$\frac{S_w^w - S_{wr}}{S_{ws} - S_{wr}} = \begin{cases} \frac{1}{[1 + (\alpha^w |\psi - \psi_a|)^{\beta^w}]^{\gamma^w}} & \psi < \psi_a \\ 1 & \psi \geq \psi_a \end{cases} \quad (13)$$

$$\frac{S_w^d - S_{wr}}{1 - S_{wr}} = \begin{cases} \frac{1}{[1 + (\alpha^d |\psi - \psi_a|)^{\beta^d}]^{\gamma^d}} & \psi < \psi_a \\ 1 & \psi \geq \psi_a \end{cases} \quad (14)$$

In Equation 13,  $S_{ws}$  represents the maximum saturation value upon rewetting of an initially air-dry soil. If no air entrapment occurs,  $S_{ws} = 1.0$ . However, if air-entrapment occurs,  $S_{ws}$  will be less than one. Parameters  $\alpha$ ,  $\beta$ , and  $\gamma$  are the van Genuchten curve shape parameters, with different values for wetting and drying. Note that  $\alpha^w$  cannot be less than  $\alpha^d$ :

$$\alpha^w \geq \alpha^d$$

Often, the following simplifications can be used (Kool and Parker 1987):

$$\begin{aligned} \beta^w &= \beta^d = \beta \\ \gamma^w &= \gamma^d = 1 - 1/\beta \end{aligned}$$

With these simplifications, only four parameters are required to characterize the hysteretic saturation-pressure head relation. The parameters are the residual saturation,  $S_{wr}$ , and the shape parameters  $\alpha^w$ ,  $\alpha^d$ , and  $\beta$ . If data are lacking,  $\alpha^w = 2\alpha^d$  may be used as a first approximation (Kool and Parker, 1987). A typical hysteretic  $S_w(\psi)$  relation is shown in Figure A-1. This figure illustrates the correspondence of the parameters in Equations 13 and 14 to the boundary wetting and drying curves.

In a hysteretic flow simulation, VAM3DCG automatically computes scanning curves in the  $S_w(\psi)$  relation to determine the appropriate saturation path for every element in the modeled domain when reversals from wetting to drying, or vice versa occur. This is achieved by defining

"pseudo" values of the residual and saturated values of  $S_w$ . In the simulation, these pseudo-values are substituted into Equations 13 and 14. This has the effect of scaling the boundary wetting and drying curves to make them pass through the reversal points. For a reversal from wetting to drying, the nominal value of 1.0 for  $S_w$  at saturation is replaced by Equation 15:

$$S'_{ss} = \frac{S_w^{rev} - S_{wr} [1 - S_e^d(\psi^{rev})]}{S_e^d(\psi^{rev})} \quad (15)$$

Where

$S_w^{rev}$  and  $\psi^{rev}$  = saturation and pressure head at the reversal point, respectively.  
 $S_e^d(\psi^{rev})$  = effective drying saturation given by the left-hand side of Equation 14 for  $\psi = \psi^{rev}$ .

Analogously, for a reversal from drying to wetting, a pseudo-value for  $S_{wr}$  is used, which is given by Equation 16:

$$S'_{wr} = \frac{S_w^{rev} - S_e^w(\psi^{rev})}{1 - S_e^w(\psi^{rev})} \quad (16)$$

Where

$S_e^w$  = effective wetting saturation corresponding to the left-hand side of Equation 13. The hysteresis subroutine in VAM3DCG checks whether each element is wetting or drying and computes the appropriate values of  $S'_{ss}$  and  $S'_{wr}$  for each element. This is achieved by means of an index variable,  $\kappa_i$ , which is set to  $\kappa_i = +1$  if the I-th element is wetting and  $\kappa_i = -1$  if the I-th element is drying. At the end of every time step, a check is made for every element to determine whether a reversal in the saturation path has occurred. A reversal occurs if

$$\frac{\bar{\psi}_i^{t-\Delta t} - \bar{\psi}_i^t}{\kappa_i} > \delta_\psi \quad (17)$$

Where

$\delta_\psi$  = pressure head iteration convergence tolerance.  
 $\bar{\psi}_i$  = average nodal pressure head for the I-th element:

$$\bar{\psi}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} \psi_j \quad (18)$$

where

$n_i$  = the number of nodes for the element.

When a reversal occurs, the code determines the new scanning curve for the element that is subsequently used to calculate  $S_w(\psi)$ . An example of such scanning curves is shown in Figure A-2. In this example, the boundary hysteresis loop is closed at saturation; i.e.,  $S_{ws} = 1.0$ . The figure shows a primary wetting scanning curve (1) and a secondary drying scanning curve (2). To completely specify the initial conditions for a hysteretic simulation, the user must specify not only the initial nodal values of  $\psi$ , but also the initial saturation values for each element and whether the element is initially wetting or drying.

### A1.5 TREATMENT OF VARIABLE UNSATURATED ANISOTROPY

Many natural soils and other geologic media exhibit some degree of stratification leading to anisotropy of hydraulic conductivity, with higher conductivity in the direction parallel to stratification than perpendicular to stratification. This anisotropy is usually expressed as a ratio (Equation 19a):

$$r = \frac{K_{11}}{K_{33}} = \frac{K_{22}}{K_{33}} \quad (19a)$$

where the indexes 1 and 2 indicate the directions parallel to stratification and 3 corresponds to the perpendicular direction. As expressed by Equation 19a, the anisotropy ratio is constant and independent of saturation. Recent research (e.g., Yeh et al. 1985; Mantoglou and Gelhar 1987; McCord et al. 1988) suggests that in reality, the relative permeability  $k_{rw}$  may be subject to strong anisotropy. This research indicates that for unsaturated conditions, the hydraulic conductivity anisotropy is inversely related to the degree of water saturation. Assuming an exponential  $k_{rw}(\psi)$  relation and using stochastic theory, Yeh et al. (1985) have developed the following expression (Equation 19b) for anisotropy as a function of pressure head for layered soils with a mean unit downward hydraulic gradient

$$r(\psi) = \frac{(Kk_{rw})_{11}}{(Kk_{rw})_{33}} = \frac{(Kk_{rw})_{22}}{(Kk_{rw})_{33}} = \exp \left[ \frac{\sigma_f^2 + \sigma_a^2 \bar{\psi}^2}{1 + \mu \bar{a} \cos \omega} \right] \quad (19b)$$

where

$\sigma_f^2$  = variance of the log saturated conductivity

$(\ln K) a$  = slope of the  $\ln(k_{rw})$  versus  $\psi$  curve

$\bar{a}$  = mean value of  $a$

$\sigma_a^2$  = variance of  $\bar{a}$

$\bar{\psi}$  = mean value of  $\psi$

$\mu$  = spatial correlation length

$\omega$  = angle between the soil layer stratification and the horizontal.

Equation 19b indicates that anisotropy increases as an exponential function of the second power of pressure head. Following Equation 19b, anisotropy will also be more pronounced when the spatial variability of hydraulic conductivity increases and the correlation length,  $\mu$ , decreases. The concept of variable anisotropy is based on mainly theoretical considerations; the predictive value of Equation 19b has not been extensively tested. Nevertheless, McCord et al. (1988) have experimentally observed patterns of water and solute plume migration in a hill slope infiltration study that are similar to results obtained by computer simulation which incorporated Equation 19b to model variable anisotropy.

VAM3DCG has been modified to simulate the effect of saturation dependent anisotropy on unsaturated flow by using Equation 19b to evaluate anisotropy as a function of pressure head. This requires input values of the variables  $\sigma_f^2$ ,  $\sigma_b^2$ ,  $\mu$  and  $\omega$ . The parameter  $\bar{a}$  can be treated either as an input variable or be evaluated by VAM3DCG as the derivative of the  $\ln[k_{rw}(\psi)]$  relation. When the latter option is used with Equations 9, 10, or pseudo-soil relative permeability functions to describe the  $k_r(S_w)$  relation, the value of  $\bar{a}$  will tend to decrease with decreasing saturation. This will magnify the predicted anisotropy compared to the case of a user-specified constant value for  $\bar{a}$ , up to a user-specified upper bound. A value of  $r_{max} = 10^7$  has been found to give satisfactory results in many cases. Further, Equation 19b provides the conductivity ratio, but not the actual values of conductivities parallel and perpendicular to stratification. To obtain the desired, monotonically decreasing  $k_{rw}(\psi)$  relations, VAM3DCG uses an empirical logarithmic interpolation procedure to ensure that  $(Kk_{rw})_{11}$ ,  $(Kk_{rw})_{22}$ , and  $(Kk_{rw})_{33}$  decrease with decreasing pressure head and that the correct anisotropy ratio is maintained for any  $\psi$  value. An example anisotropic  $k_{rw}(\psi)$  relation as modeled by VAM3DCG is shown in Figure A-3. This figure shows relative conductivity as a function of soil water pressure head. The solid curve represents the isotropic case in which conductivity is given by Equation 10. The dashed lines represent the anisotropic case with anisotropy ratio computed from Equation 19b. The following anisotropy parameters were used:

$$\begin{aligned}\sigma_f^2 &= 0.82 \\ \sigma_b^2 &= 0.0005 \\ \mu &= 40 \text{ cm} \\ \omega &= 0.0.\end{aligned}$$

Figure A-3 clearly illustrates the dramatic effect of tension (pressure head) variations on the magnitude of anisotropy.

## A1.6 PSEUDO-SOIL FUNCTIONS FOR PREDICTING WATER-TABLE LEVELS

When the soil retention and relative permeability functions of a soil are unknown, and the unsaturated zone moisture behavior is unimportant to the simulated scenario, VAM3DCG uses pseudo-relations to predict the water-table levels. With this option, the code utilizes simple linear relations to account for changes in element saturated thickness and relative permeability as a result of the transient movement of the water table in the aquifer.

These linear pseudo-soil moisture relations are provided in Equation 20:

$$S_w = 1 - (|\bar{\Psi} - \Psi_s|)/b \geq 0.001 \quad (20)$$

and

$$k_{rw} = S_w$$

Where

$S_w$  = saturation of the element defined such that  $S_w=1$  when the water table is above the top of the element.

$S_w \approx 0$  when the water table is below the bottom of the element.

$\bar{\Psi}$  = pressure head at the element centroid, which governs the pseudo-relation.

$b$  = average elemental thickness.

$\Psi_s$  =  $b/2$  is the pressure head scaling parameter.

The pseudo-relative permeability function ensures that the vertically integrated transmissivity of the element is adjusted to its saturated thickness as is done in the solution to the vertically integrated areal 2-D aquifer flow equations.

The following is a summary of the main advantages of the VSPPS modeling approach:

- The VSPPS approach is general, robust, and able to handle complex multilayer problems involving desaturation and resaturation of grid blocks (or drastic changes in the water table position).
- The VSPPS approach is efficient and practical to use because of its fixed grid formulation and linearized constitutive relations. No additional user input is required.
- The VSPPS approach is a flexible modeling approach that can be simplified to that equivalent to the areal modeling approach by using a 3-D grid with two nodes on each vertical grid line or a single element covering the entire aquifer thickness. In such a case, vertical flow components are essentially neglected. On the other hand, the VSPPS approach can be made rigorous by using a 3-D grid with multiple element subdivisions in the vertical direction, thus allowing proper account of vertical flow components, as well as accommodating the presence of seepage faces if desirable.

## A1.7 ATMOSPHERIC BOUNDARY CONDITIONS

Atmospheric boundaries may correspond to soil-air interfaces where evaporation or infiltration occurs. They may also correspond to seepage faces through which water seeps from the saturated portion of the flow domain.

Along infiltration and evaporation boundaries, conditions may change from the Dirichlet (prescribed head) to the Neuman (prescribed flux) type.

In the absence of surface ponding, a numerical solution must be obtained by maximizing the absolute value of the flux (while maintaining the appropriate sign) subject to the following requirements in Equation 21 (Hanks et al. 1969; Neuman et al. 1974):

$$|v_i n_i| \leq |E_s^*|$$

and

$$\psi_L \leq \psi \leq 0 \quad (21)$$

where

$E_s^*$  = maximum potential surface flux under the prevailing atmospheric conditions

$\psi_L$  = minimum pressure head allowed under the prevailing soil conditions.

For cases involving plant root uptake, the sink term in Equation 3 is represented by Equation 22 (Feddes et al. 1974):

$$q = K_{rl} k_{rw} (\psi - \psi_r) b' \quad (22)$$

where

$\psi_r$  = root-pressure head, and  $b'$  is the root-effectiveness function.

## A1.8 GOVERNING EQUATIONS AND INITIAL AND BOUNDARY CONDITIONS FOR THE SOLUTE TRANSPORT MODEL

The governing equation for three-dimensional transport of a nonconservative component in a variably saturated soil takes the form in Equation 23 (Bear 1979).

$$\begin{aligned} \frac{\partial}{\partial x_i} (D_{ij} \frac{\partial c}{\partial x_j}) - \frac{\partial}{\partial x_i} (v_i c) - \frac{\partial}{\partial t} [\phi S_w c + \rho_s (1 - \phi) c_s] - q c + \\ + \lambda [\phi S_w c + \rho_s (1 - \phi) c_s], \end{aligned} \quad (23)$$

$i \text{ or } j = 1, 2, 3$

Where

$D_{ij}$  = apparent hydrodynamic dispersion tensor.

- $c$  = solute concentration in the fluid.  
 $v_i$  = Darcy velocity.  
 $\rho_s$  = density of solid grains.  
 $c_s$  = adsorbed concentration.  
 $\lambda$  = first-order decay coefficient.  
 $c^*$  = solute concentration in the injected fluid.

Assuming that the relation between adsorbed and solution concentration is described by a linear equilibrium isotherm, Equation 23 can be expressed as Equation 24:

$$\begin{aligned}
 \frac{\partial}{\partial x_i} (D_{ij} \frac{\partial c}{\partial x_j}) - \frac{\partial}{\partial x_i} (v_i c) - \frac{\partial}{\partial t} \left[ \phi S_w \left( 1 + \frac{\rho_s (1 - \phi) k_d}{\phi S_w} \right) c \right] - q c \cdot \\
 + \lambda \phi S_w \left[ 1 + \frac{\rho_s (1 - \phi) k_d}{\phi S_w} \right] c
 \end{aligned} \tag{24}$$

where

$k_d$  = distribution coefficient.

Equation 24 reduces to

$$\begin{aligned}
 \frac{\partial}{\partial x_i} (D_{ij} \frac{\partial c}{\partial x_j}) - \frac{\partial}{\partial x_i} (v_i c) - \frac{\partial}{\partial t} (\phi S_w R c) + \lambda \phi S_w R c \\
 - q c \cdot
 \end{aligned} \tag{25}$$

where R is the retardation factor defined as

$$R = 1 + \frac{\rho_s (1 - \phi) k_d}{\phi S_w} = 1 + \frac{\rho_B k_d}{\phi S_w} \tag{26}$$

with the bulk density  $\rho_B$  being defined as  $(1 - \phi)\rho_s$ . By expanding the convective and mass accumulation terms of Equation 25, using the continuity equation of fluid flow, and assuming that the time derivative of  $(\rho_B k_d)$  is negligible, the equation reduces to the following:

$$\frac{\partial}{\partial x_i} (D_{ij} \frac{\partial c}{\partial x_j}) - v_i \frac{\partial c}{\partial x_i} = \phi S_w R \left( \frac{\partial c}{\partial t} + \lambda c \right) + q (c - c^*) \tag{28}$$

Note that the term  $q(c - c^*)$  is zero for the case where  $q$  corresponds to the specific discharge of a pumped well because  $c \equiv c^*$ . The hydrodynamic dispersion tensorial components are computed

in Equation 29a using the following constitutive relations for homogeneous systems (Scheidtger 1961):

$$D_{ij} = \alpha_T |V| \delta_{ij} + (\alpha_L - \alpha_T) \frac{v_i v_j}{|V|} + \tau D^o \delta_{ij} \quad (29a)$$

where

$\alpha_L$  and  $\alpha_T$  = longitudinal and transverse dispersivities, respectively

$\delta_{ij}$  = Kronecker delta

$D^o$  = bulk molecular diffusion coefficient

$\tau$  = tortuosity given by the Millington-Quirk (1961) equation as  $\tau = S_w^{10/3} \phi^{4/3}$ .

Alternatively, the hydrodynamic dispersion may be computed from the relations provided by Burnett and Frind (1987) for stratified porous media:

$$D_{xx} = \alpha_L \frac{v_x^2}{|v|} + \alpha_T \frac{v_y^2}{|v|} + \alpha_v \frac{v_z^2}{|v|} + \tau D^o \quad (29b)$$

$$D_{yy} = \alpha_T \frac{v_x^2}{|v|} + \alpha_L \frac{v_y^2}{|v|} + \alpha_v \frac{v_z^2}{|v|} + \tau D^o \quad (29c)$$

$$D_{zz} = \alpha_T \frac{v_x^2}{|v|} + \alpha_v \frac{v_y^2}{|v|} + \alpha_L \frac{v_z^2}{|v|} + \tau D^o \quad (29d)$$

$$D_{xy} = D_{yx} = (\alpha_L - \alpha_T) v_x v_y / |v| \quad (29e)$$

$$D_{yz} = D_{zy} = (\alpha_L - \alpha_v) v_y v_z / |v| \quad (29f)$$

$$D_{zx} = D_{xz} = (\alpha_L - \alpha_v) v_z v_x / |v| \quad (29g)$$

where

$z$  = index for the vertical direction.

Note that Equations 29b through 29g collapse to Equation 29a when  $\alpha_v = \alpha_T$ .

Equation 28 is the required form of the transport equation and will be approximated using the upstream weighted residual finite element technique of Huyakorn and Nilkuha (1979). The initial and boundary conditions associated with Equation 28 are as follows:

$$c(x_1, x_2, 0) = c_o \quad (30a)$$

$$c(x_1, x_2, t) = \tilde{c} \text{ on } B'_1 \quad (30b)$$

$$D_{ij} \frac{\partial c}{\partial x_j} n_i = q_c^D \text{ on } B'_2 \quad (30c)$$

$$D_{ij} \frac{\partial c}{\partial x_j} n_i - v_i n_i c = q_c^T \text{ on } B'_3 \quad (30d)$$

where

$B'_1$  = portion of the boundary where concentration is prescribed as  $\tilde{c}$ ,  $B'_2$  and  $B'_3$  = portions of the boundary where the dispersive and the total solute mass fluxes are prescribed as  $q_c^D$  and  $q_c^T$ , respectively.

## A1.9 NUMERICAL TECHNIQUES FOR VARIABLY SATURATED FLOW

### A1.9.1 Galerkin Formulation

Equation 3 is solved by the Galerkin finite element method. In the Galerkin procedure, the pressure head function is represented by a trial function of the form

$$\psi(x_i, t) = N_J(x_i) \Psi_J(t), \quad J = 1, 2, \dots, n \quad (31)$$

where

$N_J(x_i)$  and  $\Psi_J(t)$  = basis functions and nodal values of pressure head at time  $t$ , respectively  
 $n$  = the number of nodes in the finite element network, and repeated indices imply nodal summation. Applying the Galerkin criterion to Equation 3 and transforming the second-order derivative term, the following can be obtained:

$$\int_R K_{ij} k_{rw} \frac{\partial N_I}{\partial x_i} \frac{\partial N_J}{\partial x_j} \Psi_J dR + \int_R K_{ij} k_{rw} \frac{\partial N_I}{\partial x_i} e_j dR$$

$$\begin{aligned}
 & + \int_R \eta N_I N_J \frac{d\Psi_J}{dt} dR - \int_B K_{ij} k_{rw} \left( \frac{\partial \Psi}{\partial x_j} + e_j \right) N_I n_i dB \\
 & - \int_R N_I q dR = 0 \quad , \quad I = 1, 2, \dots, n
 \end{aligned} \tag{32}$$

where

$R$  = the solution domain with boundary  $B$

$n$  = number of nodes in the finite element network.

Equation 32 can be written more concisely as

$$A_{IJ} \Psi_J + B_{IJ} \frac{d\Psi_J}{dt} = F_I \quad , \quad I = 1, 2, \dots, n \tag{33a}$$

where

$$A_{IJ} = \sum_e \int_{R^e} k_{ij} k_{rw} \frac{\partial N_I}{\partial x_i} \frac{\partial N_J}{\partial x_j} dR \quad (33b)$$

$$B_{IJ} = \sum_e \int_{R^e} \eta N_I N_J dR \quad (33c)$$

$$F_I = \sum_e \left( \int_{R^e} -K_{ij} k_{rw} \frac{\partial N_I}{\partial x_i} e_j dR \right) + \int_R N_I q dR + \sum_e \left( \int_{B^e} V_n N_I dB \right) \quad (33d)$$

where

$R^e$  = the element subdomain with boundary  $B^e$   
 $V_n$  = the normal velocity at the boundary.

The sign convention for  $V_n$  is the same as for  $q$ . That is,  $V_n$  is positive for inward flow and negative for outward flow.  $A_{IJ}$  is the seepage influence matrix,  $B_{IJ}$  is the storage matrix and  $F_I$  represents all sources, sinks and other boundary conditions. The Galerkin approximation process is detailed in Huyakorn et al. (1984). The global coefficient matrices  $A_{IJ}$ ,  $B_{IJ}$ , and  $F_I$  are assembled as a sum of the element matrices for a general 8-noded and 10-noded orthogonal curvilinear element shown in Figure A-4. The 10-noded element is the transition element that can be used to grade the grid within the domain. The nodes along the edges of the element (nodes 9 and 10 of Figure A-4) are the pinch nodes. Influence coefficient techniques presented by Huyakorn et al. (1984) and Huyakorn et al. (1986) for linear basis functions along the coordinate axis can be effectively used for assembling 8-noded prism elements to avoid integration of each of the elemental matrices. The seepage influence coefficients provide the appropriate connectivity for flow between the nodes of the element. The finite element structure of 27 points has a full nearest-neighbor connectivity, and the finite difference 7-point structure excludes all diagonal connectivity. The lattice structures for the various elemental connectivities are shown in Figure A-5. The influence coefficients for the 27-point lattice connectivity are provided by Huyakorn et al. (1986, 1987), and the influence coefficients for the 7-point lattice structure are provided by Panday et al. (1992). Fully lumped or consistent mass matrix options are provided for the 27-point lattice connectivity. A fully-lumped diagonalized mass matrix is used for the 7-point lattice. The finite difference connectivity of a 7-point lattice requires least computational effort for both matrix assembly and solution, and has the smallest global matrix

structure. The finite element connectivity of 27-points requires maximum computational effort, with a global matrix structure almost four times larger.

The 10-noded curvilinear prism transition elements (see Figure A-4) are assembled into the matrix equation by considering two imaginary nodes 11 and 12 and developing the transition element influence coefficients as a combination of two 8-noded elements by static condensation. Due to the linear nature of the basis function between the nodes of an element along the local coordinate axis, the variables  $\psi_{11}$  and  $\psi_{12}$  at the imaginary nodes are eliminated from the two-element combination as

$$\psi_{11} = \frac{m_2}{m_T} \psi_2 + \frac{m_1}{m_T} \psi_3 = \alpha \psi_2 + \beta \psi_3 \quad (34a)$$

and

$$\psi_{12} = \frac{m_2}{m_T} \psi_6 + \frac{m_1}{m_T} \psi_7 = \alpha \psi_6 + \beta \psi_7 \quad (34b)$$

where

$m_1$ ,  $m_2$  and  $m_T$  = length proportions of the transition element shown in Figure A-4, and the terms of the influence coefficient matrix for the 10-noded element are obtained by combining the influence coefficients of the two 8-noded subelements using Equations 34a and 34b to give

$$\begin{aligned} & [a_{I,1}, (a_{I,2} + \alpha a_{I,11}), (a_{I,3} + \beta a_{I,11}), a_{I,4}, a_{I,5}, \\ & (a_{I,6} + \alpha a_{I,12}), (a_{I,7} + \beta a_{I,12}), a_{I,8}, a_{I,9}, a_{I,10}] = [A_{I,j}]^e \end{aligned} \quad (34c)$$

for  $I = 1, \dots, 10$ .

Transition elements with pinch nodes on edges other than those shown in Figure A-4 are assembled by mapping their structure to that of Figure A-4, so that Equations 34a through 34c are applicable. It should be noted that when transition elements are present in a system, the lattice connectivity increases to 33, and 9 for the finite element and finite-difference lattices respectively.

### A1.9.2 Picard and Newton-Raphson Schemes

Equations 33a through 33d represent a system of  $n$  nonlinear ordinary differential equations. Time integration of these equations is performed using implicit finite difference approximations. Two alternative nonlinear treatment procedures are provided in the code. The first scheme is a Picard scheme that leads to a system of algebraic equations with a symmetric coefficient matrix.

The second scheme is a Newton-Raphson scheme that leads to a system of algebraic equations with an asymmetric coefficient matrix. Both schemes are discussed briefly in this section.

In the Picard scheme, Equations 33a through 33d are approximated by the following fully implicit equation:

$$A_{IJ}^{k+1} \Psi_J^{k+1} + \frac{B_{IJ}^{k+1}}{\Delta t_k} (\Psi_J^{k+1} - \Psi_J^k) - F_I^{k+1} \quad , \quad I = 1, 2, \dots, n \quad (35)$$

where

$^k$  and  $^{k+1}$  = previous and current time level respectively  
 $\Delta t_k = t_{k+1} - t_k$ .

Equations 35 is now rearranged in the form

$$\left( A_{IJ}^{k+1} + \frac{B_{IJ}^{k+1}}{\Delta t_k} \right) \Psi_J^{k+1} - F_I^{k+1} + \frac{B_{IJ}^{k+1}}{\Delta t_k} \Psi_J^k \quad (36)$$

which represents a symmetric matrix equation in view of the fact that both [A] and [B] are symmetric matrices. Nonlinear iterations are performed within each time step to achieve a stable numerical solution. For each iteration, the most recent nodal values  $\Psi_I^{k+1}$  are used to calculate coefficient matrices and the right-hand side vector. The code uses backward difference time stepping combined with lumping (diagonalization) of storage matrix [B]. This proves to be advantageous for highly nonlinear situations where damping of oscillatory convergence behavior of the numerical solution is desirable. Central differencing of the temporal term and a consistent storage matrix assembly are also provided as options.

In the Newton-Raphson scheme, Equations 33a through 33d are replaced by the following integrated, fully-implicit finite difference approximation:

$$G_I = A_{IJ} \Psi_J^{k+1} + B'_{IJ} (\Psi_J^{k+1} - \Psi_J^k) / \Delta t_k \\ + E_{IJ} (S_w^{k+1} - S_w^k) / \Delta t \quad = \quad 0, \quad I=1, 2, \dots, n \quad (37)$$

where  $G_I$  = nonlinear (vector array) function of the nodal head values  
 $B'_{IJ}$  and  $E_{IJ}$  =

$$B'_{IJ} = \int_R S_s S_w N_I N_J dR \quad (38a)$$

$$E_{II} = \int_R \phi N_I dR \quad \text{and} \quad E_{II} (J \neq I) = 0 \quad (38b)$$

Application of the Newton-Raphson procedure to Equation 37 yields the following (see Huyakorn and Pinder 1983):

$$G_I^{r+1} - G_I^r + \left( \frac{\partial G_I}{\partial \psi_J} \right)^r \Delta \psi_J^{r+1} = 0 \quad , \quad I=1,2,\dots,n \quad (39)$$

where  $r$  and  $r+1$  denote previous and present iteration levels at the current time value, and  $\Delta \psi_J^{r+1}$  is an iteration displacement vector defined as

$$\Delta \psi_J^{r+1} = \psi_J^{r+1} - \psi_J^r \quad (40)$$

and  $(\partial G_I / \partial \psi_J)^r$  is the Jacobian of the Newton-Raphson iteration. Equations 38a through 38b can be written in the form

$$H_{IJ}^r \psi_J^{r+1} = H_{IJ}^r \psi_J^r - G_I^r \quad , \quad I=1,2,\dots,n \quad (41)$$

where

$$H_{IJ} = (\partial G_I / \partial \psi_J)^r.$$

Because  $[H]$  is an asymmetric matrix, Equation 41 represents an asymmetric matrix equation. As in the Picard scheme, it is necessary to perform nonlinear iterations within the time step to achieve a converged numerical solution. Iterations are performed until the successive change in head values are within prescribed tolerance limits. VAM3DCG utilizes automatic time-step reduction and underrelaxation procedures to handle convergence difficulties.

### A1.9.3 Matrix Solution Techniques

For a fully three-dimensional analysis, the system of algebraic equations resulting from the finite element approximation of the flow equation needs to be solved using an efficient matrix solver to obtain cost-effective simulations of realistic field problems.

The Preconditioned Conjugate Gradient (PCG) method (see Kershaw 1978) has emerged as one of the most promising iterative methods for solving large sparse matrix equations generated by finite element (or finite difference) approximations of multidimensional field problems. There have been a number of recent papers describing successful conjunctive applications of PCG and finite element or finite difference method to groundwater flow problems. These include the publications by Gambolati (1980); Kuiper (1981, 1987); Gambolati et al. (1986); Kalf (1988); and Meyer et al. (1989).

The symmetric PCG solver implemented into VAM3DCG is based on a two-step procedure developed by Meijerink and van der Vorst (1977) and extended and implemented by Kershaw (1978) and Anderson (1983). It is used in VAM3DCG to solve the system of algebraic equations resulting from the Picard scheme of the finite element flow formulation. The first step of this PCG algorithm involves preconditioning of the finite element coefficient matrix  $A$  of a general symmetric matrix system  $Ax = y$  by computing an incomplete triangular Cholesky decomposition ( $LDL^T$ ) of  $A$ . The second step involves conjugate gradient iterations on an initial guess  $x^0$  of the vector  $x$ . The CG recursive equations are as follows:

Let

$$K = (LDL^T) \quad (42a)$$

$$r^0 = y - Ax^0 \quad (42b)$$

$$p^0 = K^{-1} r^0 \quad (42c)$$

$$q^0 = Ap^0$$

Then

$i = 0, 1, 2, \dots$

$$\alpha_i = (r^i, K^{-1} r^i) / (p^i, q^i) \quad (43)$$

$$x^{i+1} = x^i + \alpha_i p^i \quad (44)$$

$$r^{i+1} = r^i - \alpha_i q^i \quad (45)$$

$$\beta_i = (r^{i+1}, K^{-1} r^{i+1}) / (r^i, K^{-1} r^i) \quad (46)$$

$$p^{i+1} = K^{-1} r^{i+1} + \beta_i p^i \quad (47)$$

$$q^{i+1} = Mp^{i+1}$$

This scheme is repeated until the  $L_2$  norm of the head error is less than a prescribed tolerance criterion.

In a case where the nonlinear variably saturated flow problem is treated using the Newton-Raphson technique, the resulting finite element matrix system is asymmetric. For such a case, VAM3DCG uses the asymmetric PCG/ORTHOMIN algorithms described later in Section 1.10.2. If VAM3DCG is implemented in a 2-D mode, a banded direct solver is used.

## A1.10 NUMERICAL TECHNIQUE FOR SOLUTE TRANSPORT

### A1.10.1 Upstream Weighted Residual Formulation

For the contaminant transport simulation, VAM3DCG solves Equation 25 for single-species transport using an upstream weighted residual finite element method.

To illustrate the application of the technique, consider Equation 25 and a trial solution for concentration be written in the following form:

$$c(x_i, t) = N_J(x_i) c_J(t) \quad (48)$$

where

$N_J(x_i)$  and  $c_J(t)$  = basis functions and nodal values of concentration at time  $t$ , respectively.

In the upstream weighted residual technique, the weighted residual integral equation is obtained using asymmetric (upstream) weighting functions (Huyakorn and Nilkuha 1979) to weight the spatial derivative terms of the transport equation, and the standard basis functions to weight the remaining mass accumulation term. Application of this procedure to Equation 25 yields

$$\int_R W_I \left[ \frac{\partial}{\partial x_i} \left( D_{ij} \frac{\partial c}{\partial x_j} - v_i \frac{\partial c}{\partial x_i} \right) - \int_R N_I \left[ \phi S_w R \left( \frac{\partial c}{\partial t} + \lambda c \right) + q (c - c^*) \right] dR = 0 \quad (49)$$

where

$W_I$  = upstream weighting functions.

Using Green's theorem to remove the second derivative and substituting for  $c$ , the following is obtained:

$$\int_R \left( D_{ij} \frac{\partial W_I}{\partial x_i} \frac{\partial N_J}{\partial x_j} + v_i W_I \frac{\partial N_J}{\partial x_i} \right) c_J dR + \int_R \phi S_w R N_I N_J \left( \frac{dc_J}{dt} + \lambda c_J \right) dR + \int N_I q (c^* - N_J c_J) dR - \int_B W_I \left( D_{ij} \frac{\partial c}{\partial x_j} \right) n_i dB = 0 \quad (50)$$

Equation 25 can be expressed in the form

$$(E_{IJ} + B_{IJ}^*) c_J + \bar{B}_{IJ} \frac{dc_J}{dt} = \bar{F}_I \quad (51)$$

where

$$\bar{F}_I = - \int_R N_I q (c \cdot N_J c_J) dR + \int_B W_I (D_{ij} \frac{\partial c}{\partial x_j}) n_i dB$$

$$E_{ij} = \int_R (D_{ij} \frac{\partial W_I}{\partial x_i} \frac{\partial N_J}{\partial x_j} + v_i W_I \frac{\partial N_J}{\partial x_i}) dR$$

$$\bar{B}_{IJ} = \int_R (\phi S_{WR}) N_I N_J dR$$

$$B_{IJ}^* = \int_R (\lambda \phi S_{WR}) N_I N_J dR$$

Once all of the element matrices have been computed and assembled into global matrices, the system of ordinary differential Equation 51 can be integrated with respect to time. This leads to the following system of algebraic equations

$$\left[ \omega (E_{IJ} + B_{IJ}^*) + \frac{\bar{B}_{IJ}}{\Delta t_k} \right] c_J^{k+1} = (\omega - 1) (E_{IJ} + B_{IJ}^*) c_J^k + \frac{\bar{B}_{IJ}}{\Delta t_k} c_J^k + \omega \bar{F}_I^{k+1} + (1 - \omega) \bar{F}_I^k \quad (52)$$

where

$\omega$  = the time weighting factor.

Equation 69 can be rearranged in the following form:

$$G_{IJ} c_J^{k+1} = R_I^{k+1} \quad (53)$$

where

$$R_I^{k+1} = (\omega - 1) (E_{IJ} + B_{IJ}^*) c_J^k + \frac{\bar{B}_{IJ}}{\Delta t_k} c_J^k + \omega \bar{F}_I^{k+1} + (1 - \omega) \bar{F}_I^k \quad (54a)$$

and

$$G_U = \omega (E_U + B_U^*) + \tilde{B}_U / \Delta t_k \quad (54b)$$

To obtain a second-order accuracy in time approximation,  $\omega$  is chosen to be 0.5, thus yielding the Crank-Nicholson time-stepping scheme. Equation 53 represents a system of linear algebraic equations with an asymmetric-banded coefficient matrix; its solution is achieved by using either a direct solver (for two-dimensional simulations) or the ORTHOMIN solver.

The finite element and finite difference lattice connectivity options are provided for the transport equation as well. The 27-point lattice connectivity values for the various influence coefficient matrices are discussed in Huyakorn et al. (1985, 1986), and the influence coefficient formulas for the 7-point lattice connectivity are provided by Panday et al. (1992). Influence coefficient matrices for the 10-noded transition elements of the transport equation are assembled in an identical manner to the 10-noded transition elements of the flow equation, with  $c$  replacing  $\psi$  in Equations 34a through 34c. A consistent mass matrix is used for the 27-point lattice connectivity and a fully-lumped matrix is generated for the 7-point lattice. In addition, all cross terms of the dispersive matrix are incorporated into the right-hand side vector in an explicit manner for the 7-point connectivity. Fully implicit and Crank-Nicholson options for time discretization provide for the alternatives of higher stability or a higher order of accuracy.

### A1.10.2 Matrix Solution Techniques

In a full three-dimensional analysis, the system of algebraic equations resulting from the finite element approximation of the transport equation is solved efficiently using an iterative solver for an asymmetric coefficient matrix. The ORTHOMIN scheme presented by Behie and Winsome (1982) is well suited for these matrices and is guaranteed to converge for an M matrix. The ORTHOMIN procedure may be considered as another variant of the standard preconditioned conjugate gradient procedure described in Section 1.9.3; their formulations are similar. The full ORTHOMIN procedure is provided in the following:

Let  $M$  be approximated by  $K \equiv LU$ . Starting with  $n = 0$ , the residual vector  $r^0$  is first evaluated as

$$r^0 = y - Mx^0 \quad (55)$$

Then for  $n = 0, 1, 2, \dots$ , the following computation is made:

$$v^{n+1} = K^{-1}r^n \quad (56a)$$

$$p^{n+1} = v^{n+1} - \sum_{i=1}^n a_i^{n+1} p^i \quad (56b)$$

$$q^{n+1} = M p^{n+1} \quad (56c)$$

$$x^{n+1} = x^n + \omega^{n+1} p^{n+1} \quad (56d)$$

and

$$r^{n+1} = r^n - \omega^{n+1} q^{n+1} \quad (56e)$$

where

$$a_i^{n+1} = (q^i, M v^{n+1}) / (q^i, q^i) \quad (56f)$$

and

$$\omega^{n+1} = (r^n, q^{n+1}) / (q^{n+1}, q^{n+1}) \quad (56g)$$

The orthogonalizations are restarted after NORTH times, where NORTH is prescribed by the user.

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Figure A-1. Example of Hysteric  $S_w(\Psi)$  Relation Showing the Boundary Wetting and Drying Curves.

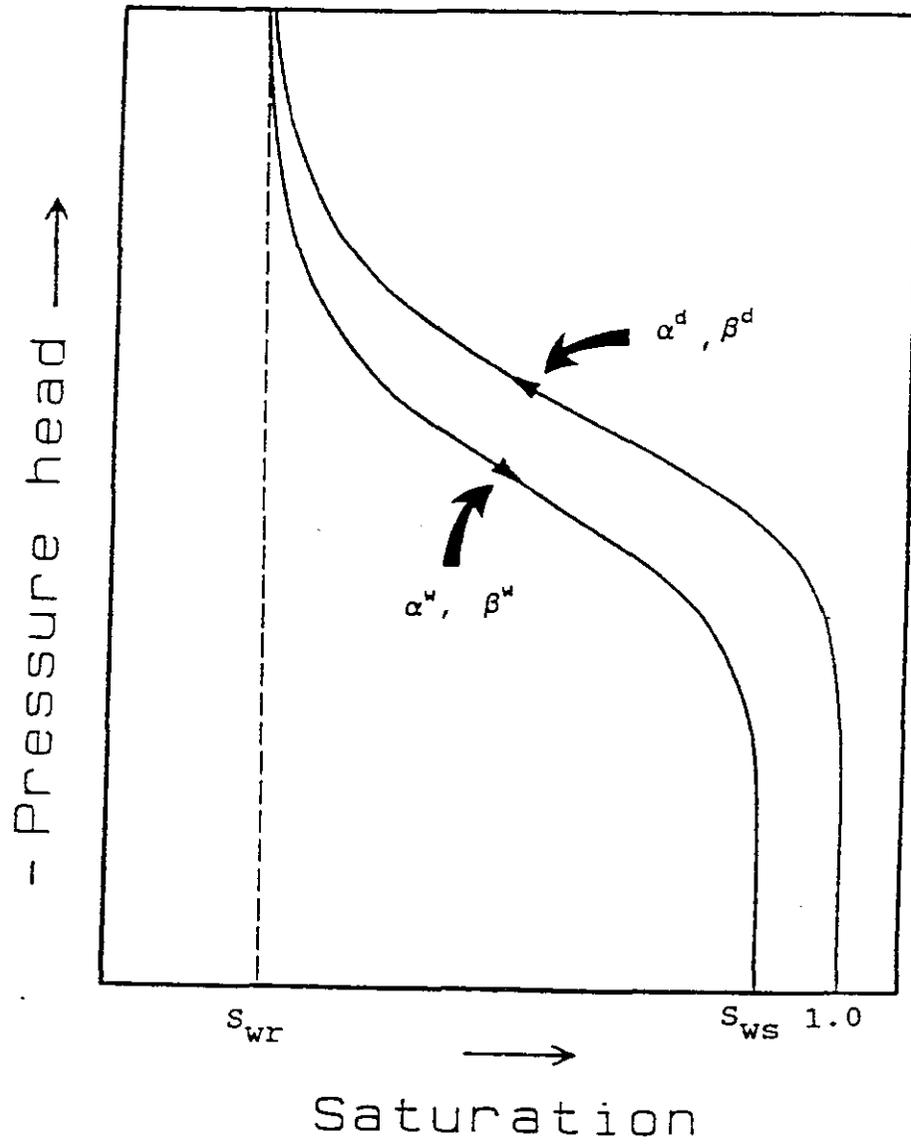
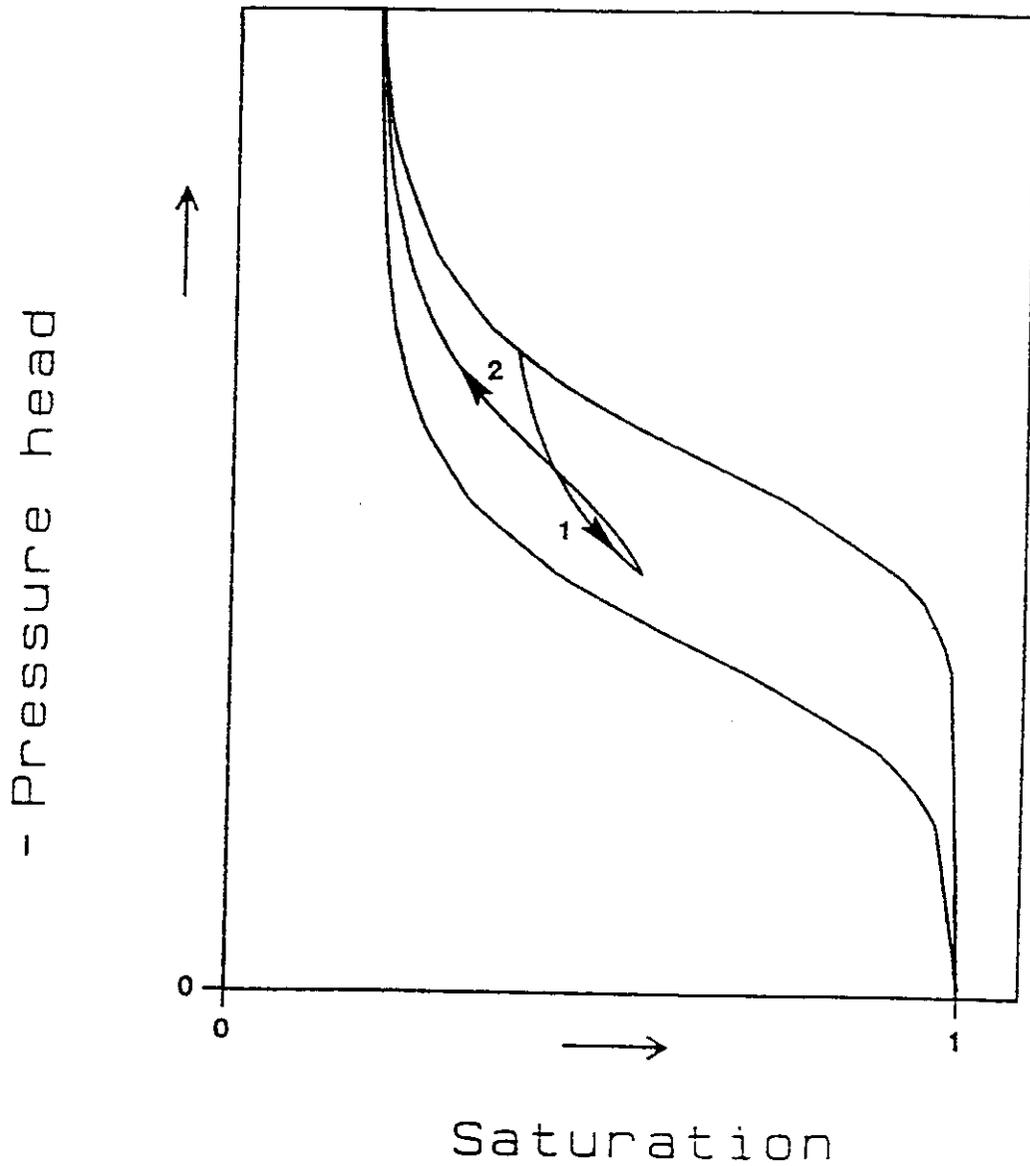


Figure A-2. Typical Scanning Curves Produced by the Hysteresis Model  
in VAM3DCG.



**Note:** Curve 1 denotes primary wetting scanning curve; and curve 2 denotes secondary drying scanning curve.

Figure A-3. Example of Anisotropic  $k_{rw}$  ( $\Psi$ ) Relation as Modeled by VAM3DCG.

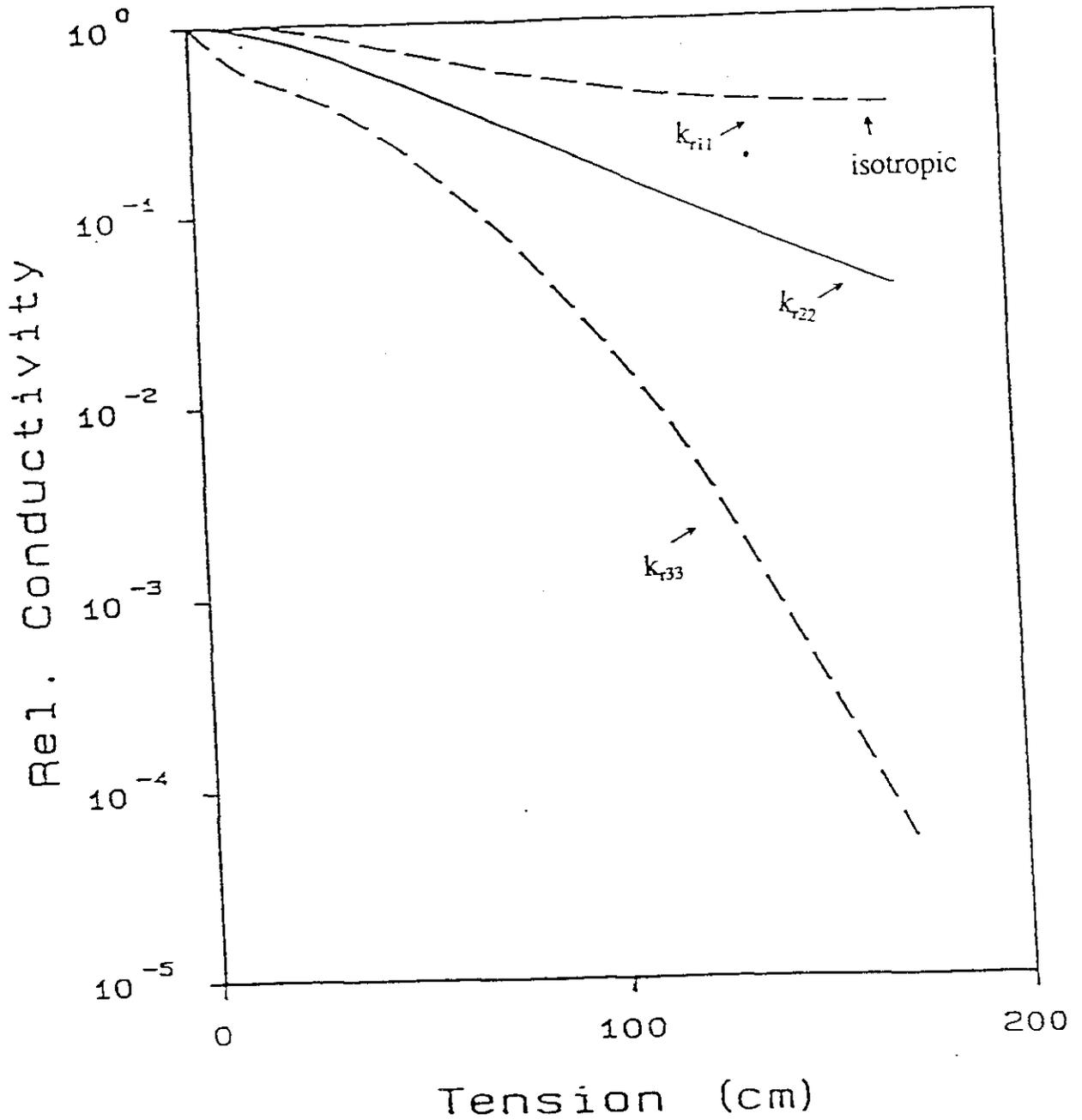
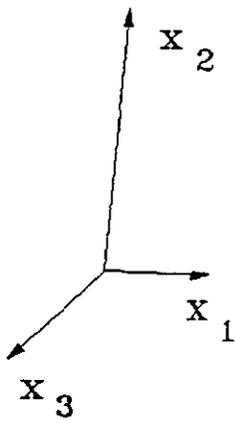
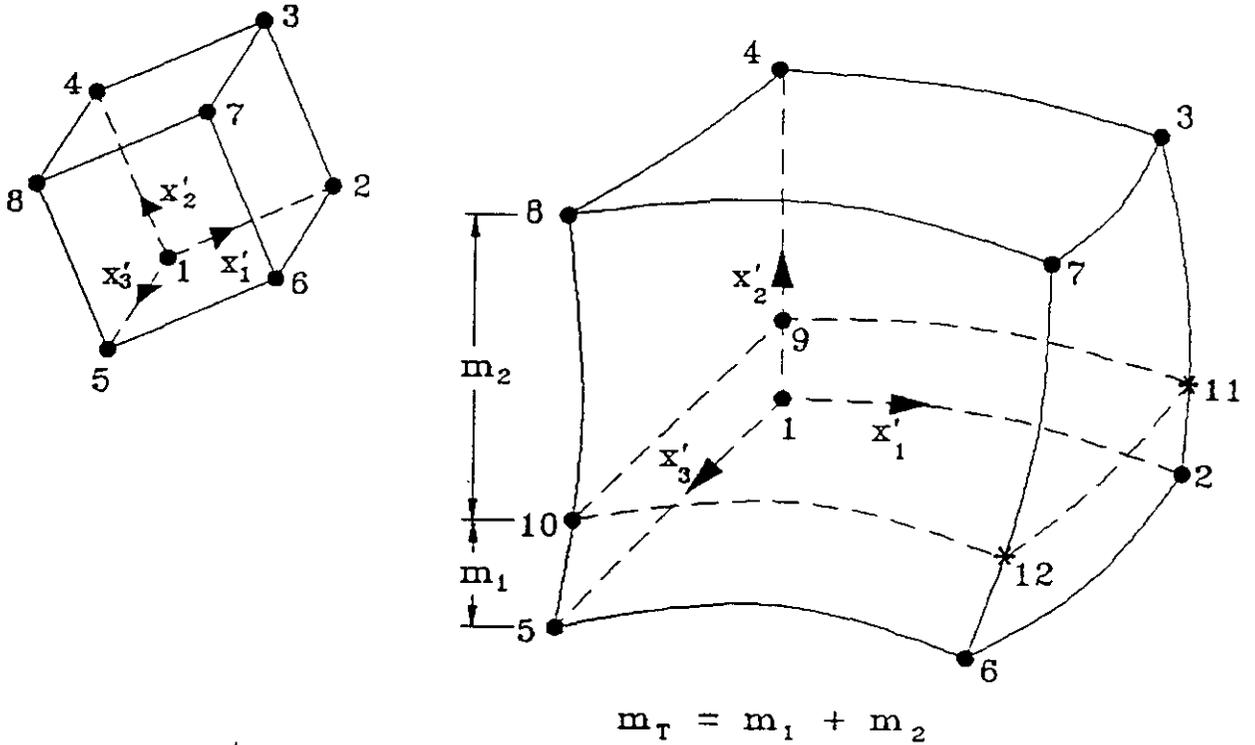
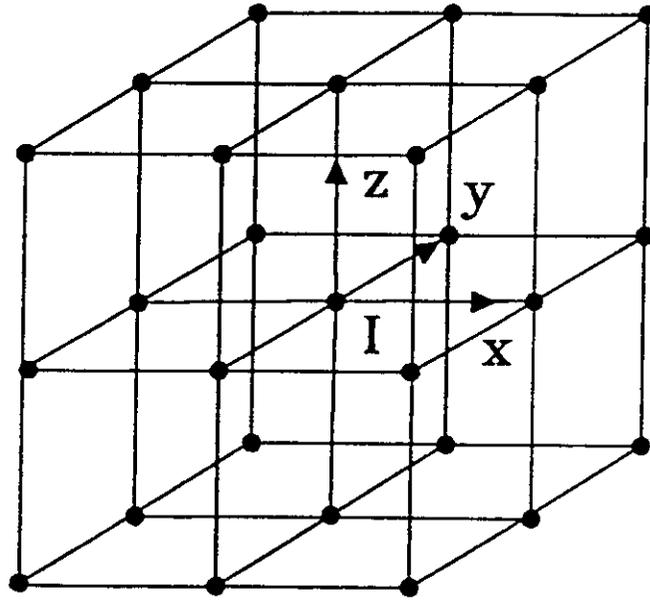


Figure A-4. Types of Elements Used by VAM3DCG.

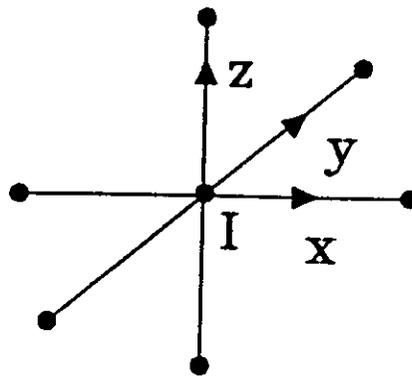


Note: 11 and 12 are imaginary nodes created for assembly of the 10 noded element.

Figure A-5. Elemental Lattice Connectivity Structures Used by VAM3DCG.



27 point lattice



7 point lattice

**APPENDIX B**  
**MODEL SENSITIVITY ANALYSIS**



## B.0 SENSITIVITY ANALYSIS

Sensitivity analyses were performed by varying a parameter (or set of parameters) from the calibrated base case to observe the change in flow and transport behavior. The objective of the analysis is to determine the effects of several modeling assumptions and to identify critical parameters and mechanisms governing flow and transport under the site. Flow and transport parameters studied were as follows:

- Hydraulic conductivity
- Hydrostratigraphy
- Tritium decay
- Dispersivity.

The model sensitivity to different parameters is investigated for water levels and fluxes, as well as influences on the tritium plume.

### B.1 HYDRAULIC CONDUCTIVITY SENSITIVITY

Two scenarios were evaluated to determine the model sensitivity to different hydraulic conductivity. The first scenario examines the effects of doubling the hydraulic conductivity for all material layers. The second evaluates the effects of doubling the hydraulic conductivity for the pre-Missoula/Hanford formation materials only.

#### B.1.1 Sensitivity to Higher Hydraulic Conductivity in All Materials

The model sensitivity to higher hydraulic conductivity was examined to determine the effects on groundwater flow and tritium transport. To perform this assessment, the hydraulic conductivity was doubled for all materials in the model domain. The effects of higher hydraulic conductivity were examined under both steady-state and transient flow conditions. All other material zone properties remained unchanged.

Water table levels for the steady state flow simulation with doubled hydraulic conductivity are presented in Figure B-1. Evident from this plot is that the groundwater mound in the 200 West Area is not present and water levels in the eastern portion of the domain are slightly lower. There is no impact to the flux into or out of the model as the recharge boundaries along Cold and Dry Creeks are set to constant flux. However, if the sensitivity analysis is conducted on the pre-calibration simulation with the recharge boundaries set as constant head, the recharge to the system is changed from 0.12 m<sup>3</sup>/sec (4.3 cfs) to 0.62 m<sup>3</sup>/sec (22 cfs) for Cold Creek and from 0.47 m<sup>3</sup>/sec to 0.96 m<sup>3</sup>/sec (16.6 cfs to 34 cfs) for Dry Creek. Discharge to the Columbia River is changed from 1.47 m<sup>3</sup>/sec to 2.72 m<sup>3</sup>/sec (51.9 cfs to 96 cfs).

Water levels for transient simulation yr 9 and 14 (1988 and 1993) are shown in Figures B-2 and B-3. The water levels also are much lower than for the base case simulations and similar to the steady state sensitivity simulation, except for the B Pond mound east of 200 East Area. No change in water levels north of Gable Mountain was observed.

Tritium concentration distributions after 9 and 14 yr of simulation are shown in Figures B-4 and B-5 respectively. The tritium plume lobes in both the eastern and western portion of the model have moved faster than for the base case. The 200,000-pCi/L contour has moved only slightly further eastward than for the base case, even with doubled conductivities, due to the dominant effect of decay (see Section B.3).

### **B.1.2 Sensitivity to Higher Hydraulic Conductivity in the Pre-Missoula/Hanford Unit**

This sensitivity analysis case examines the effect of doubling only the hydraulic conductivity of the more conductive pre-Missoula/Hanford formation. All other base case model conditions were unchanged. Water levels for the 1979 steady-state simulation are shown in Figure B-6. Heads in the Cold Creek recharge area are about 3 m (10 ft) lower than for the base case. However, immediately to the east in 200 West Area, the water levels are similar to the base case simulation. This is because the Ringold Formation is the only saturated unit in this area, and changing the hydraulic conductivity in the pre-Missoula/Hanford formation has no effect on water levels. However, further east where the pre-Missoula/Hanford formation becomes saturated, water levels are significantly lower, and even lower than for the sensitivity case where the hydraulic conductivity for both units was increased. Figures B-7 and B-8 show water table levels after 9 and 14 yr of transient simulation. These water levels also are lower than base case values as well as those in the previous sensitivity study presented in Section 4.1.1.

Transient simulation results for tritium are shown in Figures B-9 and B-10. These figures show tritium concentrations after 9 and 14 yr of simulation. The tritium plume in the western portion of the modeled domain is similar to the base case. The plume in the central and eastern portions of the domain, in particular the 200,000-pCi/L concentration contour, has traveled farther than for the base case, although slightly less than for the sensitivity analysis where conductivity values were doubled for both units. This demonstrates that both groundwater flow and contaminant transport are sensitive to hydraulic conductivity.

## **B.2 SENSITIVITY TO HYDROGEOLOGIC UNIT CONTACT**

The model sensitivity to the vertical position of the contact between the Ringold Formation and overlying pre-Missoula/Hanford formation is examined by raising the contact by 1 m (3 ft). The initial contact elevation is shown on Figure 3-6. This analysis addresses the uncertainty in position of this contact. Simulation results show that for steady-state conditions, water levels in the eastern portions of the domain, where the pre-Missoula/Hanford formation is saturated, are up to 1.8 m (6 ft) higher than for the base case (Figure B-11). This is the result of raising the

contact position and necessity of the model to saturate additional pre-Missoula/Hanford formation material. In the western portion of the domain, where the Ringold formation is the only saturated unit, water levels fell approximately 1 m (3 ft). This drop in water level is the result of increasing the saturated thickness of the Ringold Formation in the eastern portion of the model domain, which requires that water from the west be moved to saturate the increased Ringold Formation thickness. Figures B-12 and B-13 show the water table levels for the transient simulation at 9 and 14 yr. Similar changes in water levels are observed for the transient case as for the steady-state simulation discussed previously. The results of this sensitivity case demonstrate that water levels are sensitive to the contact position.

Figures B-14 and B-15 show the tritium distribution at 9 and 14 yr of transient simulation, respectively. These figures show that there is little difference between the this sensitivity case and the base case simulation for tritium transport. Therefore, it can be concluded that tritium transport is insensitive to the contact position.

### **B.3 SENSITIVITY TO TRITIUM DECAY**

The base case simulation shows that the majority of tritium loss, approximately 80 percent, is due to decay. This sensitivity case examines the behavior of the tritium plume, through 14 yr of simulation, due to decay alone. Initial tritium distributions were set along the top four nodal layers; with no advective or dispersive flow through the domain. No recharge from the cribs or ponds is allowed. Thus, the only mechanisms for tritium attenuation is decay. Figures B-16 and B-17 show the tritium distribution through the fifth nodal plane (2nd layer from top) for 9 and 14 yr, respectively. Evident from these figures is that the 200,000-pCi/L contours are more centered and larger than for the base case simulation. However, the areal extent of the plume, with greater than 5,000 pCi/L concentration, is smaller that for the base case. The domain lost a net  $2.05 \times 10^{14}$  pCi in 14 yrs of simulation, which compares well with the activity  $2.09 \times 10^{14}$  pCi lost during the base case simulation. This demonstrates the dominant effect of decay on the tritium transport simulations.

### **B.4 TRITIUM PLUME SENSITIVITY TO ADVECTIVE AND DISPERSIVE FLOW**

Due to the dominant effect of decay on the tritium plume as demonstrated for the base case simulation and in Section B.3, the impacts of advective and dispersive flow were assessed. To accomplish this, the decay of tritium is set to zero, and all other material and transport parameters held the same as for the base case. Figures B-18 and B-19 show the model results after 9 and 14 yr of transient simulation. The areal extent of the plume is slightly larger in areal extent, with the 200,000-pCi/L contour being much larger. In addition, the two plumes associated with the 200 West and 200 East Areas merge together, which was not seen in the base case simulation due to the dominant effect of decay. The movement of the eastern end of the 200,000-pCi/L contour near the Columbia River also is seen have a greater impact on the river. The model results

The model results calculate that  $1.14 \times 10^{12}$  pCi are left the domain during the 14-yr simulation period. This is approximately two orders of magnitude less than for the base case. This demonstrates that advection and dispersion have an impact on the tritium plume movement, however the plume concentrations are dominantly controlled by tritium decay.

Figure B-1. Comparison of Water Table for Doubled Hydraulic Conductivity Sensitivity Case with Base Case - 1979.

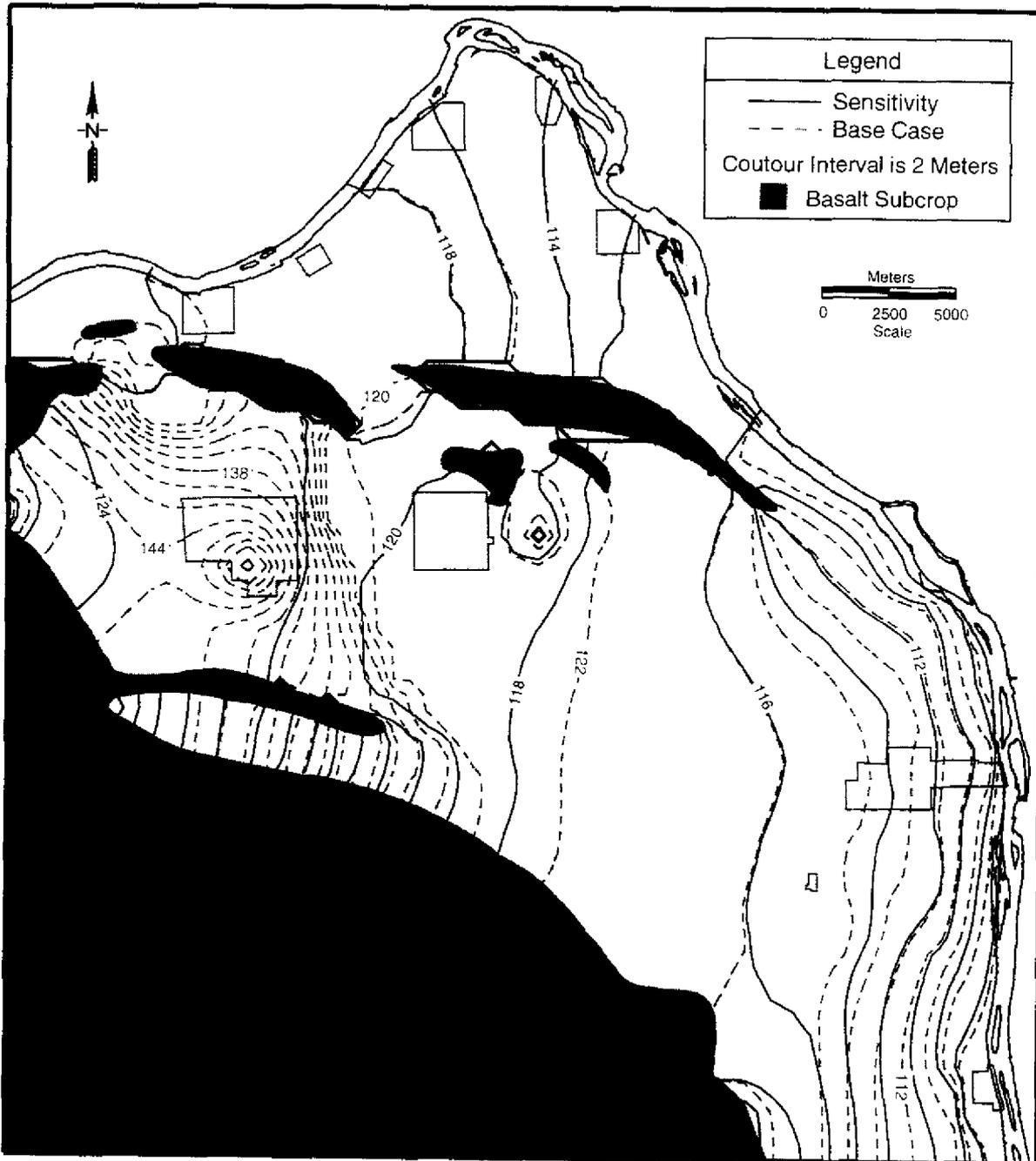


Figure B-2. Comparison of Water Table for Doubled Hydraulic Conductivity Sensitivity Case with Base Case - 1988.

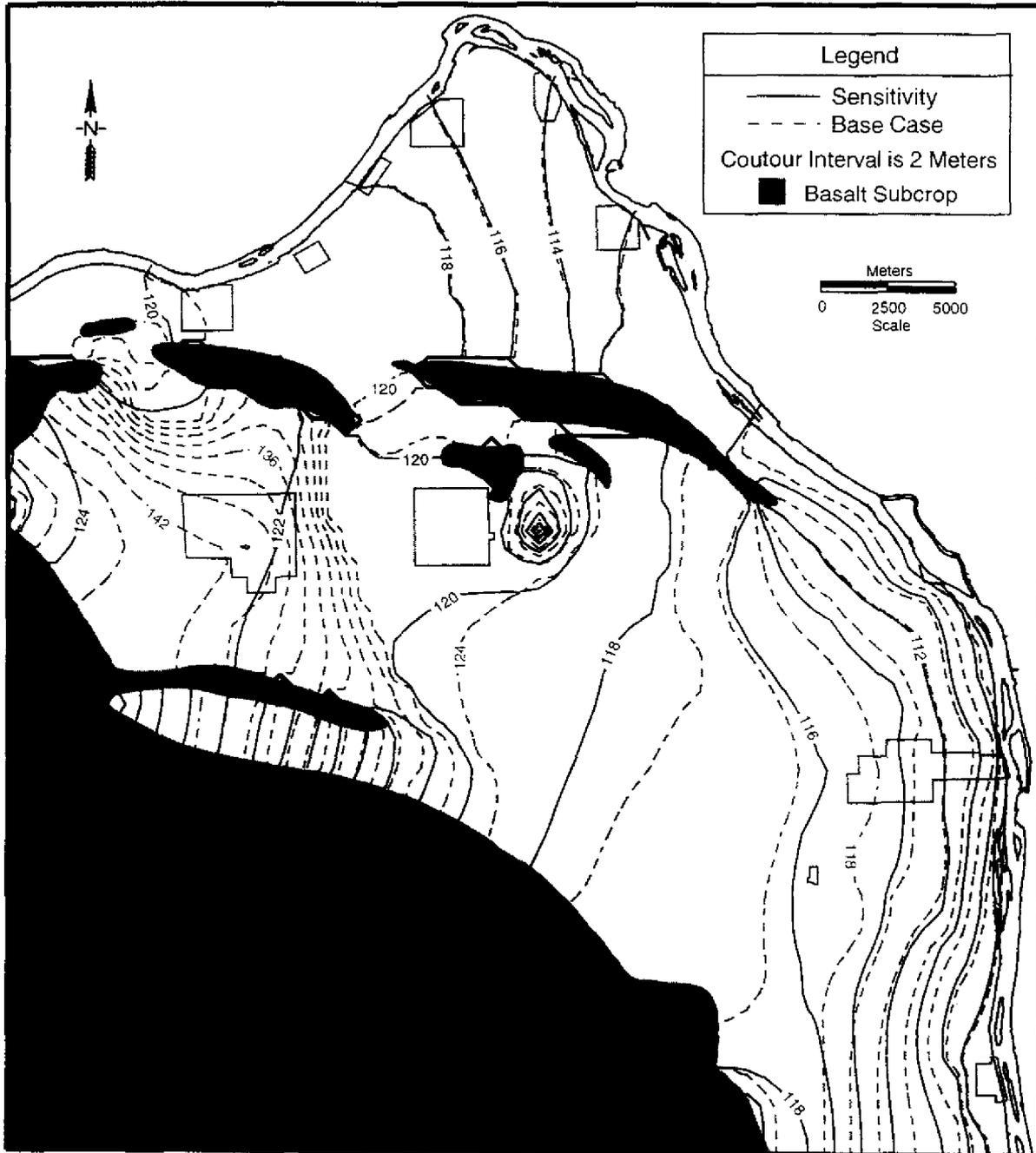


Figure B-3. Comparison of Water Table for Doubled Hydraulic Conductivity Sensitivity Case with Base Case - 1993.

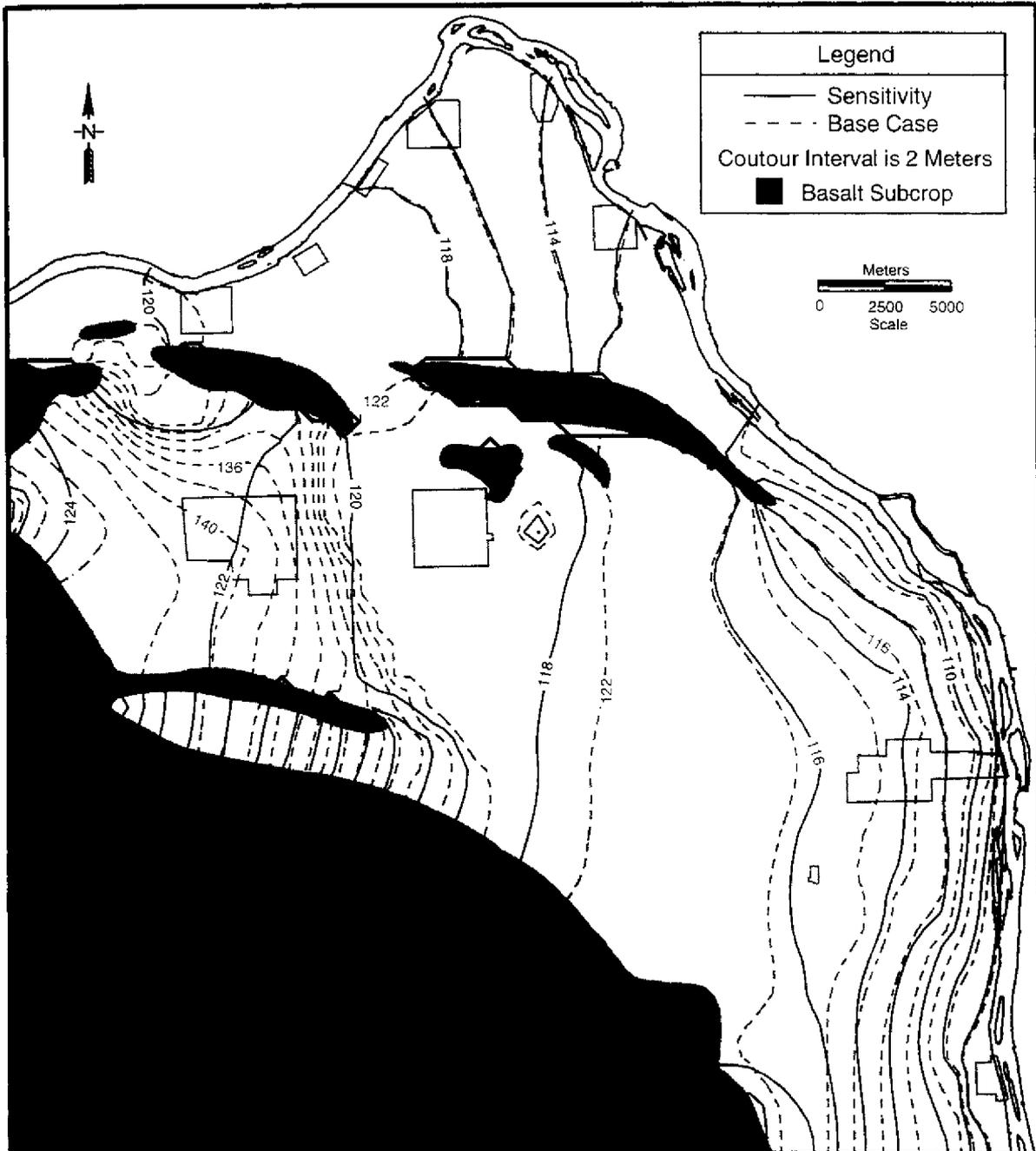


Figure B-4. Comparison of Tritium Concentrations for Doubled Hydraulic Conductivity Sensitivity Case with Base Case - 1988.

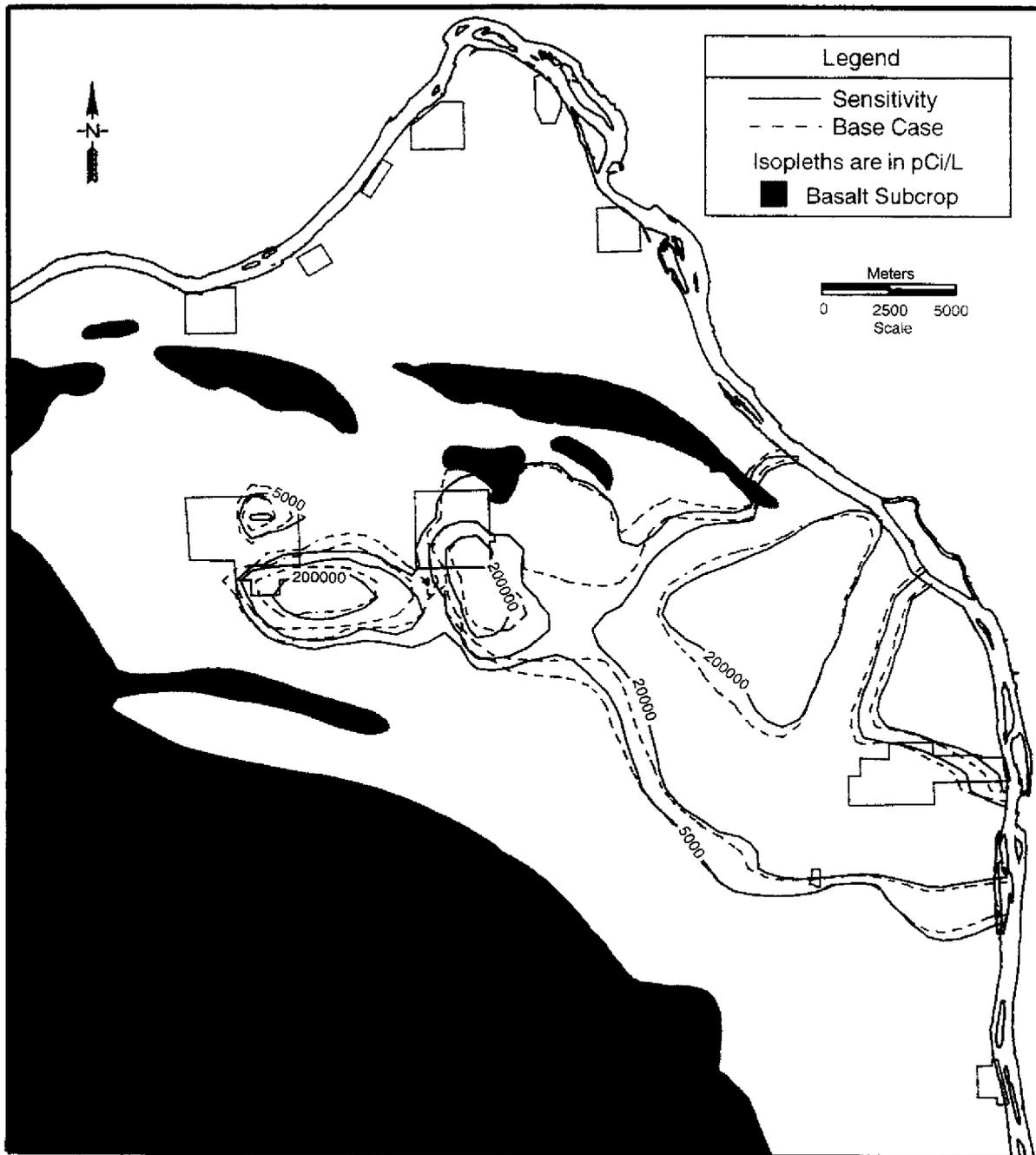


Figure B-5. Comparison of Tritium Concentrations for Doubled Hydraulic Conductivity Sensitivity Case with Base Case - 1993.

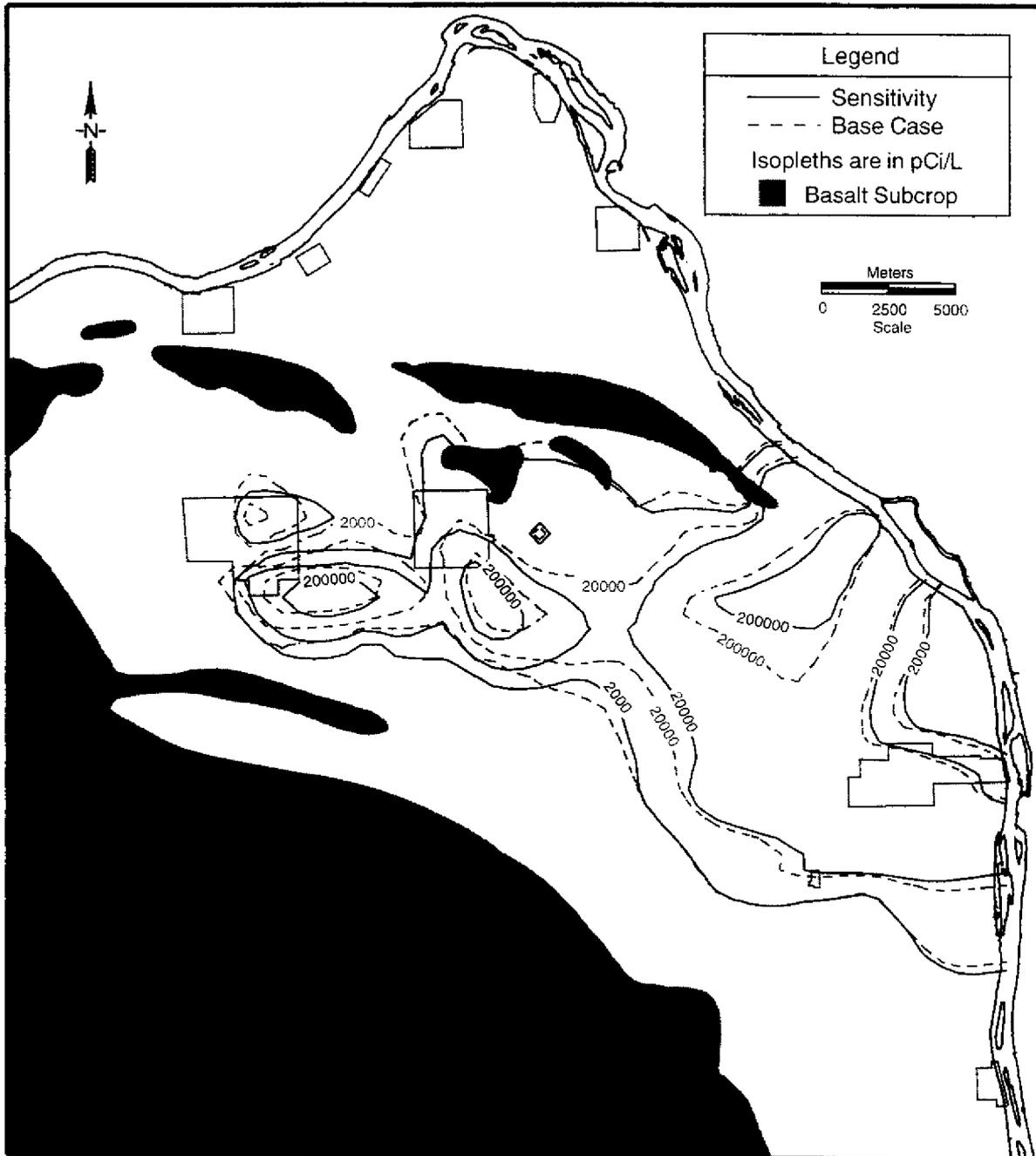


Figure B-6. Comparison of Water Tables for Doubled Hydraulic Conductivity for the Pre-Missoula/Hanford Unit Sensitivity Case with Base Case - 1979.

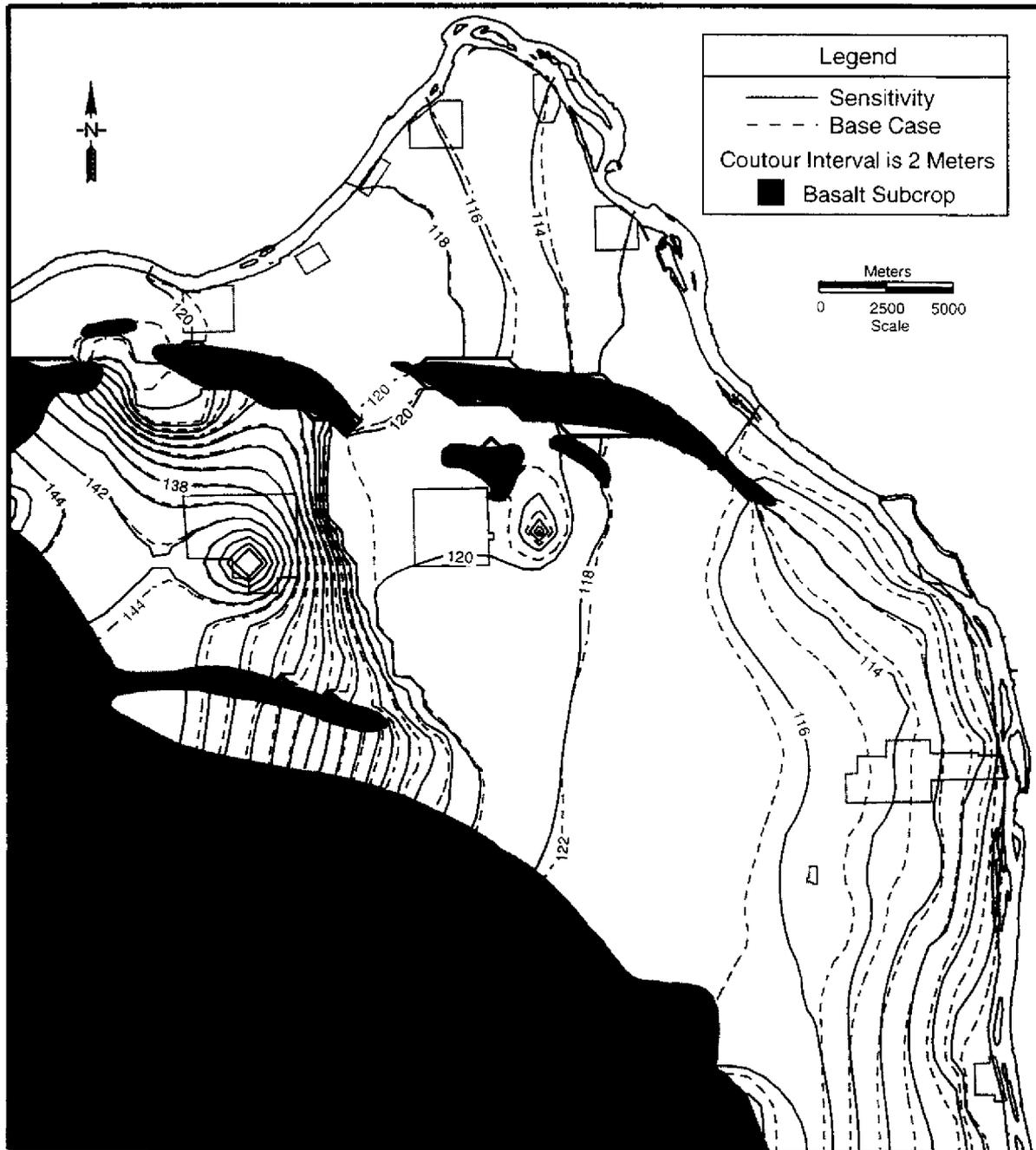


Figure B-7. Comparison of Water Tables for Doubled Hydraulic Conductivity for the Pre-Missoula/Hanford Unit Sensitivity Case with Base Case - 1988.

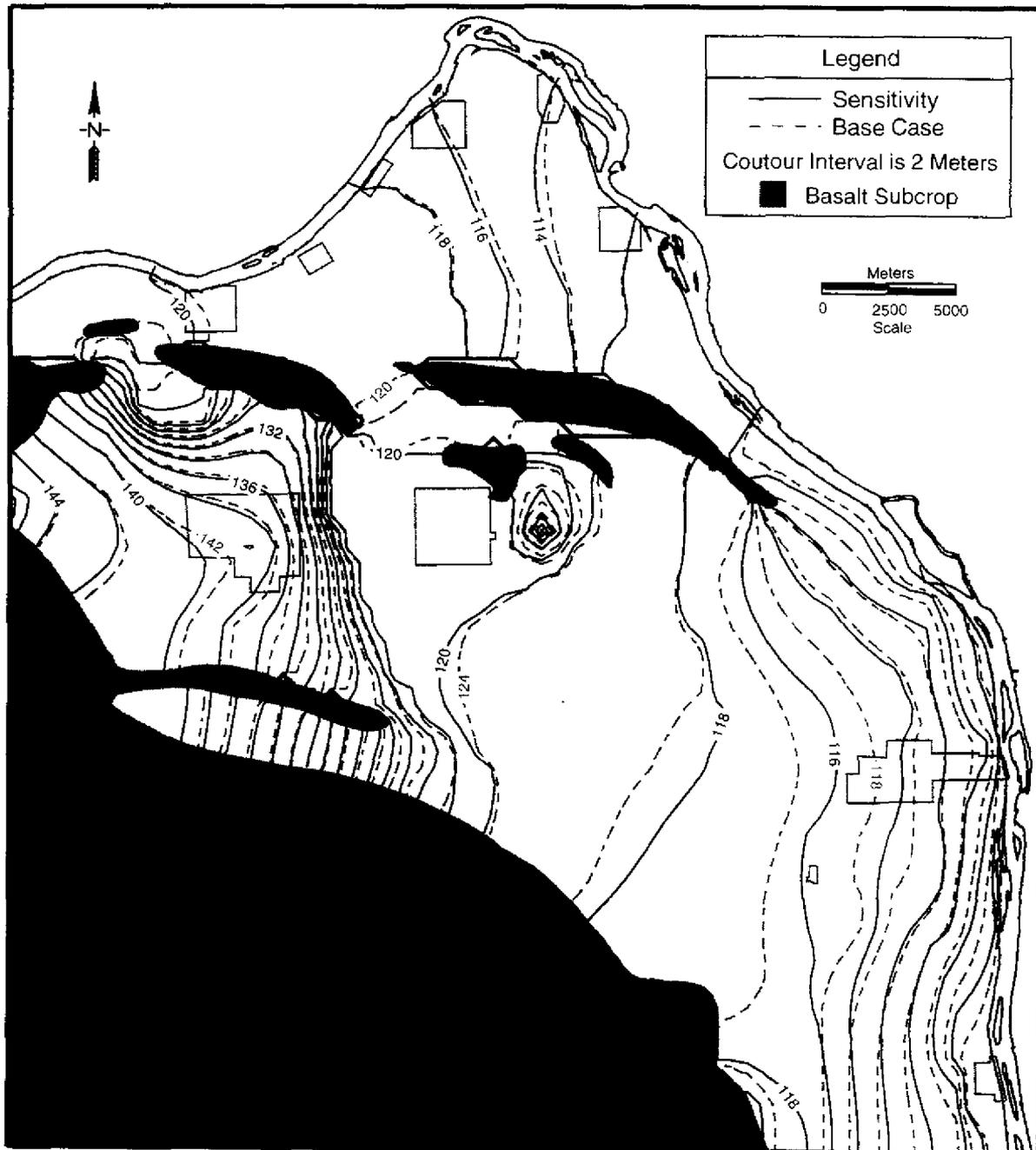


Figure B-8. Comparison of Water Tables for Doubled Hydraulic Conductivity for the Pre-Missoula/Hanford Unit Sensitivity Case with Base Case - 1993.

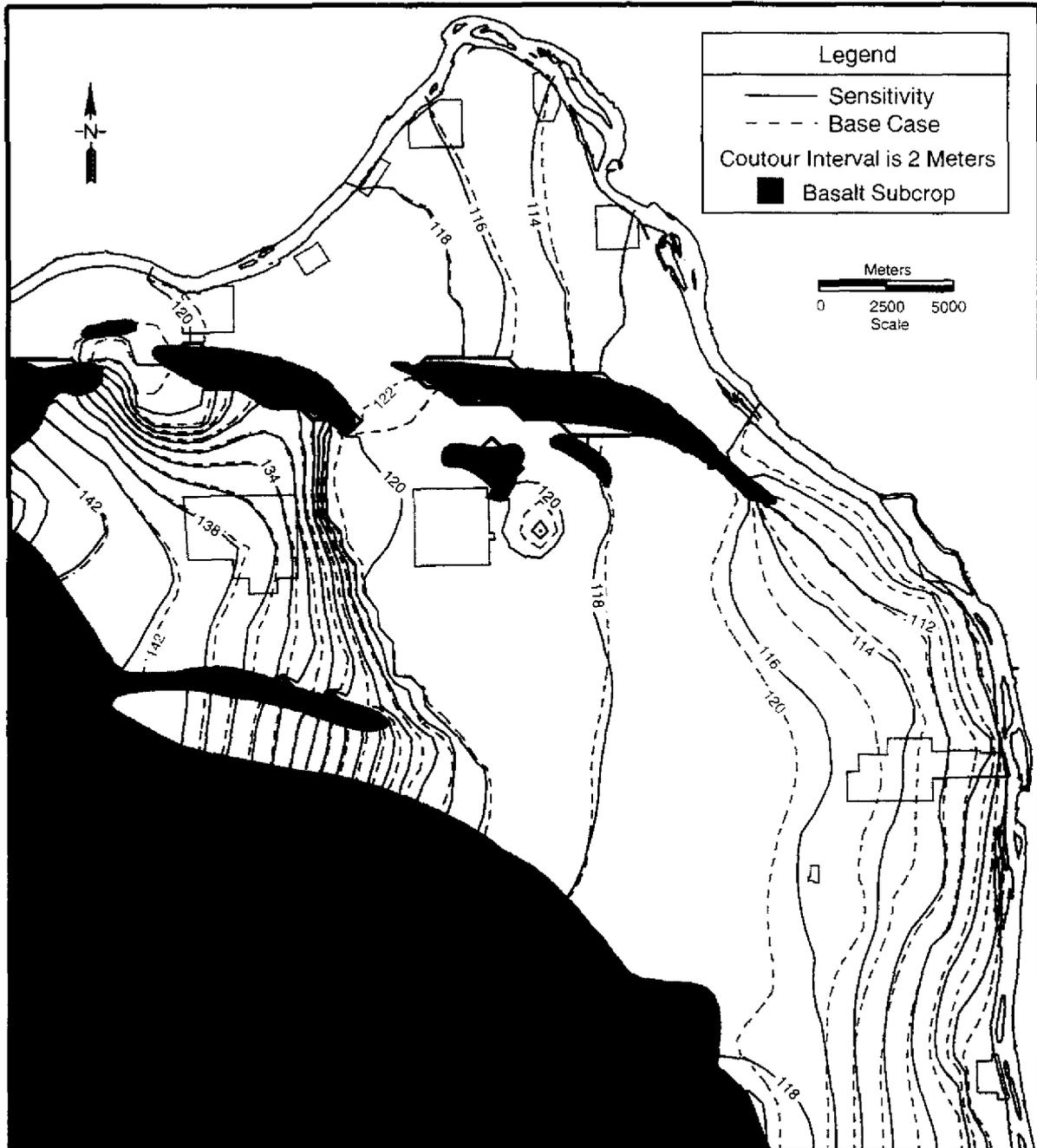


Figure B-9. Comparison of Tritium Concentrations for Doubled Hydraulic Conductivity for the Pre-Missoula/Hanford Unit Sensitivity Case with Base Case - 1988.

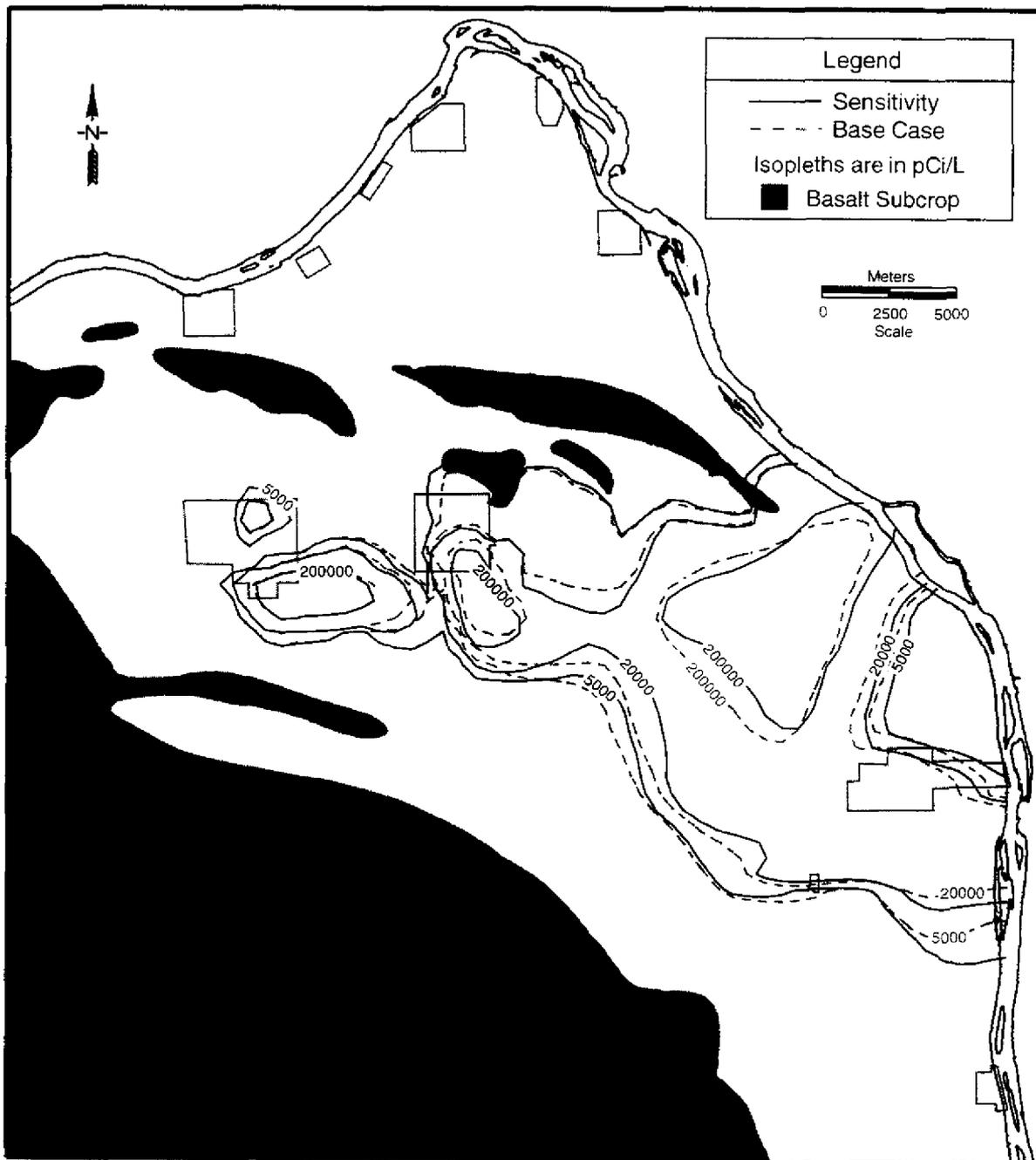


Figure B-10. Comparison of Tritium Concentrations for Doubled Hydraulic Conductivity for the Pre-Missoula/Hanford Unit Sensitivity Case with Base Case - 1993.

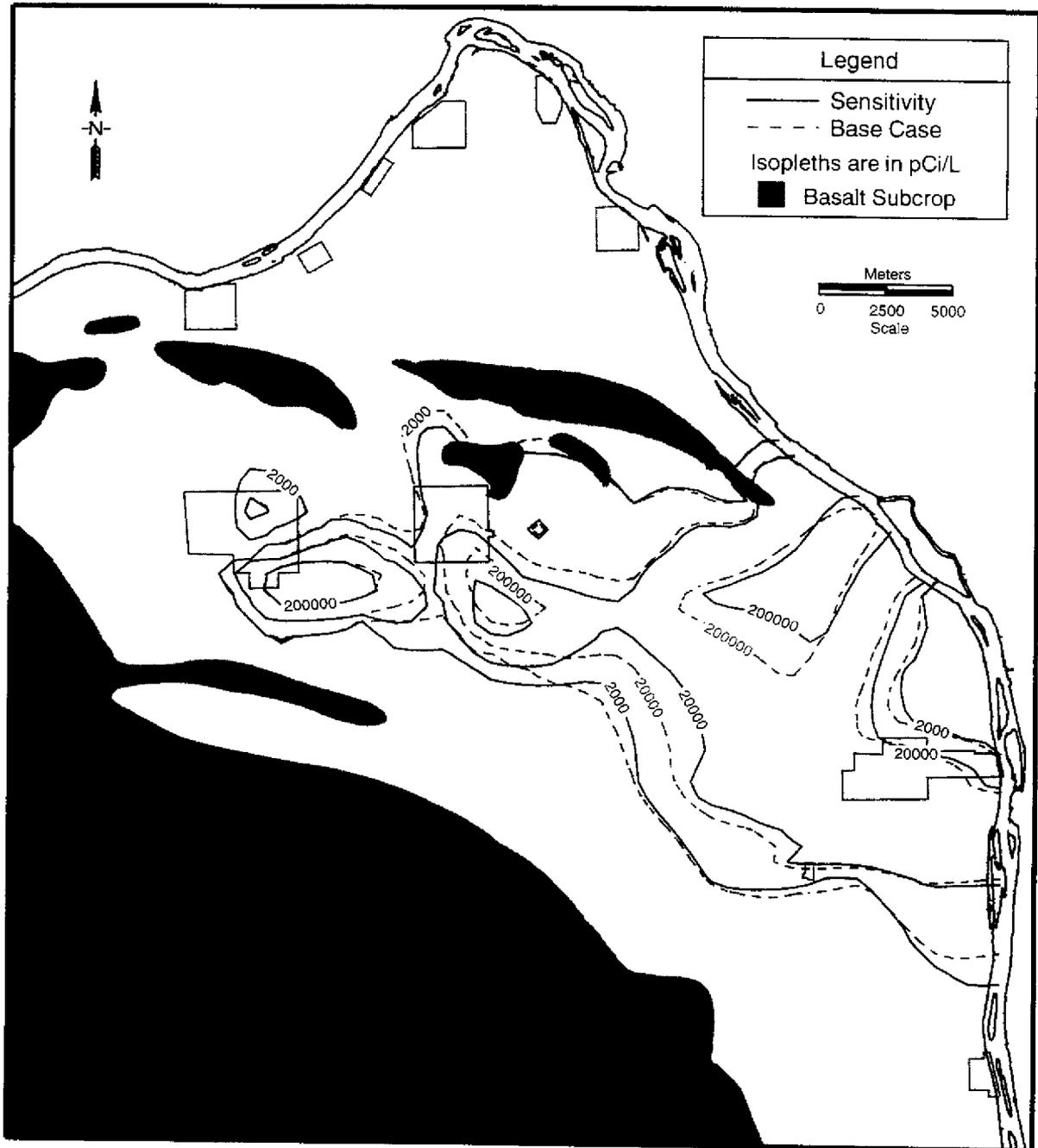


Figure B-11. Comparison of Water Table for Hydrogeologic Unit Contact Position Sensitivity Case with Base Case - 1979.

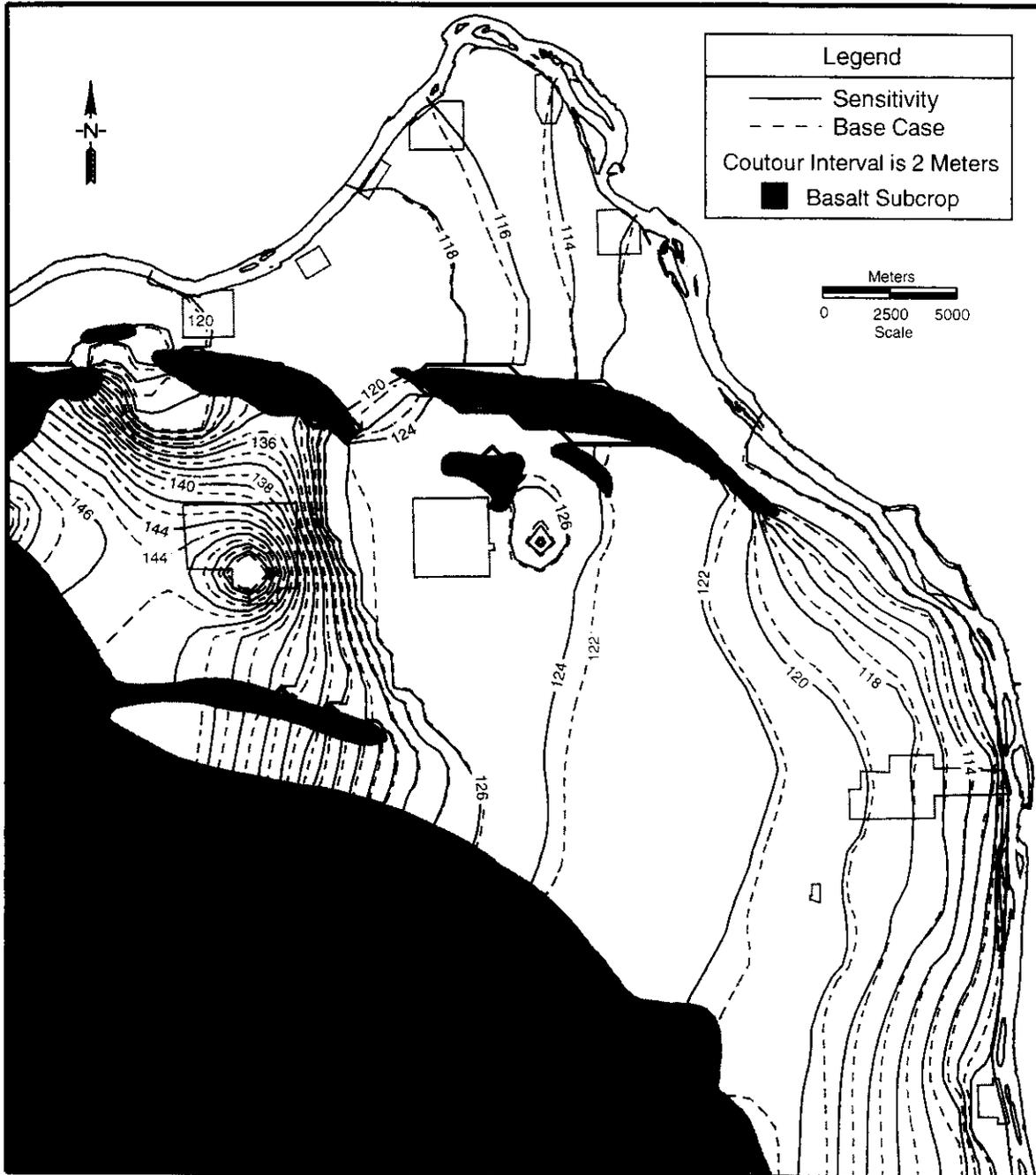


Figure B-12. Comparison of Water Table for Hydrogeologic Unit Contact Position Sensitivity Case with Base Case - 1988.

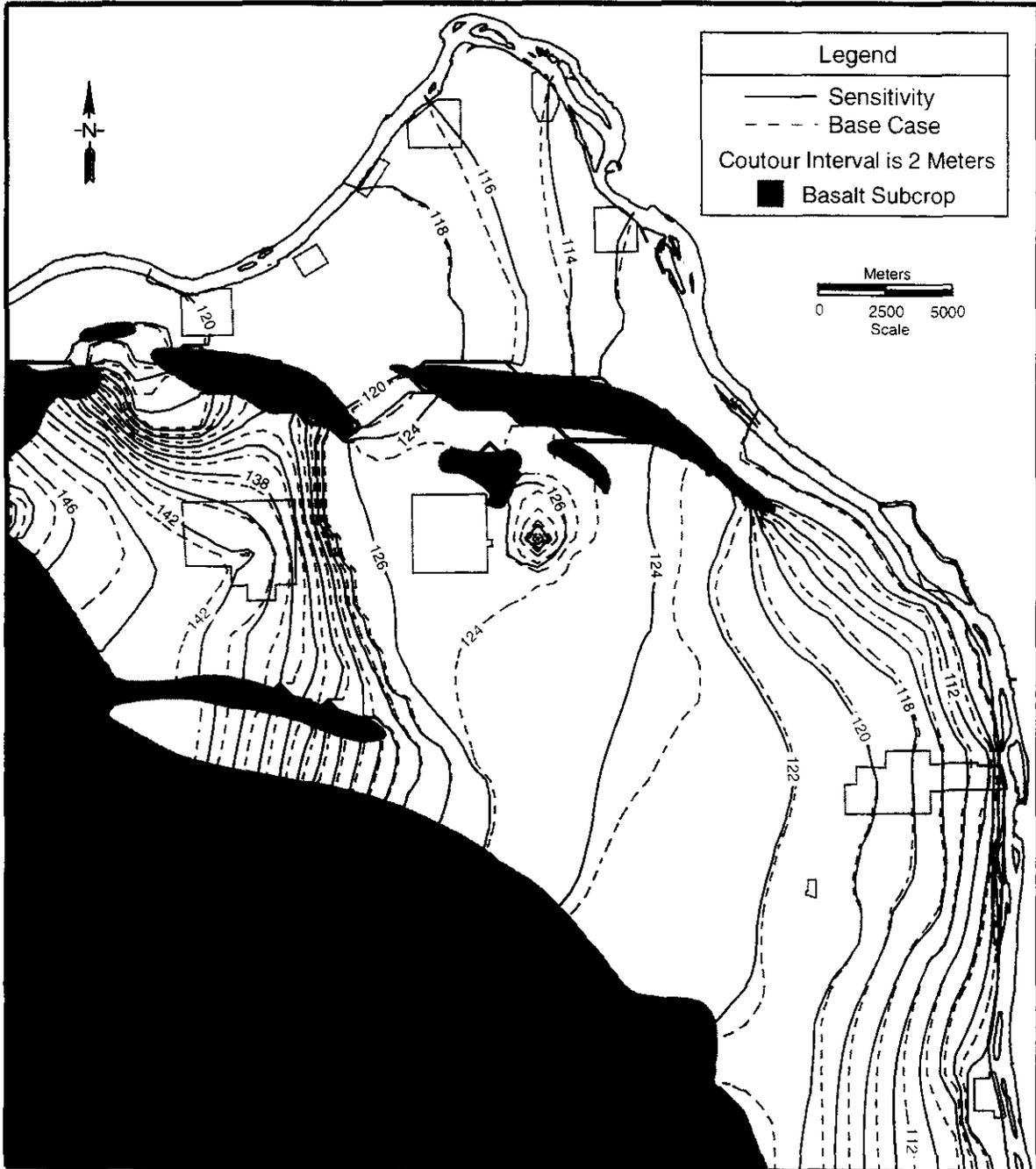


Figure B-13. Comparison of Water Table for Hydrogeologic Unit Contact Position Sensitivity Case with Base Case - 1993.

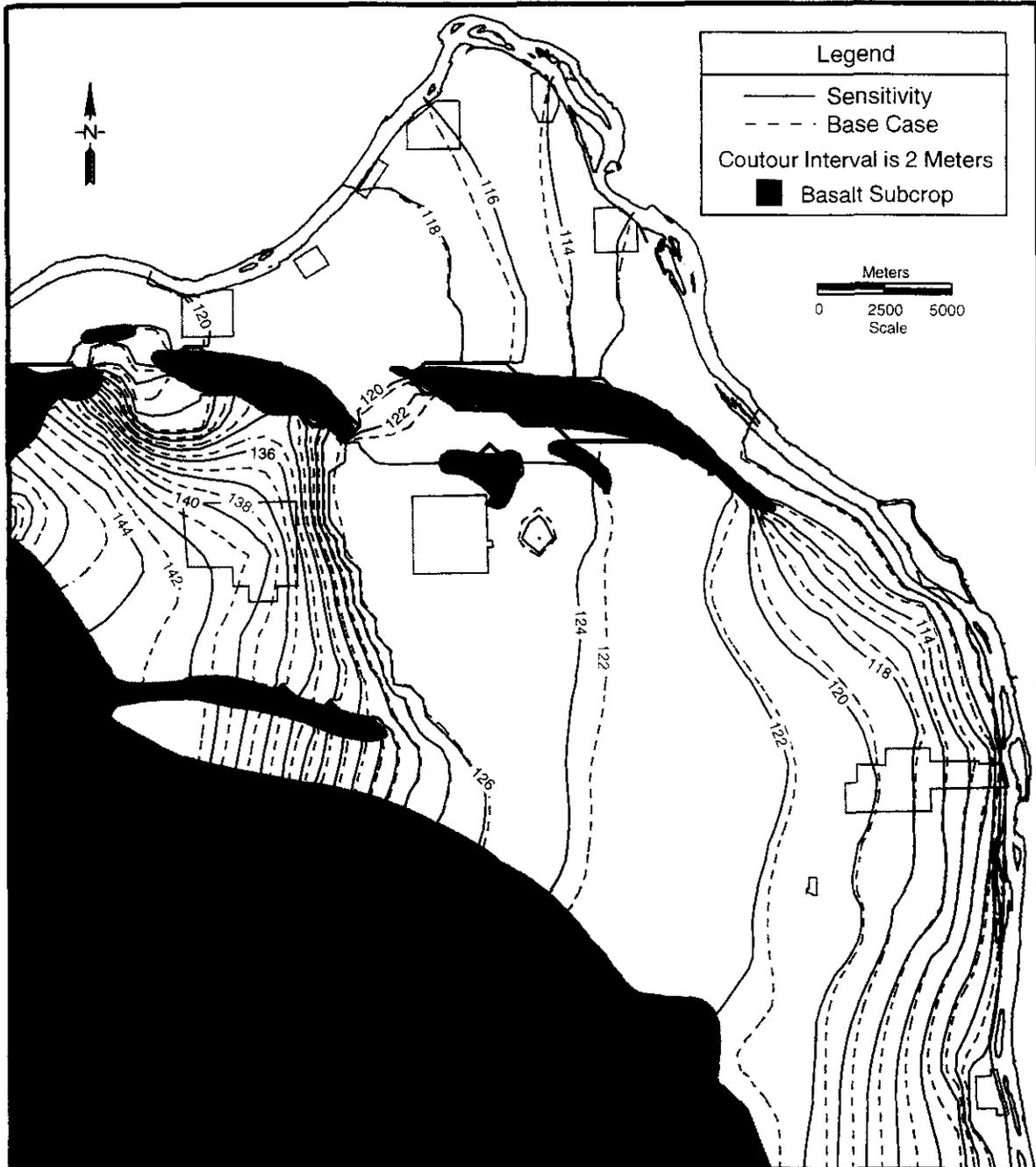


Figure B-14. Comparison of Tritium Concentrations for Hydrogeologic Unit Contact Position Sensitivity Case with Base Case - 1988.

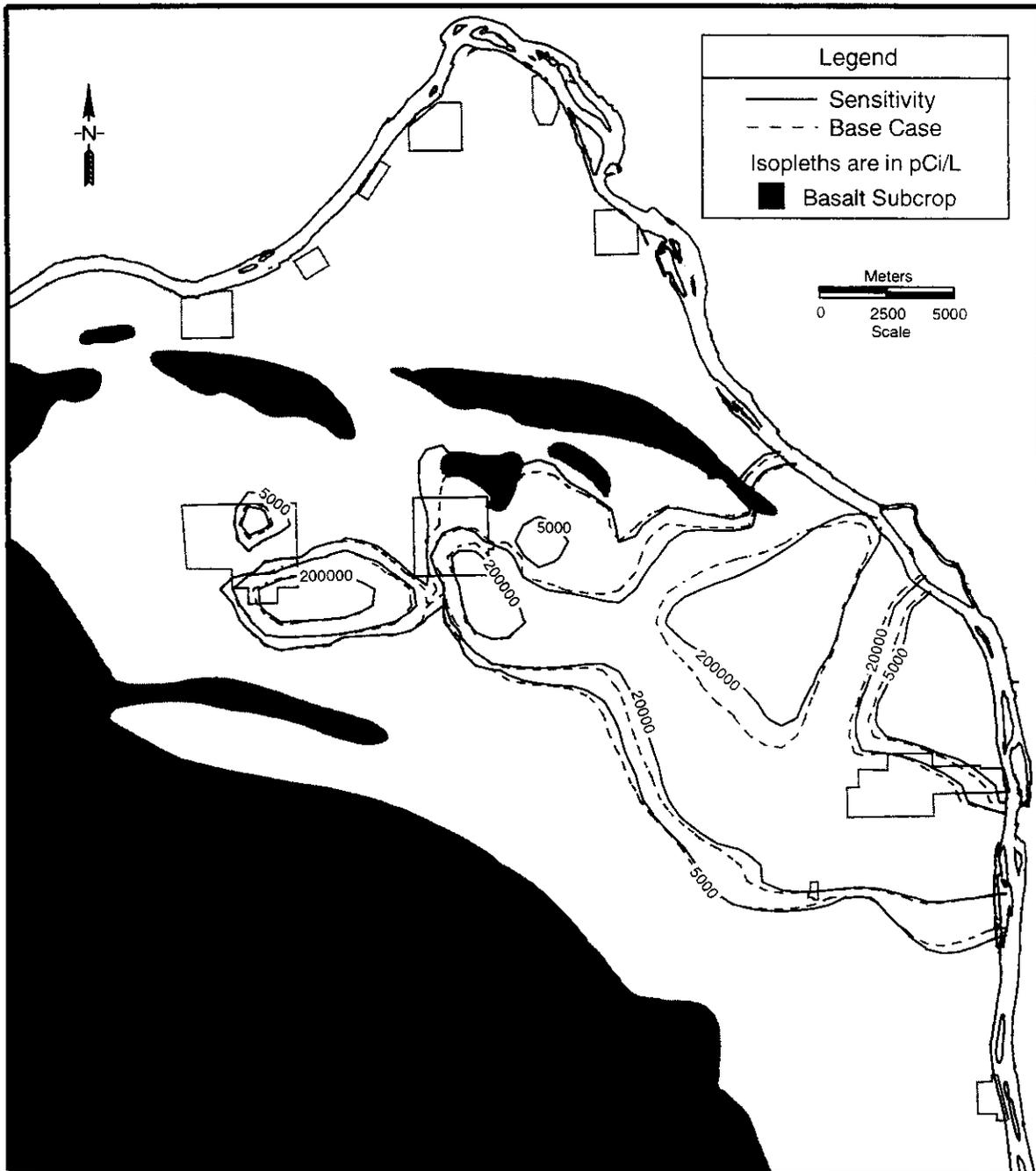


Figure B-15. Comparison of Tritium Concentrations for Hydrogeologic Unit Contact Position Sensitivity Case with Base Case - 1993.

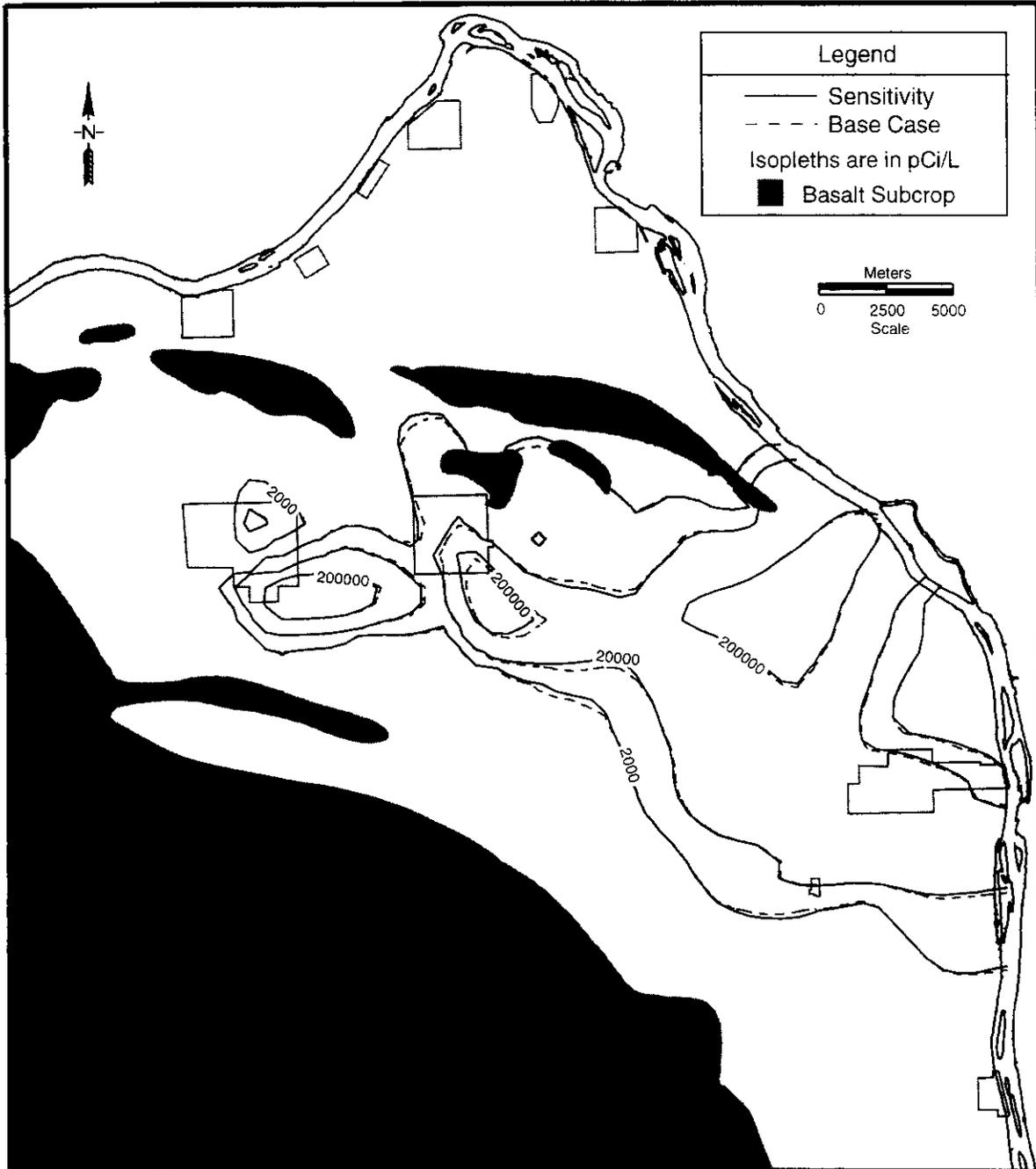


Figure B-16. Comparison of Tritium Concentrations for Sensitivity to Tritium Decay Case with Base Case - 1988.

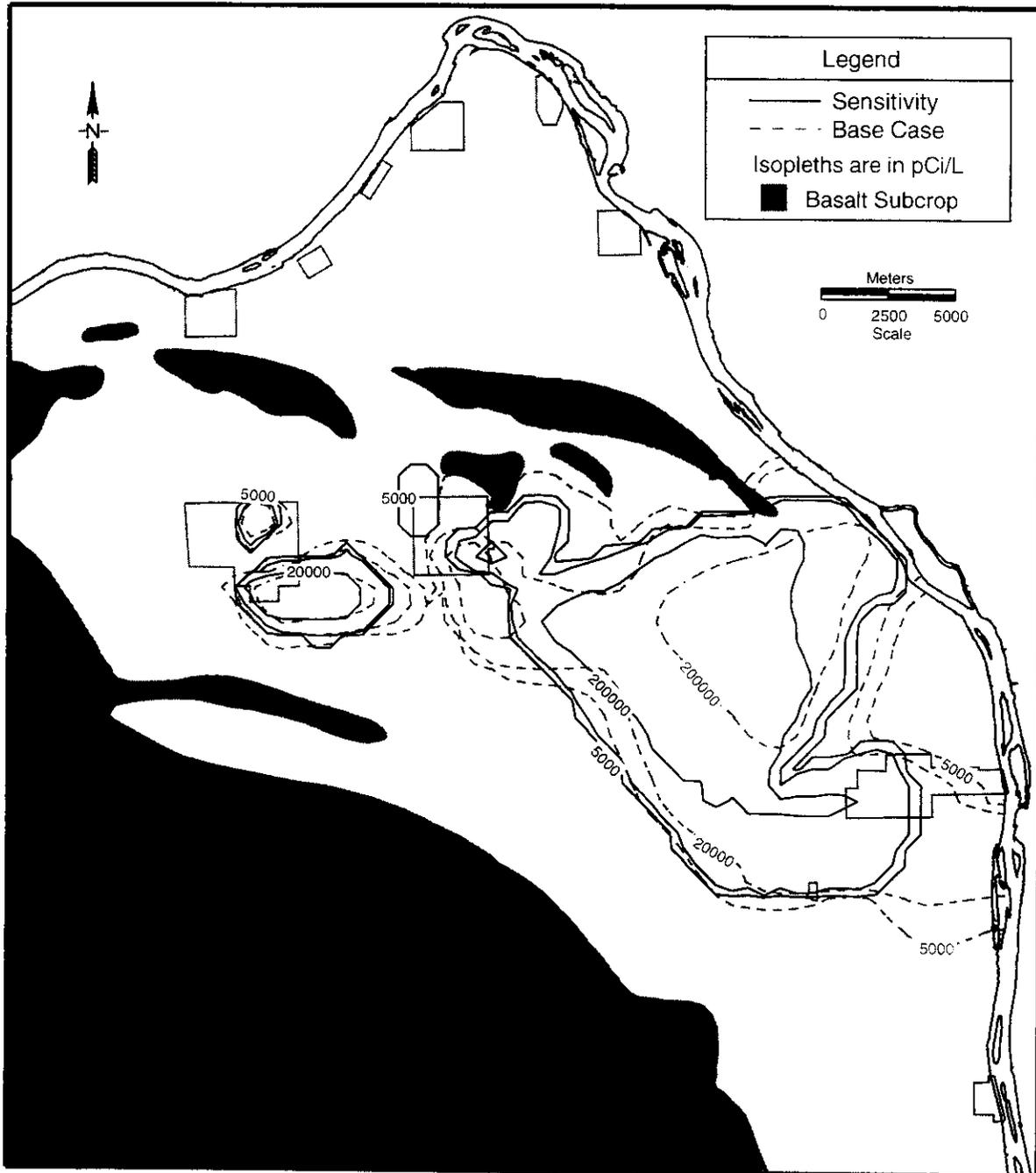


Figure B-17. Comparison of Tritium Concentrations for Sensitivity to Tritium Decay Case with Base Case - 1993.

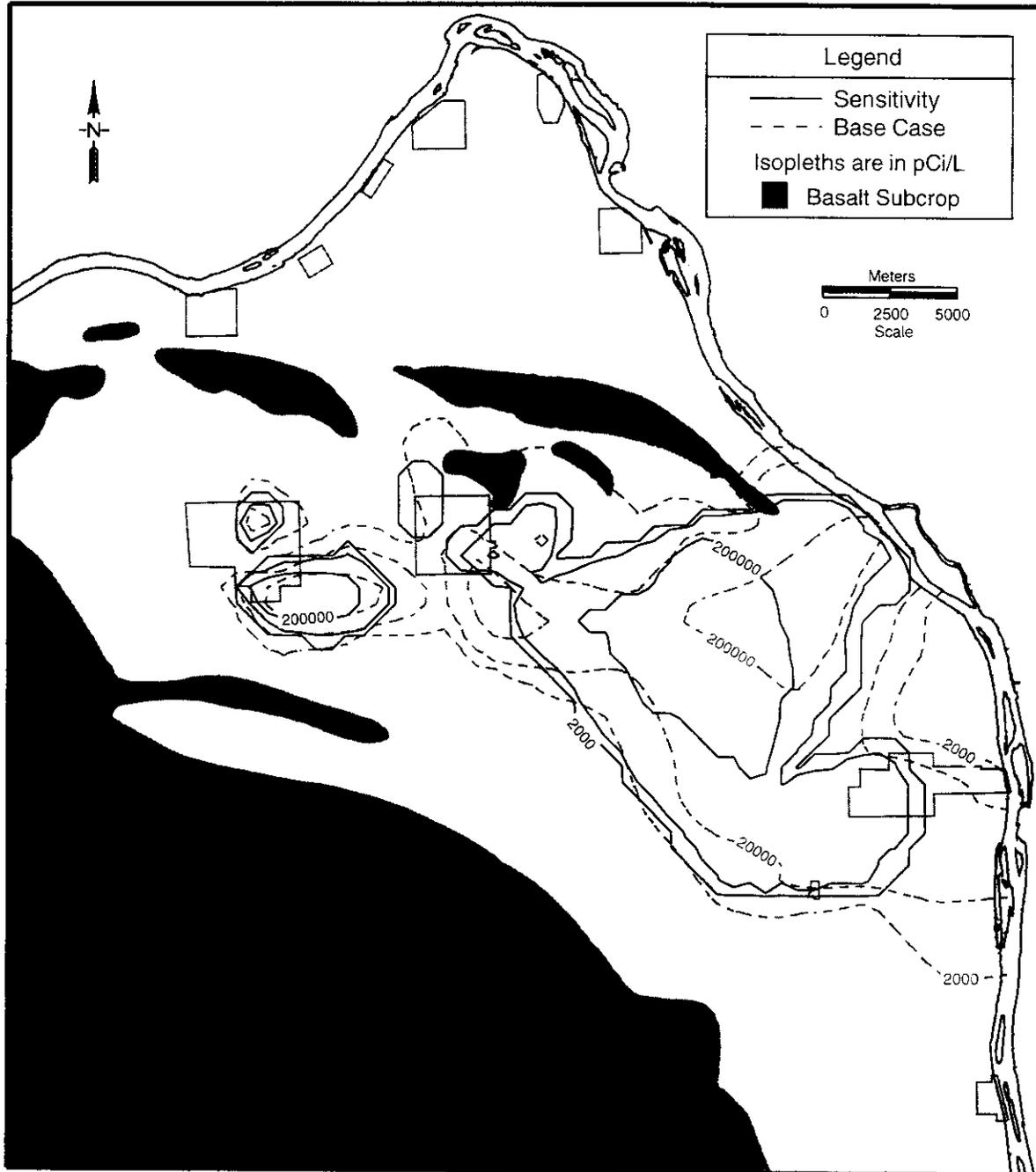


Figure B-18. Comparison of Tritium Concentrations for Advective and Dispersive Flow Sensitivity Case with Base Case - 1988.

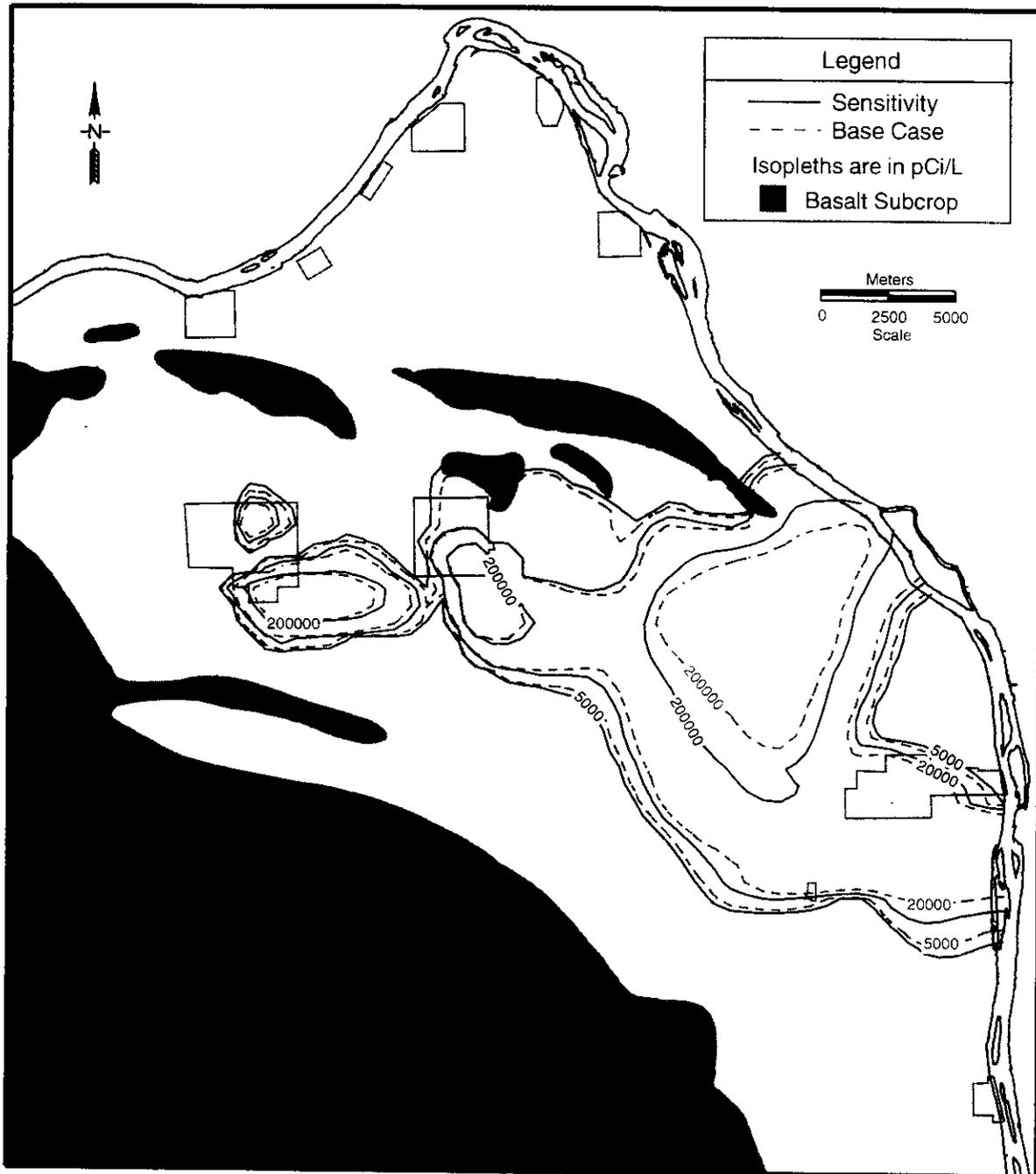
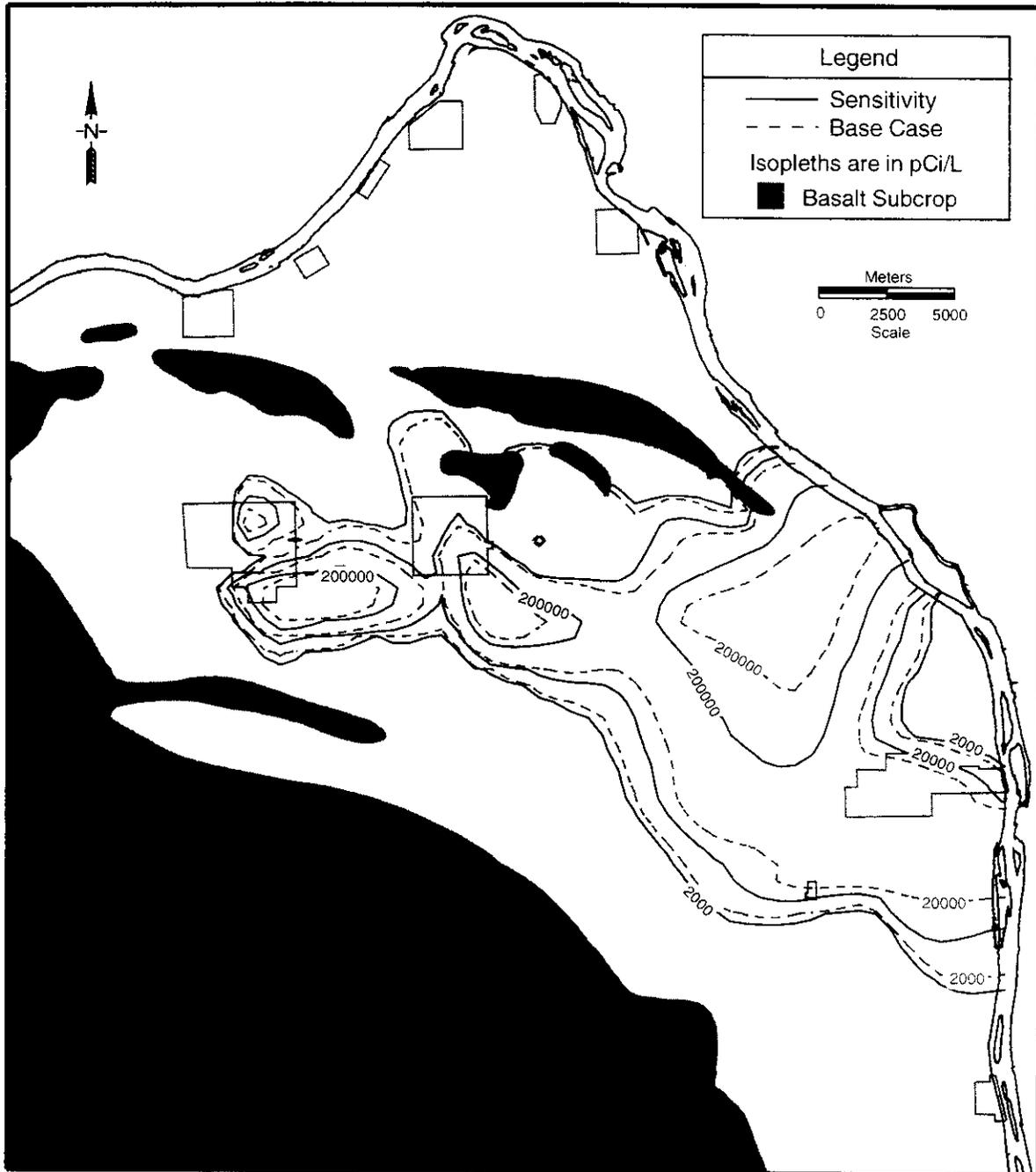


Figure B-19. Comparison of Tritium Concentrations for Advective and Dispersive Flow Sensitivity Case with Base Case - 1993.





**APPENDIX C**  
**STATISTICAL EVALUATION OF MODEL CALIBRATION**



An evaluation of the groundwater flow calibration was conducted by comparing 1979, 1988, and 1993 observed water table elevations with interpolated values from the model. By statistically comparing the observed and simulated values an assessment of the model calibration can be done. The following discussion presents the methodology used and the results of the evaluation.

The evaluation can be divided into three parts:

- Determination of wells used in the analysis
- Calculation of model water table elevations at well locations
- Statistical analysis of the results

To insure a consistent well set for the analysis, only wells with water level measurements during each of the three calibration periods (1979, 1988, and 1993) were used. Water level data, obtained from the Hanford Environmental Information System (HEIS), indicates that 196 wells fit this criteria. Seven of these wells were eliminated from the sample set because they were located within a basalt subcrop area used in the model area. These wells were further screened to exclude those wells which were screened greater than 15 m across the unconfined aquifer or the top of the screened interval was below the water table. This resulted in 124 wells that were included in the statistical analysis. The location of the wells used in the analysis is shown on Figure C-1.

Because the well locations do not correspond to grid nodes in the sitewide model, an interpolation of model water level elevations was required to obtain a value at the exact location of the observation well. The first step to accomplish this was to construct a grid of the model output using EarthVision from Dynamic Graphics. The model output for each of the calibration timesteps was input into EarthVision as scattered data and then gridded. Gridding was restricted within basalt subcrop areas and along the bank of the Columbia River to obtain an accurate physical representation of the site. Creating a grid allowed easy calculation of water level elevations at each well point with EarthVision's built in formula processor. The interpolated model values were used to determine the difference, or residual, between the observed and simulated water table elevation for each well in the data set. Table C-1 lists the wells used in the analysis and the observed and model simulated value for the three timesteps used in the calibration effort.

Summary statistics were then performed on these residuals and are presented in Table C-2. In all three simulation timesteps the mean difference between the observed and simulated water table elevations is below -0.41 m (-1.34 ft). This is reasonable considering the range of values and high gradients observed in some portions of the modeled area.

Figure C-1. Location of Wells Used in Statistical Analysis

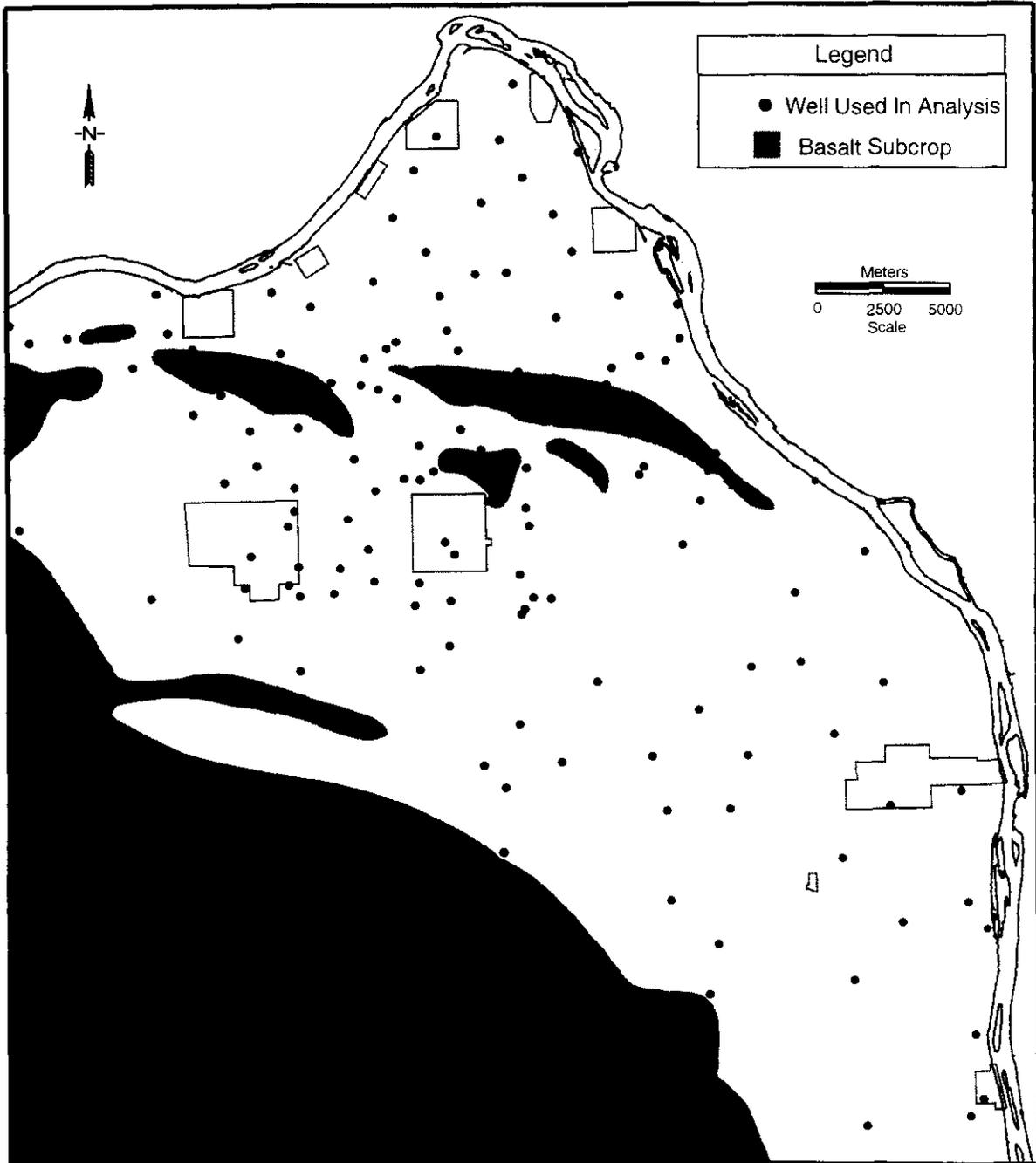


Table C-1. Comparison of Observed Verses Simulated Water Table Elevations at 124 Selected Wells

Well	1979 Simulated Elevation (ft)	1979 Observed Elevation (ft)	1979 Residual (ft)	1988 Simulated Elevation (ft)	1988 Observed Elevation (ft)	1988 Residual (ft)	1993 Simulated Elevation (ft)	1993 Observed Elevation (ft)	1993 Residual (ft)
199-D2-5	381.01	387.75	-6.74	116.14	117.53	-1.39	116.13	117.45	-1.32
299-E13-14	405.55	403.35	2.20	124.55	123.63	0.92	123.37	122.64	0.73
299-E23-1	405.57	402.77	2.80	124.68	123.65	1.04	123.20	122.59	0.62
299-E24-7	405.39	402.76	2.63	124.65	123.58	1.08	123.19	122.47	0.73
299-W11-10	458.71	458.94	-0.23	137.75	139.79	-2.04	136.07	138.34	-2.27
299-W12-1	450.75	453.16	-2.41	136.20	138.19	-1.99	134.83	136.93	-2.10
299-W15-5	497.77	480.18	17.59	142.31	143.78	-1.46	139.99	141.92	-1.93
299-W21-1	467.44	460.78	6.66	138.59	139.50	-0.91	136.95	137.77	-0.82
299-W23-11	491.99	479.56	12.43	141.68	142.60	-0.92	139.73	140.56	-0.83
699-10-E12	368.66	355.86	12.80	112.39	108.96	3.43	112.58	108.88	3.71
699-11-45A	403.94	409.48	-5.54	123.58	125.33	-1.75	123.37	125.59	-2.22
699-14-38	400.24	402.76	-2.52	122.58	123.17	-0.59	122.23	123.37	-1.14
699-14-47	404.64	409.89	-5.25	123.85	125.41	-1.56	123.54	125.58	-2.04
699-15-15A	396.10	396.45	-0.35	121.16	121.58	-0.42	121.03	121.24	-0.21
699-15-26	398.33	399.34	-1.01	121.95	122.69	-0.74	121.68	121.91	-0.23
699-17-5	389.69	385.27	4.42	118.98	118.33	0.65	119.14	118.17	0.97
699-19-43	401.72	402.35	-0.63	123.09	123.41	-0.32	122.61	122.85	-0.24
699-2-3	387.42	387.31	0.11	118.29	118.88	-0.59	118.42	118.92	-0.50
699-20-20	397.92	399.44	-1.52	121.84	122.67	-0.84	121.54	121.94	-0.40
699-24-1T	383.30	374.37	8.93	116.90	114.75	2.15	117.18	113.87	3.31
699-24-33	399.73	401.33	-1.60	122.51	123.30	-0.79	122.04	122.36	-0.32
699-25-55	405.35	412.05	-6.70	124.26	126.04	-1.78	123.57	125.72	-2.15
699-25-70	448.66	451.84	-3.18	136.06	136.99	-0.93	135.37	136.01	-0.64
699-26-15A	392.25	396.85	-4.60	119.93	121.82	-1.89	119.87	121.15	-1.28
699-27-8	388.00	392.25	-4.25	118.51	120.45	-1.94	118.60	119.83	-1.24
699-28-52A	404.48	408.97	-4.49	124.06	123.99	0.07	123.30	123.01	0.29
699-29-78	462.38	470.77	-8.39	139.87	141.84	-1.97	138.99	140.32	-1.33
699-3-45	403.71	409.26	-5.55	123.44	125.42	-1.98	123.35	115.44	7.91
699-32-43	402.47	402.10	0.37	123.63	123.72	-0.09	122.67	122.50	0.18
699-33-42	402.45	404.20	-1.75	123.66	123.75	-0.09	122.66	122.55	0.11
699-33-56	405.67	403.60	2.07	124.49	123.95	0.54	123.52	122.85	0.67
699-34-39A	401.73	402.01	-0.28	123.45	123.55	-0.10	122.46	122.50	-0.05
699-34-41B	402.35	402.19	0.16	123.68	123.78	-0.10	122.61	122.56	0.05
699-34-51	404.53	402.90	1.63	124.27	123.89	0.38	123.15	122.63	0.52
699-34-88	472.38	473.38	-1.00	143.31	143.45	-0.14	142.54	142.64	-0.10
699-35-66A	434.75	441.28	-6.53	131.89	134.16	-2.27	131.00	133.37	-2.37
699-35-70	457.56	455.69	1.87	137.10	138.00	-0.90	135.78	136.80	-1.03
699-35-9	381.94	383.56	-1.62	116.64	117.83	-1.19	116.70	117.37	-0.67
699-36-61A	406.44	408.12	-1.68	124.72	124.81	-0.09	123.66	124.13	-0.47

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Table C-1. Comparison of Observed Verses Simulated Water Table Elevations at 124 Selected Wells

Well	1979 Simulated Elevation (ft)	1979 Observed Elevation (ft)	1979 Residual (ft)	1988 Simulated Elevation (ft)	1988 Observed Elevation (ft)	1988 Residual (ft)	1993 Simulated Elevation (ft)	1993 Observed Elevation (ft)	1993 Residual (ft)
699-37-43	404.03	402.59	1.44	124.47	125.05	-0.58	122.93	122.82	0.11
699-38-65	425.28	432.37	-7.09	129.44	131.33	-1.89	128.44	130.79	-2.35
699-38-70	461.36	457.18	4.18	137.44	138.59	-1.15	135.76	139.49	-3.73
699-40-1	363.74	361.25	2.49	110.92	110.75	0.17	110.98	110.63	0.35
699-40-62	406.71	405.24	1.47	124.82	124.25	0.58	123.60	123.36	0.24
699-41-23	397.29	396.41	0.88	121.85	121.68	0.17	121.27	120.97	0.30
699-43-104	488.13	490.29	-2.16	148.56	153.20	-4.64	148.02	150.85	-2.82
699-43-42	416.15	418.51	-2.36	133.16	128.62	4.54	124.88	128.25	-3.37
699-44-64	407.36	406.04	1.32	124.97	124.41	0.57	123.75	123.71	0.05
699-45-42	410.70	413.50	-2.80	129.01	127.74	1.27	123.95	126.74	-2.79
699-46-21B	395.93	389.81	6.12	121.35	119.36	1.99	120.89	119.04	1.86
699-47-60	406.21	402.50	3.71	124.59	123.89	0.70	123.31	122.44	0.87
699-48-71	445.28	446.41	-1.13	135.17	136.31	-1.13	134.22	135.46	-1.24
699-49-28	399.32	392.16	7.16	122.59	120.14	2.45	121.79	119.97	1.82
699-49-55A	405.41	402.48	2.93	124.37	123.75	0.62	122.91	122.50	0.41
699-49-57A	405.29	402.49	2.80	124.29	123.72	0.57	122.87	122.40	0.47
699-49-79	456.36	458.12	-1.76	138.15	139.58	-1.43	137.18	138.75	-1.57
699-50-28B	399.20	391.90	7.30	122.52	120.02	2.50	121.76	119.97	1.79
699-50-42	406.62	407.88	-1.26	125.21	125.41	-0.20	122.88	125.10	-2.22
699-50-53A	405.45	402.52	2.93	124.34	123.67	0.67	122.86	122.47	0.38
699-51-63	405.90	404.78	1.12	124.47	124.00	0.47	123.33	123.24	0.10
699-51-75	450.63	449.73	0.90	136.76	137.34	-0.58	135.95	136.71	-0.76
699-52-19	361.27	360.94	0.33	110.12	110.15	-0.03	110.12	110.12	0.00
699-53-47A	405.77	411.32	-5.55	123.99	123.90	0.09	122.55	123.64	-1.09
699-53-55B	405.13	402.89	2.24	124.02	123.35	0.67	122.57	122.20	0.37
699-55-50C	405.56	402.95	2.61	123.99	123.11	0.87	122.54	122.27	0.27
699-55-70	435.30	430.51	4.79	132.67	131.90	0.77	132.57	131.49	1.08
699-55-76	439.23	443.35	-4.12	133.73	135.64	-1.91	133.38	135.20	-1.82
699-57-83A	415.76	431.62	-15.86	126.69	131.96	-5.27	126.56	131.71	-5.15
699-59-58	397.08	402.37	-5.29	121.32	123.02	-1.70	120.58	122.26	-1.69
699-59-80B	424.58	422.31	2.27	129.38	130.39	-1.01	129.21	130.92	-1.71
699-60-32	365.86	361.21	4.65	111.52	110.25	1.27	111.51	110.17	1.34
699-60-60	392.89	402.08	-9.19	119.90	123.14	-3.24	119.56	122.25	-2.69
699-61-62	391.90	402.00	-10.10	119.56	122.80	-3.24	119.31	122.25	-2.94
699-61-66	391.30	400.90	-9.60	119.35	122.77	-3.42	119.17	122.04	-2.87
699-62-31	366.23	361.16	5.07	111.64	110.22	1.42	111.62	110.17	1.45
699-62-43A	379.91	395.94	-16.03	115.83	120.93	-5.10	115.79	120.65	-4.86
699-63-25A	364.56	360.97	3.59	111.12	110.15	0.97	111.12	110.09	1.04
699-63-90	407.61	396.94	10.67	124.23	121.10	3.13	124.13	120.95	3.17

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Table C-1. Comparison of Observed Verses Simulated Water Table Elevations at 124 Selected Wells

Well	1979 Simulated Elevation (ft)	1979 Observed Elevation (ft)	1979 Residual (ft)	1988 Simulated Elevation (ft)	1988 Observed Elevation (ft)	1988 Residual (ft)	1993 Simulated Elevation (ft)	1993 Observed Elevation (ft)	1993 Residual (ft)
699-64-27	365.60	361.11	4.49	111.44	110.21	1.23	111.44	110.10	1.33
699-64-62	391.06	400.27	-9.21	119.27	122.50	-3.23	119.10	121.86	-2.76
699-65-50	388.05	399.30	-11.25	118.32	122.13	-3.81	118.25	121.62	-3.37
699-65-59A	390.42	400.16	-9.74	119.06	122.47	-3.41	118.94	121.81	-2.87
699-65-72	390.85	397.88	-7.03	119.15	121.90	-2.74	119.10	121.34	-2.23
699-65-83	395.37	396.87	-1.50	120.52	121.43	-0.91	120.46	121.07	-0.61
699-66-103	397.53	397.19	0.34	121.17	121.36	-0.19	121.16	121.45	-0.28
699-66-23	364.36	361.50	2.86	111.06	110.11	0.95	111.05	110.22	0.84
699-66-58	390.02	400.03	-10.01	118.92	122.41	-3.49	118.83	121.69	-2.86
699-67-51	390.37	399.30	-8.93	119.02	122.17	-3.15	118.94	121.67	-2.72
699-67-86	399.81	396.71	3.10	121.86	121.34	0.52	121.79	121.72	0.06
699-67-98	397.72	396.69	1.03	121.23	121.54	-0.31	121.21	121.46	-0.25
699-68-105	397.44	395.74	1.70	121.14	120.96	0.18	121.14	119.92	1.22
699-69-38	377.21	402.47	-25.26	115.00	122.40	-7.40	114.97	122.68	-7.71
699-70-23	365.03	362.01	3.02	111.26	110.66	0.60	111.26	110.64	0.62
699-70-68	390.15	398.32	-8.17	118.94	120.60	-1.66	118.89	121.40	-2.50
699-71-30	367.37	371.83	-4.46	111.98	112.99	-1.01	111.98	112.85	-0.87
699-71-52	389.17	398.51	-9.34	118.66	121.97	-3.31	118.59	121.41	-2.81
699-72-73	390.55	395.78	-5.23	119.05	121.20	-2.15	119.03	120.73	-1.70
699-72-88	394.22	398.86	-4.64	120.16	121.94	-1.78	120.15	121.70	-1.55
699-73-61	389.55	398.67	-9.12	118.76	121.94	-3.17	118.71	121.42	-2.70
699-74-44	380.11	396.41	-16.30	115.89	121.04	-5.14	115.86	120.84	-4.98
699-74-48	383.26	397.56	-14.30	116.86	121.59	-4.73	116.81	121.12	-4.31
699-77-36	371.53	376.63	-5.10	113.25	114.76	-1.51	113.24	114.54	-1.30
699-77-54	389.08	397.09	-8.01	118.62	121.37	-2.75	118.57	120.89	-2.32
699-8-17	395.98	396.46	-0.48	121.10	121.60	-0.50	121.01	121.21	-0.20
699-8-25	397.48	397.84	-0.36	121.62	122.08	-0.46	121.45	121.60	-0.14
699-81-38	373.05	379.47	-6.42	113.71	115.64	-1.93	113.71	115.54	-1.83
699-81-58	388.48	396.66	-8.18	118.42	121.09	-2.67	118.40	119.76	-1.36
699-83-47	379.10	388.95	-9.85	115.56	118.74	-3.17	115.55	118.42	-2.87
699-86-42	375.35	384.68	-9.33	114.41	117.29	-2.88	114.41	117.20	-2.79
699-87-55	384.56	388.71	-4.15	117.22	118.17	-0.95	117.21	117.69	-0.47
699-89-35	371.36	371.02	0.34	113.19	112.98	0.21	113.19	112.93	0.26
699-9-E2	384.49	370.87	13.62	117.35	113.34	4.01	117.52	113.46	4.06
699-90-45	376.15	384.59	-8.44	114.66	117.12	-2.46	114.66	117.05	-2.39
699-97-43	375.58	378.61	-3.03	114.48	115.44	-0.97	114.48	115.44	-0.97
699-S12-3	383.04	377.98	5.06	116.85	115.73	1.12	117.07	116.10	0.97
699-S14-20A	394.04	400.27	-6.23	120.31	122.13	-1.82	120.51	122.14	-1.63
699-S19-E13	350.00	343.40	6.60	106.03	104.75	1.28	106.03	104.74	1.30

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Table C-1. Comparison of Observed Verses Simulated Water Table Elevations at 124 Selected Wells

Well	1979 Simulated Elevation (ft)	1979 Observed Elevation (ft)	1979 Residual (ft)	1988 Simulated Elevation (ft)	1988 Observed Elevation (ft)	1988 Residual (ft)	1993 Simulated Elevation (ft)	1993 Observed Elevation (ft)	1993 Residual (ft)
699-S27-E14	350.00	341.27	8.73	106.00	103.98	2.02	106.00	104.00	2.00
699-S29-E12	349.92	345.76	4.16	105.96	105.24	0.72	105.96	105.36	0.61
699-S3-25	396.12	397.48	-1.36	121.07	121.75	-0.68	121.10	121.54	-0.44
699-S3-E12	360.72	353.06	7.66	109.99	107.94	2.05	110.09	107.94	2.15
699-S31-1	376.64	374.81	1.83	114.80	114.93	-0.13	114.93	114.06	0.86
699-S6-E4D	377.06	370.33	6.73	115.02	113.42	1.60	115.19	113.52	1.67
699-S8-19	394.47	394.35	0.12	120.49	120.79	-0.30	120.62	120.91	-0.29

Table C-2. Model Summary Statistics

Statistic	1979 Data	1988 Data	1993 Data
Residual Mean	-0.41 m (-1.34 ft)	-0.22 m (-0.72 ft)	-0.21 m (-0.68 ft)
Residual Standard Deviation	2.00 m (6.57 ft)	0.60 m (1.96 ft)	0.61 m (2.01 ft)
Residual Range	13.06 m (42.85 ft)	3.64 m (11.93 ft)	4.76 m (15.6 ft)



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