Numerical Simulation of Ground-Water Flow Paths and Discharge Locations at Puget Sound Naval Shipyard, Bremerton, Washington

By Edmund A. Prych

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in)	25.4	millimeter
inches per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
parts per thousand (ppt)	1	grams per kilogram

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Information about ground-water flow paths and locations where ground water discharges at and in the vicinity of Puget Sound Naval Shipyard is necessary for understanding the transport of subsurface contaminants by ground water at the shipyard. The design of some remediation alternatives would be aided by knowledge of whether ground water flowing at specific locations beneath the shipyard will eventually discharge directly to Sinclair Inlet of Puget Sound, or if it will discharge to the drainage system of one of the shipyard's six dry docks.

To obtain the desired information, a steady-state, multilayer numerical model for simulating the flow of ground water of uniform density was constructed of the shipyard and surrounding area. The model simulated discharge to the dry-dock drainage systems and to Sinclair Inlet and other parts of Puget Sound, and the effects on ground-water flow of sheet-pile cutoff walls beneath the dry docks and of shoreline bulkheads along the shipyard's waterfront. Hydraulic characteristics of the subsurface material--mostly fill beneath the shipyard and glacial and interglacial sediments beneath the fill and most of the surrounding area--were assumed to be uniform, both areally and with depth, throughout the modeled region. The model was calibrated by adjusting values of the horizontal and vertical hydraulic conductivity of the subsurface sediments, and values of the leakage coefficients for the sheet-pile cutoff walls and shoreline bulkheads to obtain agreement between simulated and observed ground-water levels in the shipyard, total fresh-water discharge to the dry docks, and total saline-water discharge to the dry docks. Values of horizontal and vertical hydraulic conductivity obtained by model calibration equal 10^{-3} and 10^{-7} feet per second, respectively. The former value is probably representative of the top 50 feet of sediments at the shipyard, but may not be representative of the deeper sediments beneath the shipyard or much of the natural sediment in the area around the shipyard.

Simulated ground-water flow paths indicate that ground water flowing beneath nearly all but the western end of the shipyard discharges to the dry-dock drainage systems. Only shallow ground water flowing beneath the western end of the shipyard discharges directly to Sinclair Inlet. This result implies that most transportable contaminants in ground water beneath the shipyard will be transported to the dry-dock drainage systems and will not discharge directly into Sinclair Inlet.

INTRODUCTION

Puget Sound Naval Shipyard and the Fleet and Industrial Supply Center (formerly the Navy Supply Center) are two contiguous U.S. Navy facilities on Sinclair Inlet of Puget Sound. They are located on the north shore of the inlet, on the south side of the City of Bremerton in Kitsap County of western Washington (fig. 1). The shipyard and supply center are under different naval commands; however, because the latter is bordered by the shipyard on three sides and because the area occupied by the shipyard is about ten times the size of the supply center, the entire area occupied by both facilities is commonly referred to as the shipyard. For convenience, this common terminology is used in this report.

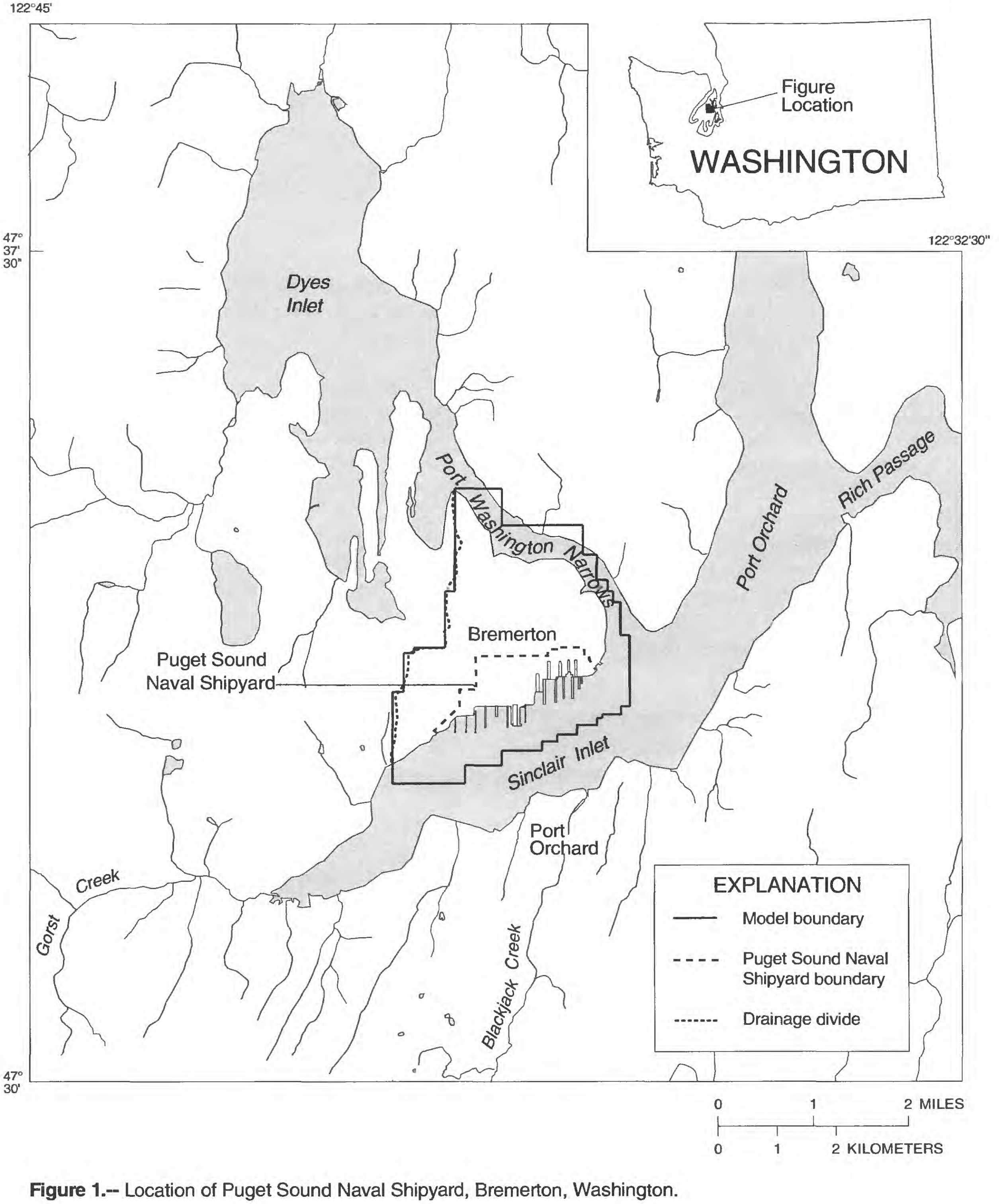


Figure 1.-- Location of Puget Sound Naval Shipyard, Bremerton, Washington.

Background

Major past and present work at the shipyard includes building, modifying, overhauling, repairing, outfitting, supplying, and dismantling ships. Construction of the shipyard began in the 1890's, and the yard has been active since that time. A consequence of this long history of work is that concentrations of some metals and organic compounds in soil and ground water at the shipyard are elevated and in some places exceed regulatory limits (URS Consultants, Inc., 1994). Some of the major concerns about these contaminants are the exposure of shipyard personnel to them, and the movement of contaminants by ground water from the shipyard to Sinclair Inlet. Consequently, the Navy and its consultants are conducting investigations to determine the magnitude and extent of contamination of soil and ground water at the shipyard, and of the water, sediments, and biota of Sinclair Inlet. This information will be used to decide if and where environmental remediation work is necessary and to plan the work. These investigations, including the one that is the subject of this report, are part of the Navy's CLEAN (Comprehensive Long-Term Environmental Action Navy) program.

Most work at the shipyard is centered on the six dry docks, which are numbered in the order in which they were constructed and are commonly referred to as DD-1 through DD-6 (fig. 2). These dry docks are stationary concrete or stone structures with tops at land surface and floors below sea level. All but one of the dry docks (DD-2) were constructed with gravity drains to relieve horizontal hydrostatic forces on the backs of their sidewalls and headwalls, and hydrostatic uplift forces on their floors when they are not flooded. Water from these drains discharges into collection channels within the dry docks where it flows to sumps from where it is pumped into Sinclair Inlet.

Because the dry docks are dry more than 95 percent of the time, the dry-dock drainage systems act as wells or ground-water sinks, and much of the ground water that passes through the shipyard may discharge to the dry docks rather than directly to Sinclair Inlet (URS Consultants, Inc., 1992b). (As is shown later in this report, most of the ground water flowing beneath the shipyard does discharge to the dry docks.) Consequently, information on the types, concentrations and amounts of contaminants that are discharged from the ground-water system could be obtained by monitoring discharges to or from the dry-dock drainage systems, and, if pumping and treating ground water is a remediation alternative, then the pumping part of this system (the dry-dock drainage systems) is effectively in place. The piers and moorings at the shipyard (fig. 2) are built on piles and have little effect on ground-water flow.

Purpose and Scope

The purpose of this investigation and report is to provide information about ground-water flow at the Puget Sound Naval Shipyard and, in particular, the effects of the dry docks on ground-water flow paths and discharge locations. This information is necessary for understanding the movement of contaminants by ground water, which in turn is necessary for making decisions about the need for remediation work and for the design of effective and efficient remediation programs.

Information about ground-water flow was obtained with the aid of a numerical model. A steady-state, multilayer model for simulating the flow of ground water of uniform density was constructed of the shipyard and surrounding area. Ground-water flows simulated by this model were used as input data to a set of computer programs for computing and displaying ground-water flow paths. The flow model was calibrated using observed ground-water levels and rates of ground-water discharges to the dry docks. The data on discharge rates to the dry docks were collected as part of the current study (Prych, 1995), and the data on ground-water levels were collected by others (URS Consultants, Inc., 1992a, and 1994). Because the water in Sinclair Inlet has a salinity of about 30 parts per thousand, it is about 2.3 percent more dense than fresh ground water. Consequently, the flow model with uniform water density is expected to overestimate the proportion of ground-water discharge to Sinclair Inlet relative to the discharge to the dry docks. Because the model simulates only steady-state flow, it does not simulate the periodic flushing of the near-shore soil and sediment by water that flows into and out of the ground-water system with each tide cycle, nor does it simulate flow during periods when one or more of the dry docks are flooded.

This report describes how the numerical ground-water-flow model was constructed and calibrated and presents maps that show simulated discharge locations for ground-water particles that originate from different areas and depths at the shipyard.

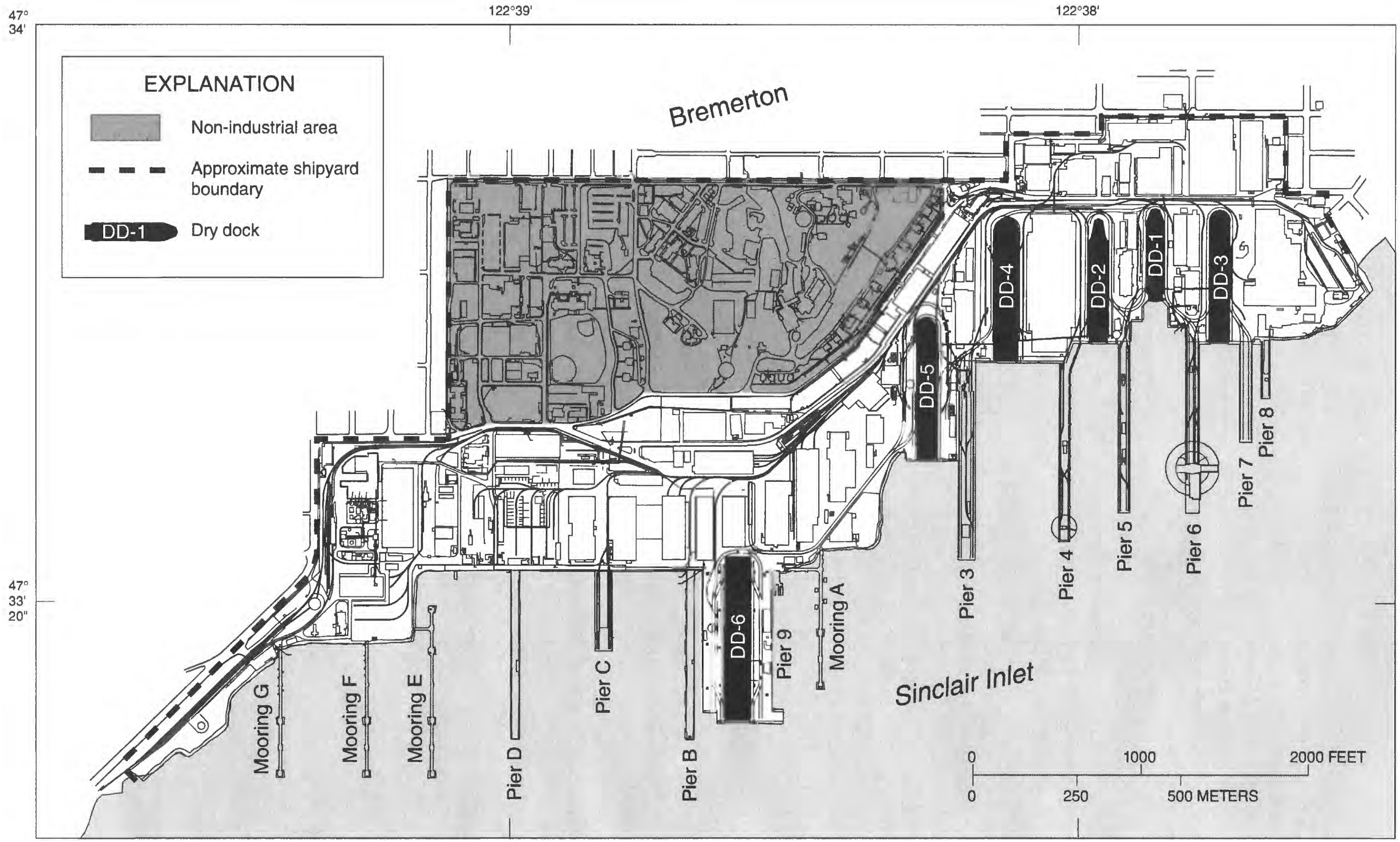


Figure 2.-- Puget Sound Naval Shipyard and locations of dry docks.

Previous Work

A predecessor to the current (1995) series of studies being done at the shipyard under the CLEAN program was an initial assessment of contamination and physical features and ecology of the shipyard and surrounding area (Naval Energy and Environmental Support Activity, 1983). This study identified 6 potentially contaminated sites at the shipyard, and a preliminary assessment supplemental report (Naval Energy and Environmental Support Activity, 1990) identified 5 additional sites. Eight of the 11 sites were recommended for inclusion in a site-inspection study. The site-inspection study, which was the first major study of the shipyard under the CLEAN program, included 12 sites (URS Consultants, Inc., 1992a); 11 were equivalent to the 8 recommended in the initial and supplemental assessment reports (one of the sites was divided into three), and the twelfth was a site on the Fleet and Industrial Supply Center. As part of the site inspection study, information on stratigraphy and contaminants in soil was collected by boring 79 holes and collecting and analyzing soil samples from the holes. Wells for measuring water levels and collecting water samples were installed in 30 of the holes, and slug tests for estimating horizontal hydraulic conductivity were conducted on 26 of the wells.

A number of individual or groups of sites (called operable units) that were the subjects of the site-inspection study have also been the subjects of numerous follow-up studies (URS Consultants, Inc., 1993a, 1993b, 1993c, 1993d and 1994). Most of these studies were conducted to collect additional information on the geohydrology and degree and extent of contamination in order to determine the human and environmental health risks posed by the contaminants, to decide if remediation work is necessary, and to evaluate the feasibility of different remediation alternatives.

URS Consultants, Inc. (1992b) described a numerical model of ground-water flow and solute-transport in the shipyard and immediate area that was constructed to evaluate effects of general ground-water flow, tidal action and saltwater intrusion on the fate and transport of subsurface contaminants. This model was constructed using the finite-difference computer code HST3D (Kipp, 1987), which is capable of simulating non-steady flow of a fluid with a nonuniform density. The modeled area was digitized on an 11 by 17 rectangular grid of points in each of two layers. Simulations with the model indicated that much of the ground water at the shipyard flows to the drainage systems of the dry docks. However, because the dimensions of a model cell were about as large or larger than the dimensions of a typical dry dock, the model was not capable of resolving details of ground-water flow to individual dry docks, except for perhaps to DD-6, which is more than 1,000 ft from the other dry docks (fig. 2). Simulations with and without tides indicated that tides do not affect ground-water flow directions farther than about one grid space (about 700 ft) inland from the shoreline. Ground-water levels in simulations with the density of water in Sinclair Inlet greater than the density of fresh ground water were 0 to 0.81 m (0 to 2.7 ft) higher than in simulations with the density of water in Sinclair Inlet the same as the density of fresh ground water.

During the summer of 1994, Prych (1995) made a single set of measurements to determine the quantity and quality of water flowing into and out of the dry docks. He used these data to calculate rates of fresh and saline ground-water discharge into each dry dock. These discharges are used to calibrate the numerical ground-water model of the present study and are summarized later in this report (see table 4).

DESCRIPTION OF THE SHIPYARD AND SURROUNDING AREA

Puget Sound Naval Shipyard occupies a strip of land no more than 0.6 mi wide that stretches along 1.8 mi of the north shore of Sinclair Inlet near its mouth (fig. 1). The area of interest in this study includes only the shipyard and the offshore area where ground water from the shipyard may discharge into Sinclair Inlet; however, the modeled area also includes other offshore areas and most of the peninsula occupied by the City of Bremerton in order to provide the model with suitable hydrologic boundaries.

Topography, Hydrography, and Land Use

The peninsula upon which the shipyard and the City of Bremerton sit is about 3 mi long in the east-west direction and about 2 mi wide in the north-south direction. The peninsula is bordered on the south, east, and north by various bays and inlets of Puget Sound (fig. 1). Land-surface altitudes on the peninsula range from sea level to a maximum of about 240 ft on north-south trending hills that form a drainage divide on the west side of the peninsula. Land surface altitudes east of these hills are mostly between 50 and 150 ft. Nearly all land on the peninsula has been developed. The downtown area of Bremerton is adjacent to and north of the west end of the shipyard, and commercial properties abut most other parts of the shipyard's northern boundary. Most other land on the peninsula contains high-density single-family housing and commercial developments. The entire peninsula is served by public water supplies and a sanitary sewer system, and many areas have storm drains.

Nearly all land at the shipyard within about 1,000 ft of the shoreline is developed for industrial use, which includes workshops, the dry docks, piers, material and equipment holding and staging areas, a power plant, railway lines, cranes, roads, parking areas, and office buildings (fig. 2). Most of this area is flat, paved, and is about 12 ft above sea level. The original natural land surface over much of the industrial area was lower than present land surface and was raised by filling. The northwestern and north-central parts of the shipyard contain recreational, commercial and residential areas. Land in the northwestern part is flat and about 12 ft above sea level; however, land-surface altitude in the north-central part rises to a maximum of about 180 ft in the area north of DD-5. The southern parts of these hills have been removed to create flat land for the industrial area, and the excavated material was used to fill some of the previously low lands. The recreational, commercial and residential areas have lawns and trees among buildings, roads and parking lots.

Sinclair Inlet is deepest near its mouth, where it is about 70 ft deep at mean tide. The inlet is shallowest at its western end, where large mud flats are exposed at low tide. Typical depths in front of the piers and dry docks of the shipyard are about 45 ft, and typical depths in Port Washington Narrows on the eastern side of the peninsula are about 30 ft.

Tides in Puget Sound and Sinclair Inlet are diurnal, with two unequal high and two unequal low tides during each tidal cycle (about 24.8 hours). The mean tide range (difference between mean lower low and mean higher high water) is about 12 ft. Salinity of the water in the inlet is typically about 30 parts per thousand, but it varies a few parts per thousand both spatially and temporally. Stratification is slight, probably because no large freshwater streams discharge to the inlet or elsewhere nearby to the sound.

Geology

The shipyard and surrounding area are located within the Puget Sound Trough, a north-south trending structural basin that is partly filled with unconsolidated glacial, interglacial and marine sedimentary deposits. In the vicinity of the shipyard, the total thickness of these deposits ranges from about 600 to 1,800 ft (fig. 3). The most common geologic units exposed at land surface in the Bremerton area are Vashon till and outwash (fig. 3). Bedrock is exposed at land surface about 2 mi north of the shipyard (fig. 3) and also in another area about 2 mi west of the shipyard (not shown). Although the different geologic units have been mapped at land surface, little is known about their individual thicknesses or areal distributions at depth in the study area. In other areas, thicknesses of individual units range up to a few hundreds of feet (M.A. Jones, in press).

In addition to the natural sediments, a large part of the industrial area of shipyard is built on fill that is as much as 50 ft thick near the shoreline (from information in URS Consultants, Inc., 1994). The fill consists of construction and demolition debris, other waste material, and natural sediments from nearby excavations.

Hydraulic Conductivity

Hydraulic conductivity is a property of a porous material, such as a sediment deposit, that quantifies the ease with which water can flow through the material. More specifically, it is the volume of water that will flow though a unit area of material per unit time with a hydraulic gradient of unity. The hydraulic conductivity of a material can be a function of direction, and for most natural sediments it is larger in the horizontal than in the vertical direction. Values of horizontal hydraulic conductivity for natural sediments range over many orders of magnitude (see Freeze and Cherry, 1979, table 2.2)

J.J. Vaccaro and others (in press, table 3) summarized published estimates of horizontal hydraulic conductivity of sediments in the Puget Sound Lowland. Estimates for glacial and interglacial sediments range from a low of about 10^{-9} ft/s for interglacial silty clays and till to a high of about 10^{-1} ft/s for outwash and other coarse-grained material. In their numerical model of the shipyard, URS Consultants, Inc. (1992b) used values of horizontal hydraulic conductivity that ranged from about 10^{-5} to 10^{-1} ft/s in the horizontal direction and 10^{-2} times these values in the vertical direction.

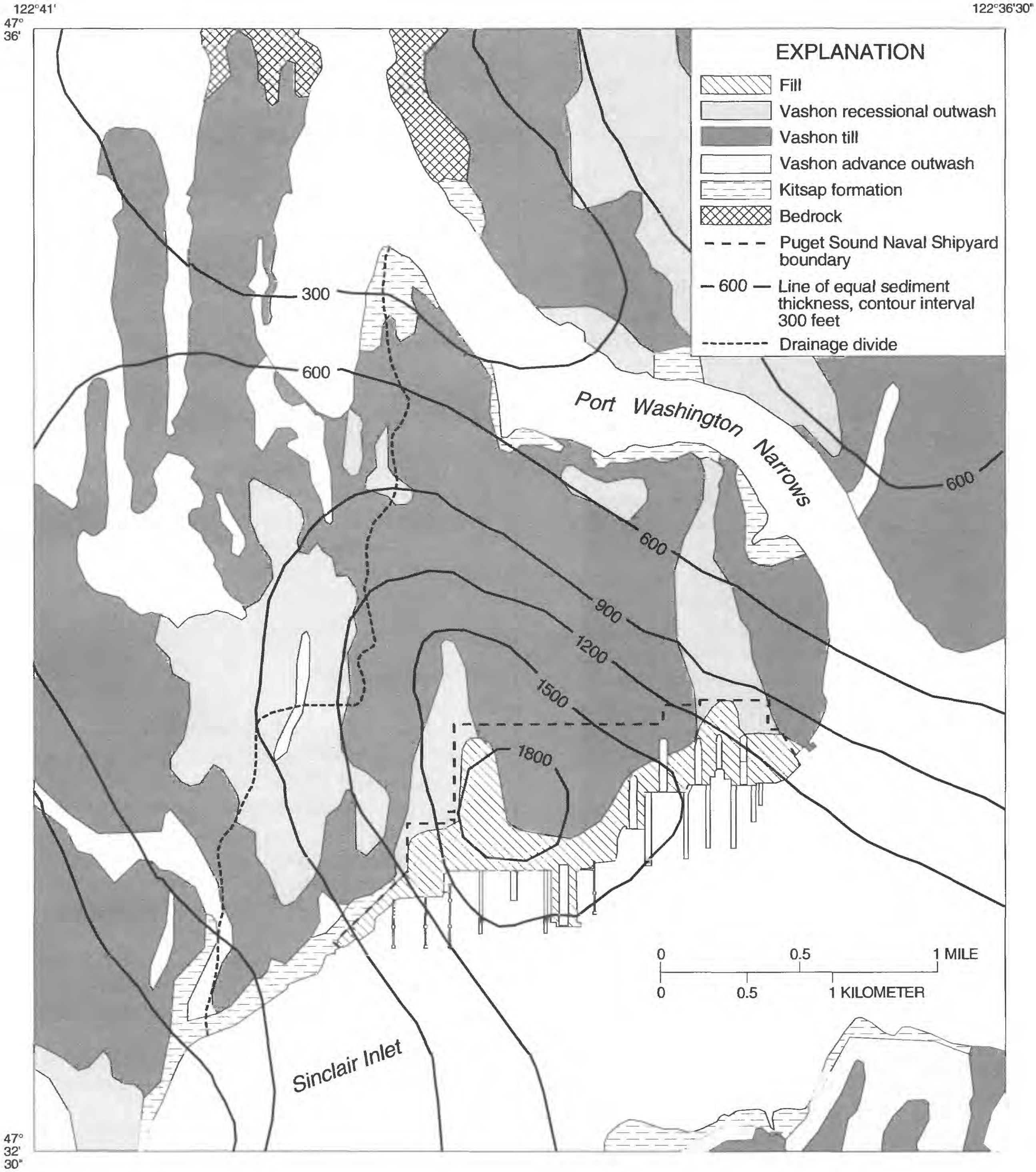


Figure 3.-- Surficial geology and sediment thickness in the vicinity of Puget Sound Naval Shipyard. Sediment thickness and surficial geology, with the exception of fill, modified from Jones (in press); area of fill estimated from information in URS Consultants, Inc. (1994, vol. 1; and 1995, vol.1).

As part of the site inspection study of the shipyard, URS Consultants, Inc. (1992a, vol. 2, Appendix E-2) report horizontal hydraulic conductivities estimated from slug tests of wells. In a slug test, the water level in a well is abruptly raised or lowered by adding or removing a small volume of water (the slug) from the well or by submerging or removing a solid rod from the well. The hydraulic conductivity is estimated from the rate at which the water level in the well recovers to its original level. The estimates (table 1 and fig. 4) range from 5.9×10^{-6} to 3.6×10^{-3} ft/s, with a median value of 0.10×10^{-3} ft/s. Although the largest value is nearly 1,000 times the smallest value, there is no obvious correlation between the estimated hydraulic conductivity and the type of sediment (fig. 4), nor is there an obvious areal pattern of hydraulic conductivity when the values are plotted on a map (not shown).

Dry Docks and Bulkheads

The main shoreline features at the shipyard are the six dry docks, which are used for repairing ships, and shoreline bulkheads, which provide deep water for moorage along much of the shipyard waterfront. All the dry docks have north-south longitudinal axes with entries at their southern ends (fig. 2). Although the dry docks are primarily fixed concrete or stone structures, the entries are closed by steel cofferdams that are floated into place and then flooded. The dry docks range in size from about 650 ft long by 108 ft wide (DD-1) to about 1,150 ft long by 190 ft wide (DD-6). Floor altitudes range from about 20 ft below sea level (DD-3) to 49 ft below sea level (DD-6). As mentioned previously, all dry docks except DD-2 were constructed with gravity drains behind their side and head walls and beneath their floors (fig. 5). These drains discharge to collection channels and sumps in the dry docks from where the water is pumped into Puget Sound. Although the walls and floor of DD-2 were constructed sufficiently heavy and strong so that pressure-relief drains were not necessary, some water does drain into this dry dock (Prych, 1995). However, the path by which the water drains into DD-2 is not known.

In addition to the drainage systems, the dry docks were constructed with sheet-pile cutoff walls, which consist of rows of steel or timber sheet piles beneath the entrances of all the dry docks and beneath the side walls and other parts of some of the dry docks (fig. 5 and 6, table 2). (Note that fig. 6 shows a rectangular grid, which is used by the numerical model that is described in a later section of this report). Cutoff walls are commonly used to reduce hydrostatic pressure and seepage beneath hydraulic structures. Information on the locations and depths of the cutoff walls was obtained from a series of facility certification reports (Fay, Spofford & Thorndike, 1979a, 1979b, 1980a, 1980b, 1980c, and 1980d).

The shoreline bulkheads were constructed of concrete or of rows of steel or timber sheet piles. The tops of the bulkheads are at land surface (about 12 ft above sea level), and their bottoms extend into the bottom sediments of the inlet. Because the altitudes of the bottoms of these bulkheads are unknown but are required for constructing the ground-water flow model, they were estimated to be about equal to the altitudes of the bottoms of the cutoff walls beneath nearby dry docks (table 2).

The ease with which water can flow through the cutoff walls and shoreline bulkheads is also unknown but required information for the model. Parameters for characterizing this hydraulic property are defined later in this report, and values were obtained by calibrating the model (see the section "Description of the Numerical Model").

Hydrologic Setting

Direct recharge from precipitation is the major source of fresh water to the ground-water system in the Bremerton area. The only other source of water is percolation of excess water from public supplies applied to lawns and gardens. Because there are no major streams in the area, all water from precipitation either runs off to storm sewers, returns to the atmosphere by evapotranspiration, or percolates to the water table. All ground water must discharge either directly to Puget Sound, to springs along the shoreline, or to the dry docks at the shipyard. Because the entire study area is served by public water systems there are few wells in the area and little is known about ground-water levels except at the shipyard.

Table 1.--*Water levels, screened intervals, and estimated horizontal hydraulic conductivities at observation wells at Puget Sound Naval Shipyard, Bremerton, Washington*

[ft/s, feet per second; --, information not available]

Well number[1]	Well identifier in other reports	Altitudes of observed water levels (feet, sea level)		Altitudes of well screen[4] (feet, sea level)		Model-cell indices[1]			Horizontal hydraulic conductivity[5] (10^{-3} ft/s)	Type of material at well screen[5]
		A[2]	B[3]	Top	Bottom	Row	Column	Layer		
201	PS03-MW01	--	4.2	5.8	-8.8	6	8	4	.017	F,B
202	PS03-MW02	--	1.9	4.4	-5.2	5	7	4	.012	F
203	PS03-MW03	--	0.1	1.9	-7.7	5	6	4	.11	F
301	PS12-MW01	-4.3	-3.6	-1.2	-10.7	11	15	4	.046	A,B
302	PS12-MW02	--	-3.2	-1.7	-11.2	11	15	4	.024	A,U
303	PS12-MW03	-1.2	-1.4	-2.2	-11.7	11	13	4	1.2	A
304	PS10W-MW04	-4.3	-5.2	-6.1	-15.6	13	14	4	.085	U
305	PS02-MW01	-1.6	--	3.1	-11.9	10	13	4	--	--
307	PS02-MW03	-1.5	--	3.8	-6.2	10	15	4	--	--
308	PS02-MW04	-3.9	--	2.8	-7.2	10	16	4	--	--
310	--	-35.3	--	-26.3	-46.3	16	14	7	--	--
312	--	-0.1	--	-3.4	-18.4	13	12	4	--	--
313	--	0.2	--	-3.4	-18.4	11	12	4	--	--
316	--	-3.9	--	-3.0	-13.0	12	17	4	--	--
317	--	-18.2	--	-28.1	-43.1	15	15	7	--	--
318	--	-4.5	--	-3.1	-13.1	13	16	4	--	--
351	--	-0.2	--	-98.2	-103.2	13	13	12	--	--
377	--	0.9	--	1.6	-18.4	14	18	4	--	--
378	--	-4.4	--	-2.4	-22.4	13	16	4	--	--
379	--	-3.1	--	1.5	-18.5	12	16	4	--	--
380	--	-9.1	--	-2.9	-22.9	16	13	4	--	--
382	--	-35.4	--	-30.6	-50.6	16	16	7	--	--
386	--	-9.7	--	-0.2	-20.2	13	15	4	--	--
388	--	-5.5	--	-0.8	-20.8	12	15	4	--	--
389	--	1.0	--	11.6	-13.4	13	12	4	--	--
390	--	-1.2	--	3.6	-26.4	12	13	3	--	--
400	PS01-MW01	2.2	-.9	3.1	-6.4	27	14	4	--	--
401	PS01-MW02	-0.8	-.9	3.9	-5.6	26	13	4	.13	F
402	PS07-MW01	-14.6	-14.9	-18.4	-27.9	48	28	5	.11	U
403	PS07-MW02	-1.8	1.1	0.5	-9.0	47	29	4	.0059	U
404	PS08-MW01A	-4.6	-5.3	-2.1	-11.6	57	23	4	.066	F
405	PS08-MW01B	--	-20.1	-30.2	-39.7	57	23	6	.14	U,A
406	PS08-MW02A	--	-2.0	-2.6	-12.1	56	23	4	.22	U,A
407	PS08-MW02B	--	-13.4	-60.1	-69.6	56	23	9	.16	T
408	PS08-MW03A	-1.6	-1.3	1.3	-8.2	55	23	4	.036	F,U

Table 1.--*Water levels, screened intervals, and estimated horizontal hydraulic conductivities at observation wells at Puget Sound Naval Shipyard, Bremerton, Washington--Continued*

Well number[1]	Well identifier in other reports	Altitudes of observed water levels (feet, sea level)		Altitudes of well screen[4] (feet, sea level)		Model-cell indices[1]			Horizontal hydraulic conductivity[5] (10^{-3} ft/s)	Type of material at well screen[5]
		A[2]	B[3]	Top	Bottom	Row	Column	Layer		
409	PS08-MW03B	--	-13.4	-50.7	-60.2	55	23	9	.25	T,U
410	PS09-MW01B	-36.5	-36.3	-35.6	-45.1	20	14	7	3.6	U
411	PS10E-MW01	1.6	-2.3	3.4	-6.1	63	22	4	2.1	F
412	PS10C-MW01	-2.2	-3.7	-3.3	-12.8	24	13	4	1.1	F,O
413	PS10C-MW02	-13.8	-15.9	-19.0	-28.5	30	18	5	.019	B
414	PS10C-MW03	-33.9	-35.7	-33.6	-43.1	36	21	7	.031	U
415	PS10C-MW04	-36.6	--	-34.7	-44.2	37	22	7	.020	O
416	PS10W-MW01	4.2	4.2	3.0	-6.5	6	9	4	.20	F,U
417	PS10W-MW02	7.2	7.7	4.2	-5.3	7	17	4	.059	U
418	PS10W-MW03	--	2.5	4.6	-4.9	8	11	4	.036	F
419	RPW-1B	2.0	--	4.5	-4.5	7	10	4	--	--
420	RPW-2	2.1	--	0.9	-8.1	7	10	4	--	--
421	RPW-3B	2.3	--	2.1	-6.9	7	10	4	--	--
422	--	-0.7	--	-6.4	-26.4	63	26	5	--	--
423	--	1.0	--	6.2	-13.8	55	29	4	--	--
424	--	--	--	-122.8	-137.8	55	29	13	--	--
425	--	-38.5	--	-35.2	-55.2	42	28	7	--	--
426	--	-41.1	--	-33.4	-53.4	34	24	8	--	--
427	--	-38.7	--	-30.0	-50.0	28	19	7	--	--
428	--	-36.8	--	-32.0	-52.0	25	17	7	--	--
429	--	--	--	-225.0	-235.0	25	17	14	--	--
430	--	-35.8	--	-31.0	-51.0	19	15	7	--	--
431	--	--	--	-65.0	-85.0	13	26	10	--	--
432	--	-22.5	--	-18.0	-38.0	46	27	6	--	--
433	--	-7.5	--	-36.3	-51.3	51	27	7	--	--
670	PS11-MW03	--	-35.2	-30.7	-40.7	18	22	7	--	--
671	PS11-MW04	--	--	-33.8	-48.8	18	21	7	--	--
672	PS11-MW05	--	-35.7	-33.5	-43.5	18	20	7	1.4	U
673	PS11-MW06	--	--	-47.0	-62.0	19	23	8	--	--

[1]Locations shown on figure 7.

[2]Data from URS Consultants, Inc. (1994) and Paul Johnson, 1995, written commun.; average of measurements at high and low tides mostly on July 8, 1994.

[3]Data from URS Consultants, Inc. (1992a, v. 2, appendix E-1); average of measurements at high and low tides on various days in May and June 1991.

[4]Data from URS Consultants, Inc. (1992a, v. 2, appendix E-2)(1994); Paul A. Johnson, 1995, written commun.

[5]Data from URS Consultants, Inc. (1992a, v. 2, appendix E-2); A, alluvium; B, beach deposits; F, fill; O, outwash deposits; T, till; U, undifferentiated native material.

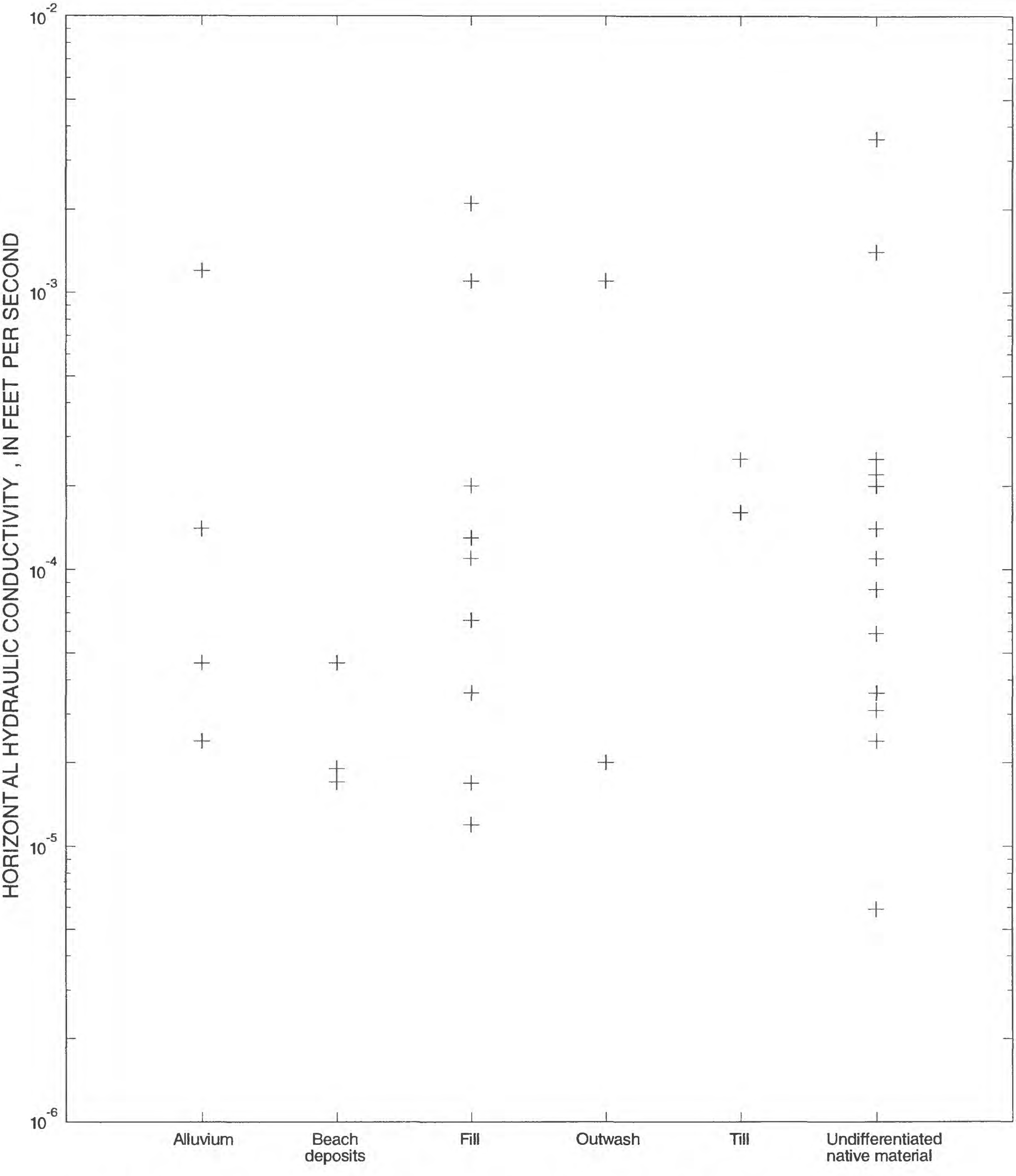


Figure 4.-- Horizontal hydraulic conductivity estimated from slug test of well as a function of the type of geologic material at the depth of the well screen. Data from URS Consultants, Inc. (1992a, vol. 2, Appendix E). Where two types of material are present in the screened interval, a point is plotted on the graph for each type.

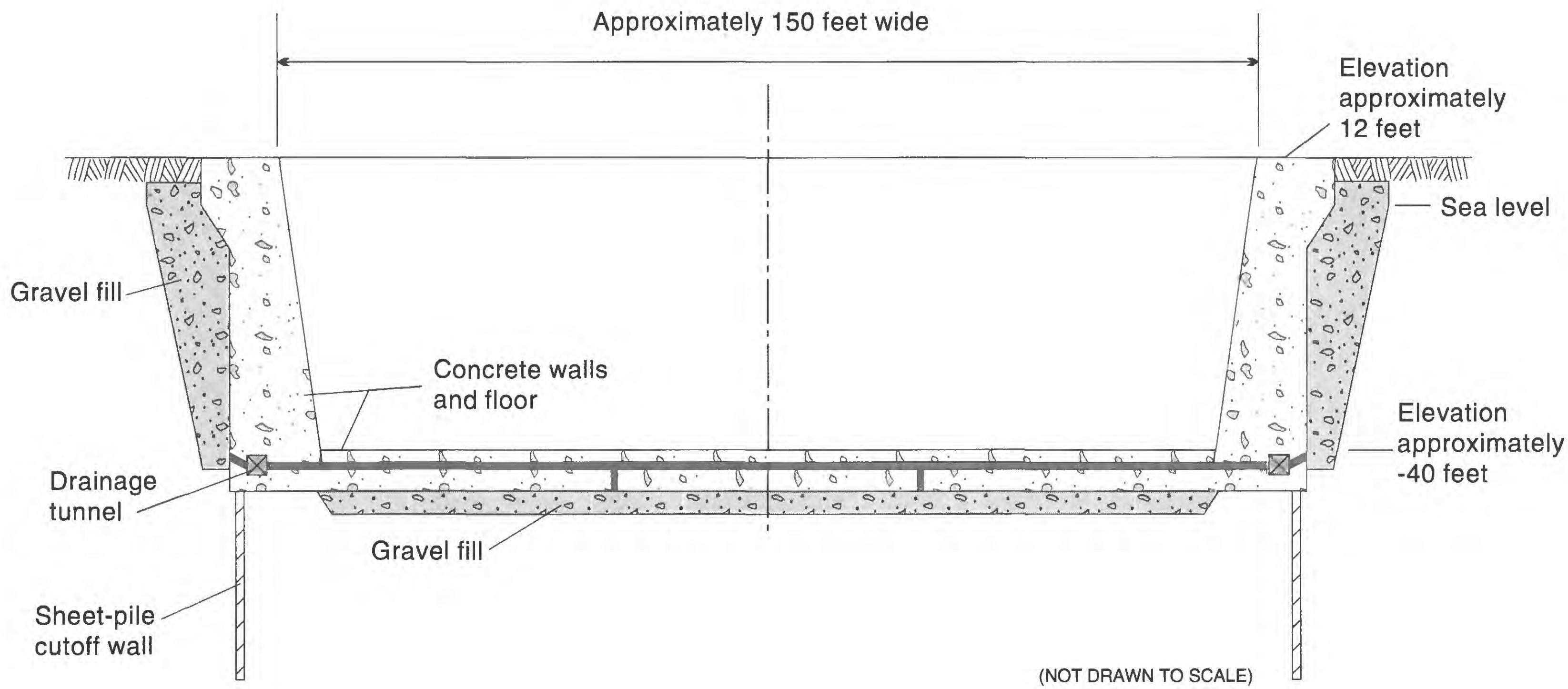


Figure 5.--Schematic cross section of a typical dry dock at Puget Sound Naval Shipyard.

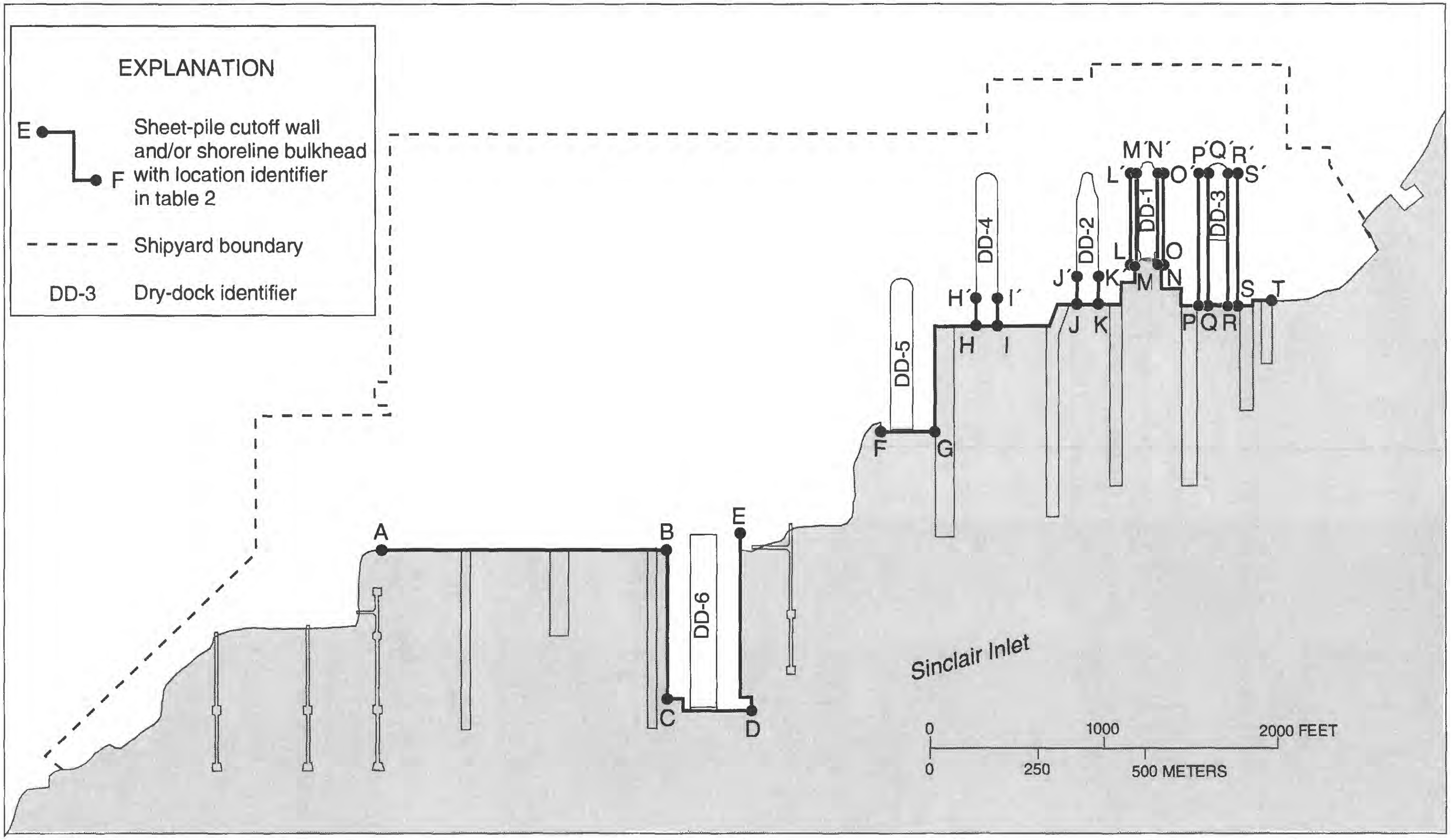


Figure 6.-- Locations of sheet-pile cutoff walls beneath dry docks and shoreline bulkheads of Puget Sound Naval Shipyard.

Table 2.--*Shoreline bulkheads and sheet-pile cutoff walls beneath drydocks at Puget Sound Naval Shipyard, Bremerton, Washington[*

[est, estimated value]

Location[1]	Altitude Top (feet above sea level)	Altitude Bottom (feet above sea level)	Remarks[2,3]
A to B	12	-55 est	Concrete bulkhead.
B to C	12	-60 to -88	Steel sheet-pile bulkhead and cutoff wall
C to D	12	-90	Steel sheet-pile cutoff wall below entrance structure to DD-6
D to E	12	-90 to -73	Steel sheet-pile bulkhead and cutoff wall
E to F			Riprap bank, no wall or bulkhead
F to G	-51	-80 to -70	Steel sheet-pile cufoff wall beneath entrance structure to DD-5
G to H	11	-70	Steel sheet-pile bulkhead and cutoff wall
H to I	-51	-70	Steel sheet-pile cutoff wall beneath entrance structure to DD-4
H to H' and I to I'	-51	-70	Steel sheet-pile cutoff wall beneath sidewalls and of DD-4
I to J	11	-70 est	Steel sheet-pile bulkhead
J to K	-40	-63	Timber sheet-pile cutoff wall beneath entrance structure to DD-22
J to J'	-40	-63	Timber sheet-pile cutoff wall beneath sidewalls andof DD-2
K to K'			
K to M	11	-55 est	Sheet-pile bulkhead
M to N, and M to M', N to N' M' to N'	-33	-53	Timber sheet-pile cutoff walls beneath entrance structure, and side and headwalls of DD-1
L to L' and O to O'	11	-10	Timber sheet-pile cutoff walls about 90 feet and from centerline of DD-1
N to Q	11	-45 est	Sheet-pile bulkhead
Q to R, and Q to Q', R to R' Q' to R'	-27	-37	Timber sheet-pile cutoff walls beneath entrance structure, and side and headwalls of DD-3
P to P', and S to S	11	-25 est	Timber sheet-pile cutoff walls outside of and sidewalls of DD-3
R to T	11	-35 est	Sheet-pile bulkhead

[1]Locations are shown on figure 6.

[2]Cutoff walls beneath drydocks connect to bottom of drydocks.

[3]Information from Fay, Spofford & Thorndike, Inc., 1979a, 1979b, 1989a, 1980c, and 1980d.

Climate

The climate in the Puget Sound region is moderate, due to the influence of Puget Sound and the Pacific Ocean. Winter air temperatures usually remain above freezing, and summer temperatures are seldom above 90 degrees Fahrenheit (32 degrees Celsius). Most precipitation occurs as rain. The mean annual precipitation at a weather station in Bremerton is 50.4 in (calculated from data in U.S. National Oceanic and Atmospheric Administration, 1989). Precipitation varies greatly with the seasons, with most occurring during the fall and winter months. Average monthly precipitation during each of the three wettest months (November, December, and January) is more than 7 in.; during each of the three driest months (June, July, and August) it is less than 2 in. In the Bremerton area, for a soil with a 6-in. water holding capacity, the estimated annual potential and actual evapotranspiration are 25.9

and 18.1 in., respectively (Phillips, 1968). (Note that the mean annual precipitation used to make these estimates was 38.7 in., which is considerably less than the 50.4 in. mentioned above. If 50.4 in., rather than 38.7 in. of precipitation were used to estimate evapotranspiration, the estimated evapotranspiration values probably would have been larger than those obtained.)

Ground-Water Recharge

J.J. Vaccaro and others (in press; table 4) summarize published estimates of single- or multi-year average rates of direct ground-water recharge from precipitation for 26 areas in the Puget Sound Lowland. The estimates, made using soil-moisture accounting with daily or more frequent climate data, range from about 5 to 29 in/yr, with a median value of 14 in/yr. The areas range in size from 0.8 to 72 mi^2, and precipitation on these areas range from about 25 to 61 in/yr, with a median value of 38 in/yr. Direct surface or shallow subsurface runoff occurred from all but two of the areas.

An estimated value of the maximum average annual ground-water recharge in the Bremerton area is the difference between the estimated values of precipitation and evapotranspiration given in the "Climate" subsection,

$$50.4 \text{ in/yr} - 18.1 \text{ in/yr} = 32.3 \text{ in/yr}.$$

This computation assumes no surface runoff and yields a rate that is about 10 percent larger than the largest value reported by J.J. Vaccaro and others (U.S. Geological Survey, written commun., 1996). Ground-water recharge estimates that include a more realistic rate of surface runoff are given in the "Model Input" section of this report.

Ground Water at the Shipyard

To measure water levels and collect samples of ground water, numerous observation wells have been installed during previous investigations at the shipyard (fig. 7). Most of the observation wells were installed in the industrial area of the shipyard, where land surface is about 12 ft above sea level. Although the altitudes of the bottoms of these wells range from about 5 to 235 ft below sea level, not many extend deeper than 50 ft below sea level (table 1). Water levels in these wells have been measured near times of high and low tide during two different periods (URS Consultants, Inc., 1992a, and 1994; and written commun., Paul Johanson, URS Consultants, 1995), and averages of the observations at high and low tide are used in the current study (table 1). Observed water levels range from about 8 ft above to 41 ft below sea level. Typically, differences between water levels at high and low tide (not shown) were larger in wells near the shoreline than in wells far from the shoreline. Although differences ranged from nearly 5 ft at well 386 to less than 0.1 ft at many of the wells, differences were less than 1 ft in 32 of the 45 wells where data were collected in 1994 and in 16 of the 27 wells where data were collected in 1991.

Contours of water levels observed at times of both high and low tide during the 1994 observations indicate that the directions of ground-water flow (inferred from the direction of decreasing water level) beneath much of the shipyard were towards the dry docks (URS Consultants, Inc. 1994, fig. 3-3 and 3-4; fig. 8 in the present report). An exception is the part of the shipyard west of pier D, where the inferred flow direction was to the south and southeast toward Sinclair Inlet. However, even in this area water appears to flow from Sinclair Inlet into the ground-water system at low tide.

Although the contours drawn on the basis of the observed water levels may not be rigorously valid because the observation wells are of varying depths, the inferred directions of ground-water flow are supported by other analyses of the data. For example, most of the observed ground-water levels are below sea level, even at high tide, which means that ground water at the observation wells must eventually discharge at a location where the water level is below sea level. The only such locations nearby are the dry docks. Also, observed water levels in the deeper wells tend to be lower than in the shallower wells, indicating ground-water flow has a downward component. This trend can be seen in the graph of observed water level as a function of the altitude of the screened interval for all observation wells (fig. 9). Although in some cases this trend may be caused by wells being screened deeper at locations where the water table is deeper, decreasing water levels with depth were observed at three locations between DD-2 and DD-3 where there are pairs of closely spaced wells that are screened at different altitudes (well pairs 404-405, 406-407, and 408-409; fig. 7 and table 1).

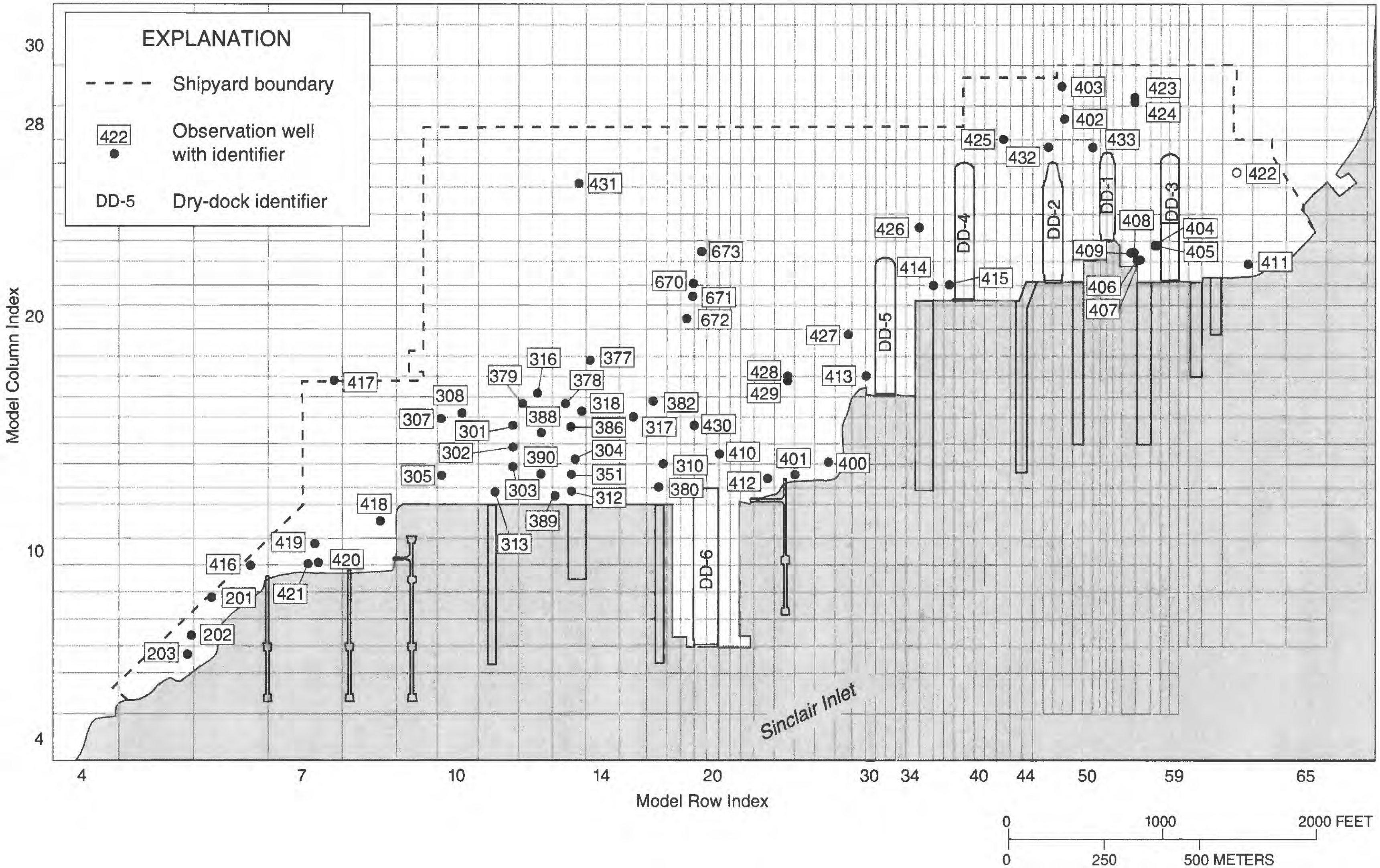


Figure 7.-- Locations of selected observation wells at Puget Sound Naval Shipyard.

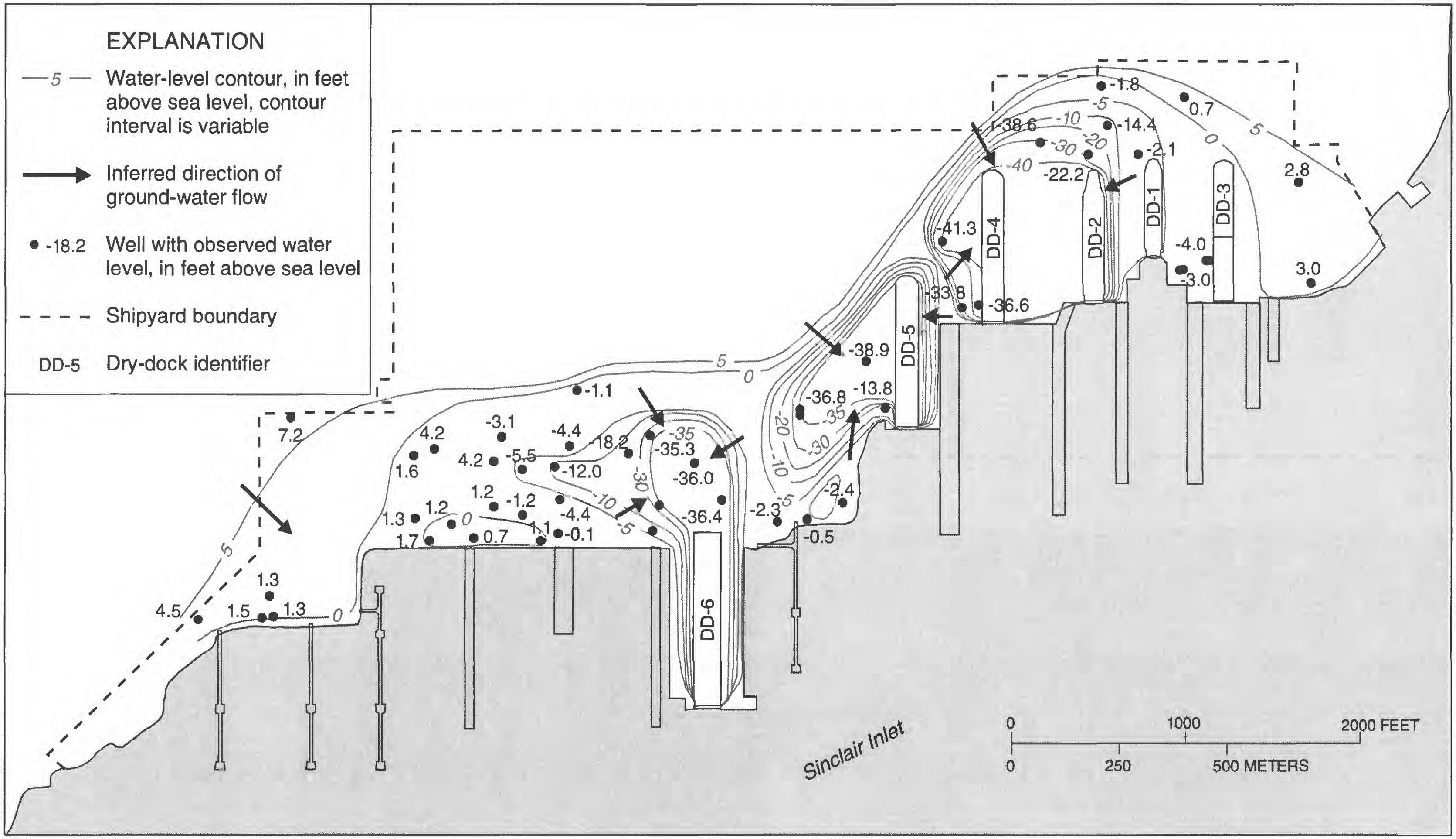


Figure 8.--Observed ground-water levels and inferred flow paths at high tide (Modified from URS Consultants, Inc., 1994, fig. 3-4; Measurements mostly on July 8, 1994).

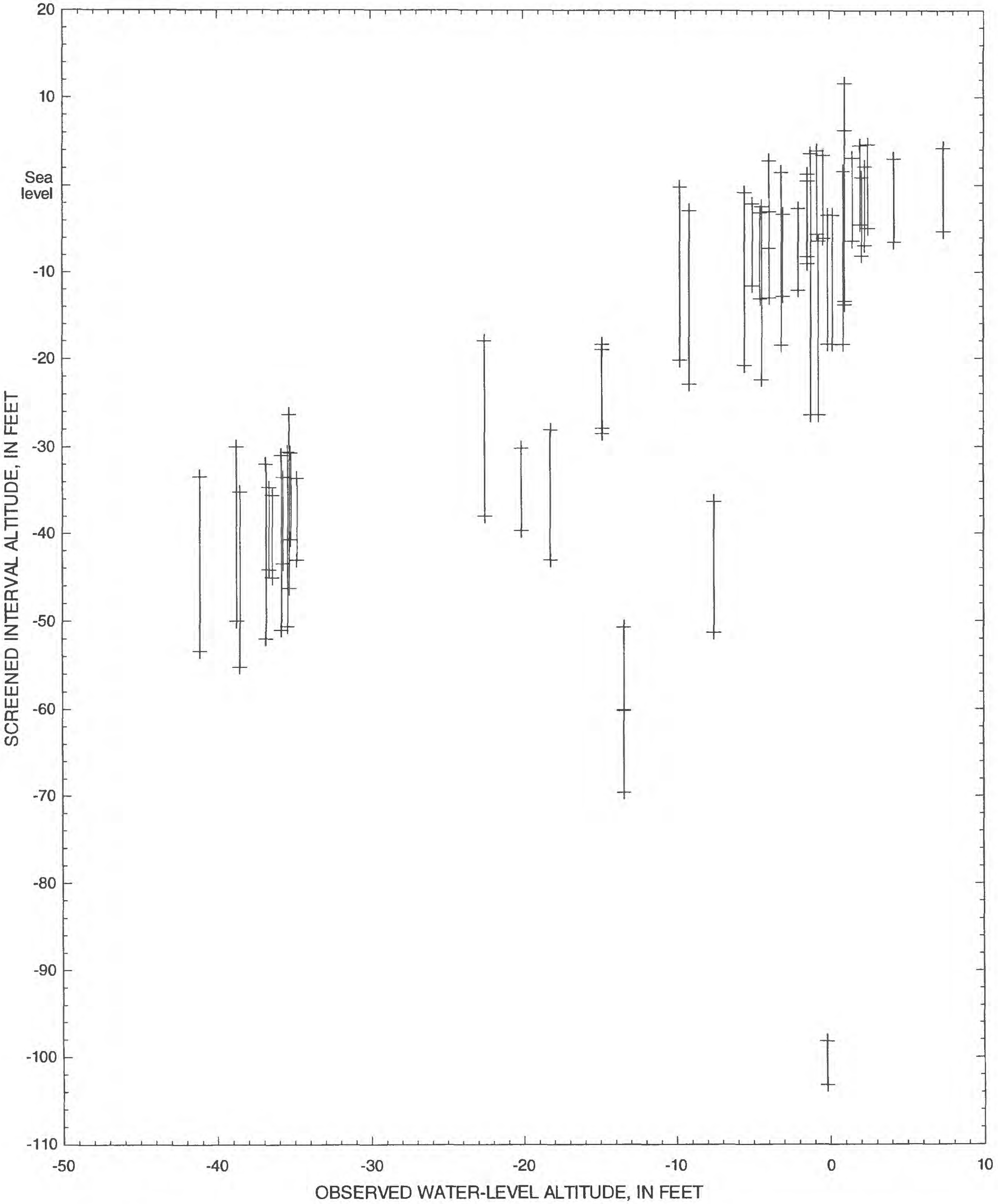


Figure 9.--Observed water-level altitude as a function of the altitude of the screeded interval of observation well. Vertical line connecting crosses shows length of well screen. (Observed water levels from table 1).

DESCRIPTION OF THE MODEL

A steady-state, three-dimensional, numerical model of ground-water flow beneath the shipyard and surrounding area was constructed using MODFLOW (McDonald and Harbaugh, 1988). This model uses a rectangular grid and finite-difference methods to solve the equations of motion governing the flow of ground water of uniform density. Ground-water heads and flow rates computed by this model were used as input data to a set of computer programs, MODPATH and MODPATH-PLOT (Pollock, 1994), for computing and displaying ground-water flow paths. Because the saline ground water that originates in Sinclair Inlet is denser than the fresh ground water that originates inland, the model would tend to overestimate the discharge of fresh water to the inlet and underestimate the discharge of saline water to the dry docks.

Modeled Area and Boundary Conditions

The modeled area includes the shipyard and most of the peninsula occupied by the City of Bremerton (fig. 10). The west boundary is a drainage divide, and the northern, eastern and western boundaries are approximately at the centers of the surrounding inlets and channels of Puget Sound. No-flow conditions are specified at these perimeter boundaries, which are located at distances that are assumed to be sufficiently far from the shipyard so that the conditions specified on these boundaries do not greatly affect simulated flows at the shipyard. This assumption is discussed and verified in a later section titled "Effects of Model Boundaries".

The bottom boundary of the model is the bottom of the unconsolidated sediments, and the top boundary is the water table or the bottom of Puget Sound. A no-flow condition is specified on the model's bottom boundary; recharge from precipitation is specified at the water table; ground water is allowed to flow into or out of the ground-water system from Puget Sound; and ground-water is allowed to discharge to drains in the headwalls (northern), sidewalls, and floors of all dry docks except DD-2. Drainage to DD-2 is not simulated because this dry dock was constructed without drains; although some ground water does drain into this dry dock, the way in which it does this is unknown. Inflows and outflows to the model are shown schematically on fig. 11.

Model Input

To use the ground-water flow model MODFLOW the modeled region is divided areally with a rectangular grid and vertically into layers to create a large number of rectangular blocks of sediment called model cells. The geometry, geohydrologic characteristics, and boundary conditions for each cell are part of the model-input data.

Model Grid and Layers

The model grid contains 70 rows and 40 columns and is aligned so that rows run north-south and columns run east-west (row indices increase from west to east, and column indices increase from south to north, fig. 10). Grid dimensions in the north-south direction range from 125 to 1,000 ft, and in the east-west direction range from 47 to 600 ft. Dimensions are smallest in the vicinity of dry docks where the greatest resolution is required; each dry dock is two rows wide and three to six columns long (figs. 7 and 10). The full thickness of the unconsolidated sediment is divided into up to 14 layers that range in thickness from 10 ft to a maximum of 1,650 ft (table 3). The thinnest layers are located between 90 ft below and 12 ft above sea level, which includes the dry docks. The top layer includes a water table, but all other layers are assumed to be fully saturated. Because the top and bottom altitudes of the sediment are not uniform over the modeled area, the areal extent of all the layers is not the same. The top and bottom of each layer is a horizontal plane except where the layer is truncated by the top or bottom surface of the sediments. Where truncation by the top sediment surface causes a cell to be less than about 2 ft thick, that cell is deleted from the model and its thickness incorporated into the cell below.

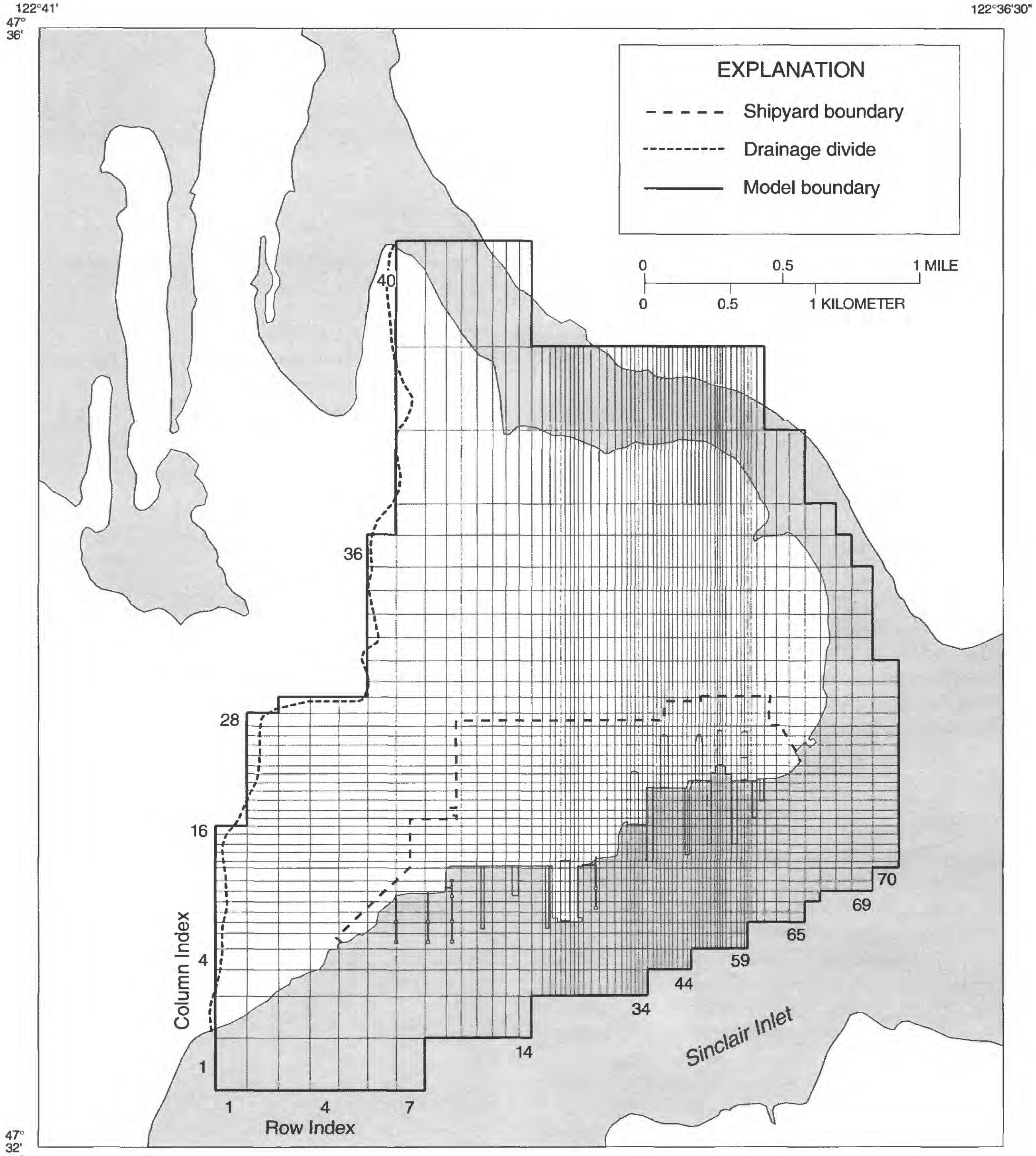


Figure 10.-- Areal boundary and grid of the numerical model.

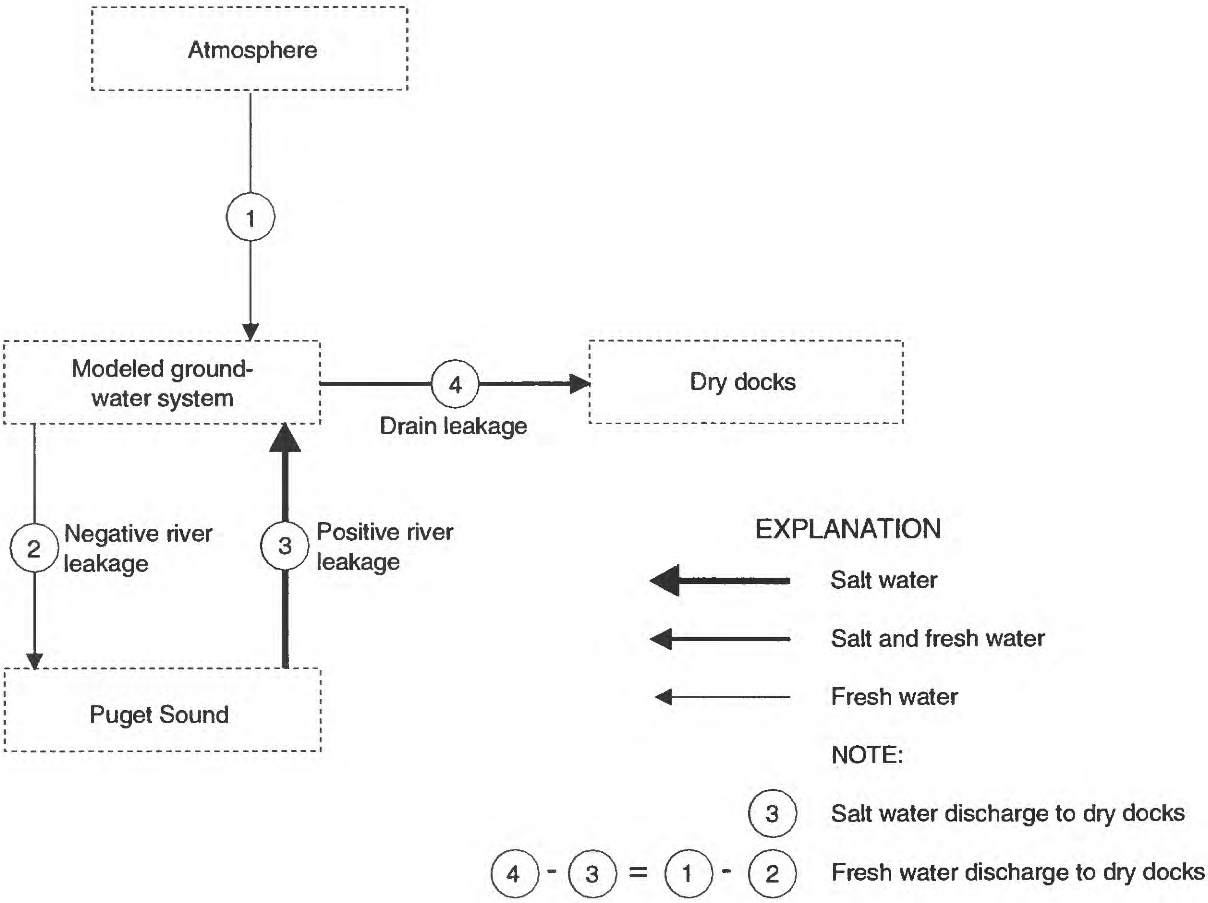


Figure 11.-- Schematic diagram of inflows and outflows from the ground-water model.

Table 3.--*Altitudess of tops and bottoms of layers in numerical model*

Model layer index	Altitude (feet above sea level)[1]
1	
	40
2	
	12 - and surface at shipyard
3	
	0
4	
	-15
5	
	-25 - bottom of shallowest dry dock
6	
	-35
7	
	-45
8	
	-55 -- bottom of deepest dry dock
9	
	-65
10	
	-75
11	
	-90
12	
	-110
13	
	-150
14	
	-1,788 - (minimum elevation)

[1]Altitudes of top and bottom of a model layer may differ at some locations from values given because of variations in elevations of the land surface, the bottom of Puget Sound, or the bottom of the sediments, or if the given elevation results in a cell thickness less than about 2 feet.

Transmissivity

Transmissivity is the model-input parameter that controls the rate of horizontal movement of ground water in the interior of the model. The discharge of ground-water per unit width in a layer is equal to the product of transmissivity and the horizontal gradient of the ground-water head. The transmissivity, T, of a cell is given by

$$T = K_h \Delta z \quad , \qquad (1)$$

where K_h is the horizontal hydraulic conductivity of the sediment in the cell (which in this study is assumed to be the same in all horizontal directions), and Δz is the thickness of the cell.

Vertical Conductance

Vertical conductance is the model-input parameter that controls the vertical movement of ground water between model layers. The discharge of ground water per unit horizontal area between layers is equal to the product of the vertical conductance and the difference between ground-water heads in the two layers. Vertical conductance, C_v, between two vertically adjacent cells estimated with the equation

$$C_v = \frac{2(K_v)_u(K_v)_l}{[(K_v)_u(\Delta z)_l + (K_v)_l(\Delta z)_u]} \quad , \qquad (2)$$

where K_v is the vertical hydraulic conductivity, and the subscripts u and l refer to the upper and lower cells, respectively.

Discharge to Puget Sound

The model simulates the discharge of ground water to and from Puget Sound through the top faces of all model cells that represent the top of the sediments on the bottom of the sound, and through vertical faces of cells exposed to the sound along the shoreline (cells B and S, respectively, on fig. 12). These discharges are simulated using the River Package of MODFLOW, which uses the equation

$$Q_s = k_s(h_s - h) \quad , \qquad (3)$$

where Q_s is the discharge to or from an individual cell (a negative value denotes flow from the ground-water system to the sound); k_s is a discharge coefficient for the cell; h_s is the head in the sound; and h is the model-simulated head for the cell. Both k_s and h_s are model-input data.

Because the saline water in Puget Sound is denser than fresh ground water, equivalent freshwater heads on the bottom of the sound are greater than zero (above sea level), and they increase with depth. However, because the model does not account for variations in water density, h_s is assigned a uniform value of zero to prohibit simulation of the implausible result of water from Puget Sound flowing into one discharge face and out another. As a result, the model most likely overestimates the discharge of fresh ground water to the sound and underestimates the discharge of fresh and saline water to the dry docks.

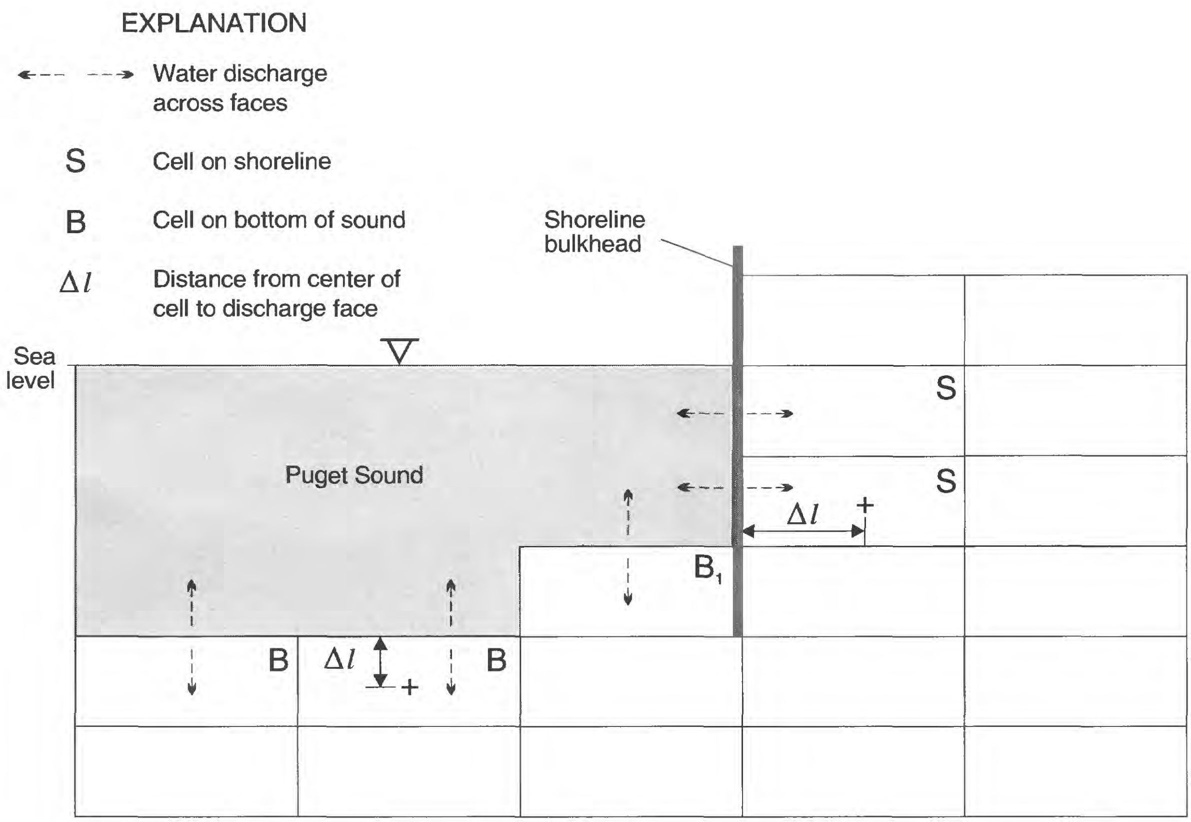


Figure 12.-- Schematic vertical section showing model cells with discharge to or from Puget Sound.

The coefficient k_s is estimated with the equation

$$k_s = \frac{c_b K_* A}{\Delta l} \quad , \qquad (4)$$

where K_* equals the vertical or horizontal hydraulic conductivity of the sediments, depending on whether the cell is on the bottom of the sound or on the shoreline, respectively; A is the area of the face through which the water discharges; and Δl is the length of the flow path from the center of the cell to the discharge face. The variable c_b, a bulkhead coefficient, is introduced to account for the resistance to discharge caused by bulkheads along the shoreline. The value of c_b can range from zero for a cell with a water-tight bulkhead, to unity for a cell either with an extremely leaky bulkhead or with no bulkhead. Shoreline bulkheads are placed in the model at the locations shown on fig. 6 and as described in table 2. Because bulkheads typically extend below the sediment surface, they can also hinder the horizontal flow of ground water in the interior of the model (for example, between cell B_1 and the cell to its right, fig. 12). The effects of the subsurface parts of the bulkheads are simulated in the model in the same way as are the effects of the sheet-pile cutoff walls beneath and near some of the dry docks. (See the subsection "Sheet-pile Cutoff Walls".)

Discharge to Dry Docks

The model simulates ground-water discharge to the dry-dock drainage systems from model cells that are adjacent to dry-dock sidewalls or headwalls and from cells below dry-dock floors. These discharges are simulated in a manner analogous to that for simulating discharge to Puget Sound; however, the model uses the Drain Package of MODFLOW for this task. Ground-water discharge from a cell to a dry dock is computed by the model using the equations:

$$Q_d = k_d\left(h_d - h\right), \text{ if } h>h_d, \text{ and} \tag{5a}$$

$$Q_d = 0, \text{ if } h<h_d \quad , \tag{5b}$$

where Q_d is the rate of discharge from a cell; k_d is a drainage coefficient for the cell; and h_d is a reference drain altitude for the cell. Both k_d and h_d are model-input data. The reference drain altitude for a cell adjacent to a dry-dock wall is assumed equal to the altitude of the midpoint of the cell, whereas the reference altitude for a cell beneath a dry-dock floor is assumed to equal the altitude of the top of the concrete floor.

The drainage coefficient for a cell is calculated as

$$k_d = \frac{K_* A}{\Delta l} \quad , \tag{5b}$$

where K_* is the horizontal hydraulic conductivity if the cell is adjacent to a dry-dock wall, or the vertical hydraulic conductivity if the cell is beneath the floor; A is the area of the discharge face of the cell that is in contact with the wall or floor; and Δl is the length of the flow path from the center of the cell to the discharge face.

Sheet-Pile Cutoff Walls

The sheet-pile cutoff walls beneath the dry docks and the subsurface parts of the shoreline bulkheads can inhibit the horizontal flow of ground water in the interior of the model. This phenomenon is simulated by using the Horizontal-Flow Barrier Package (Hsieh and Freckleton, 1993). This feature of the model increases the resistance to horizontal flow between two adjacent cells in a layer by adding the resistance of a horizontal-flow barrier to the resistance offered by the sediments contained in the cells. The location of a barrier and its resistance to flow are input data to the model. The resistance of the barrier per unit width of the boundary between the two cells is input in the form of a conductance (the reciprocal of resistance). For fully saturated model cells, this conductance is equal to the product of the cell thickness and an equivalent horizontal hydraulic conductivity of the barrier divided by the thickness of the barrier in the direction of flow. Horizontal-flow barriers are placed in the model at the locations of the bulkheads and cutoff walls on fig. 6 and table 2.

Ground-Water Recharge

Direct recharge of water from precipitation is the only process by which freshwater enters the modeled ground-water system. Recharge, which is model-input data, is applied to the uppermost active cell on all land areas in the model. The recharge rate over the residential and light commercial areas is assumed to be 70 percent of the maximum estimated average annual recharge rate for pervious surfaces in the area (22.6 in/yr; fig. 13) (see section titled "Hydrologic Setting"). The entire estimated recharge rate for pervious surfaces is not used because it is assumed that 30 percent of this area is impervious and drains to the storm-sewer system, which drains to the sound. A recharge rate of 3.2 in/yr, which is 10 percent of the estimated rate for pervious surfaces, is assumed for the industrial areas of the shipyard and the downtown Bremerton area. The recharge rates used in the model for both heavily developed areas may be high; however, they are used in order to simulate a conservative (larger-than-actual) discharge of freshwater directly to the sound. Even with the suspected high recharge rate, the resulting total recharge on the modeled area is only 4.1 ft^3/s, which is only about one-third larger than the 3.1 ft^3/s of freshwater that was observed to be discharging to the dry docks.

Model Calibration

Model calibration is a trial-and-error process in which values of model-input parameters are varied within realistic ranges until acceptable agreement is obtained between model-simulated and observed quantities. This section of the report describes the calibration process for the ground-water flow model, gives the values of the parameters that were determined by calibration, and compares model-simulated and observed quantities. No additional calibration was performed for simulation of ground-water flow paths.

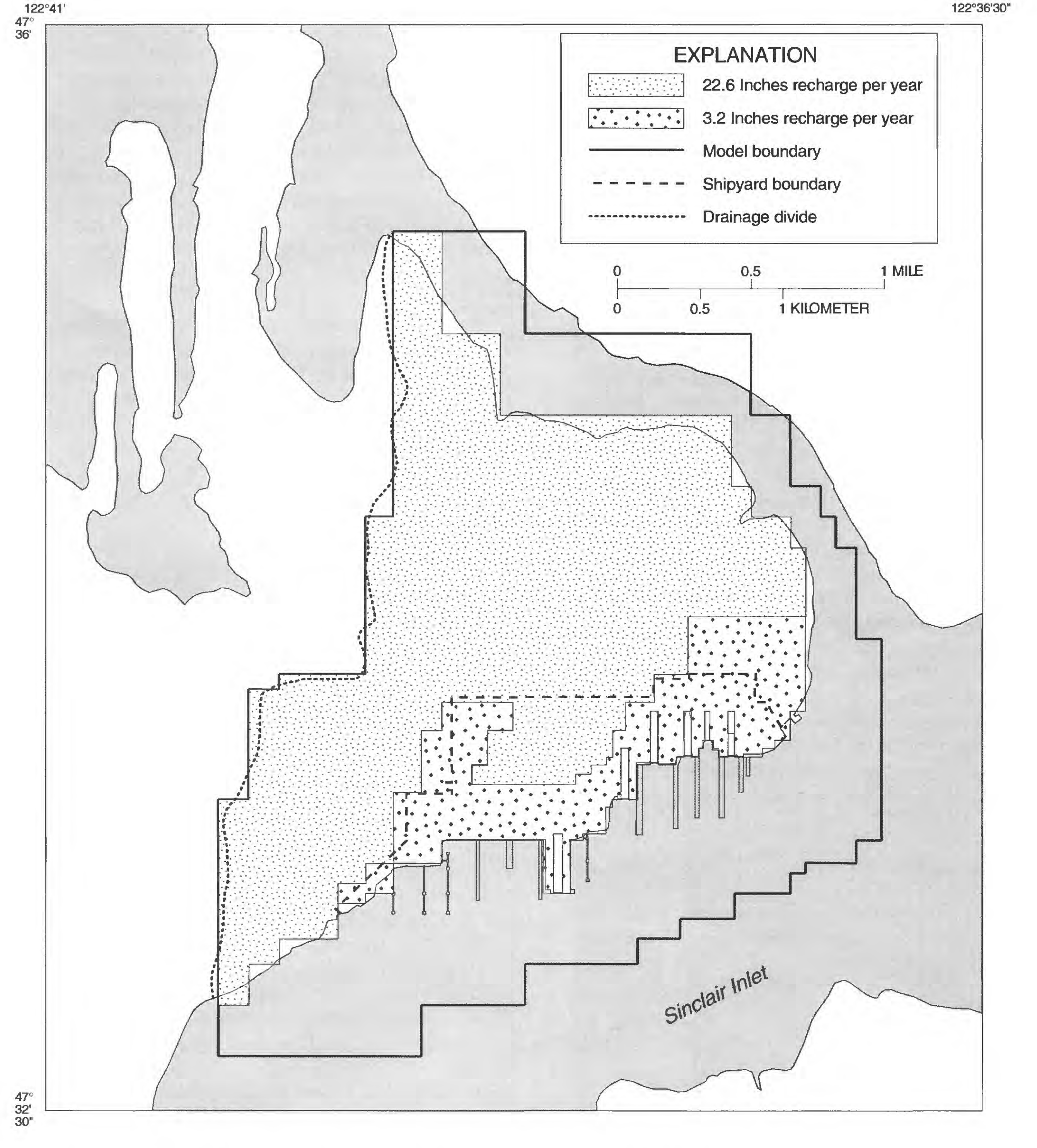


Figure 13.-- Estimated ground-water recharge from precipitation on modeled land areas.

Calibration Process

The model was calibrated by adjusting values of horizontal hydraulic conductivity, vertical hydraulic conductivity, bulkhead coefficient, and horizontal-flow-barrier conductivity so that simulated total freshwater discharge to dry docks, total saline-water discharge to dry docks, and ground-water heads in the shipyard approximated observed values of these quantities (tables 2 and 4). When a fundamental variable such as horizontal or vertical hydraulic conductivity was adjusted, all input parameters that are functions of this variable were also changed. For example, when hydraulic conductivity was adjusted, transmissivities, coefficients for discharge to the sound, and coefficients for drainage to the dry docks were all changed simultaneously. Also, input values of the bulkhead coefficients and the conductivities of the horizontal-flow barriers were adjusted proportionally so that the buried and exposed parts of bulkheads and the sheet-pile cutoff walls all provided nearly the same hindrance to the flow of water.

Values of the horizontal and vertical hydraulic conductivities, the bulkhead coefficient, and the horizontal-flow-barrier conductivity were made uniform throughout the model--they were not varied areally or with depth. Although the author realizes that the hydraulic characteristics of the sediments are not uniform, the assumption of uniformity is necessitated and partly justified by the lack of evident differences in estimated horizontal hydraulic conductivities among the different sediment types (fig. 4). The assumption of uniformity limited detail in the model to that justified by available knowledge and greatly simplified calibration, but it limited the degree to which simulations could be made to agree with observations.

Results of Calibration

Calibration of the flow model resulted in the following values of the fundamental variables:

Horizontal hydraulic conductivity, K_h	=	10^{-3}ft/s
Vertical hydraulic conductivity, K_v	=	10^{-7}ft/s
Bulkhead coefficient, c_b	=	0.02
Horizontal-flow-barrier conductivity	=	$2\text{x}10^{-6}$ft/s

The value of horizontal hydraulic conductivity (10^{-3} ft/s), is near the upper end of the range of values that were estimated from slug tests (table 1 and fig. 4), and is in the range of values used in the numerical model described by URS Consultants, Inc. (1992b), is typical of values for outwash and other coarse-grained deposits summarized by J.J. Vaccaro and others (U.S. Geological Survey, written commun., 1996), and is a typical value for clean or silty sand (Freeze and Cherry, 1979, table 2.2). However, the value is much larger than those for glacial till reported by J.J. Vaccaro and others (in press). Consequently, it is probably representative only of about the upper 50 ft of sediments at the shipyard and of some of the outwash deposits in the surrounding area; but it may not be representative of deeper sediments at the shipyard or of the till exposed at land surface over much of the surrounding area.

The calibrated value of vertical hydraulic conductivity (10^{-7} ft/s) is typical of fine-grained deposits such as till or silt. Although this value may be reasonable if there are layers of fine-grained material in the fill and other subsurface material at the shipyard, the 10,000-to-1 ratio of horizontal to vertical hydraulic conductivity is 100 times the ratio in the model described by URS Consultants, Inc. (1992b).

The values of the bulkhead coefficient (0.02), and the corresponding horizontal-flow-barrier conductivity ($2\text{x}10^{-6}$ ft/s) are in the realm of possibility, but there are no data to confirm these values. These values imply that the bulkheads and cutoff walls reduce water discharge to 2 percent of the rate that would occur if they were not there and if their presence did not cause hydraulic gradients to change. The horizontal-flow barrier provides the same resistance to horizontal flow as a series of 50 model cells having approximately the same properties of cells near the dry docks, each one being 100 ft long and 10 ft thick, with a horizontal hydraulic conductivity of 10^{-3} ft/s

Total freshwater discharge, total saline-water discharge and total combined discharge to the dry docks that are simulated by the calibrated model are within 10 percent of corresponding observed discharges (table 4). However, the model substantially underestimates the combined fresh and saline-water discharges to DD-6 and overestimates the combined discharges to DD-1, DD3, DD-4 and DD-5. (See fig. 11 for methods used to compute the simulated discharges to dry docks. The fractions of simulated discharge to each dry dock that are fresh and saline water are not easily obtained from the model and were not computed.) Ground-water heads simulated by the calibrated model tend to be similar to observed heads (fig. 14). However, in some places, simulated heads differ from observed values by as much as 20 ft.

Although it may have been possible to improve the agreement between simulated and observed discharges to individual dry docks or between simulated and observed heads by making local adjustments to model-input parameters, the author chose to accept the errors of the existing model with uniform hydraulic characteristics of the sediments rather than to reduce the errors by changing local hydraulic characteristics of the sediments without geologic information to justify the changes. Although it is possible to obtain more information about the vertical and areal variation of the hydraulic characteristics of the sediments, collecting sufficient information to define the spatial distribution of the characteristics may not be practical because of the extreme variability of the fill.

Table 4.--*Observed and simulated ground-water discharges to dry docks at Puget Sound Naval Shipyard, Bremerton, Washington*

[See figure 11 for method of computing separate fresh and simulated saline water discharges to drydocks; --, value not computed]

	Discharges, in cubic feet per second								
	Observed[1]			Simulated					
				No-flow boundaries			Specified-head boundaries		
Drydock	Fresh water	Saline water	Com-bined	Fresh water	Saline water	Com-bined	Fresh water	Saline water	Com-bined
1	0.06	0.01	.07	--	--	0.57	--	--	0.60
2	0.02	.28	.30	--	--	0	--	--	0
3	0.21	.08	.29	--	--	.25	--	--	.26
4	0.34	.27	.61	--	--	2.03	--	--	2.18
5	0.53	.65	1.18	--	--	2.30	--	--	2.42
6	1.9	4.3	6.2	--	--	3.43	--	--	3.59
Total	3.1	5.6	8.7	2.8	5.7	8.58	--	--	9.05

[1]Observed discharges from data in Prych (1995) and are the results of one set of measurements made in the summer of 1994.

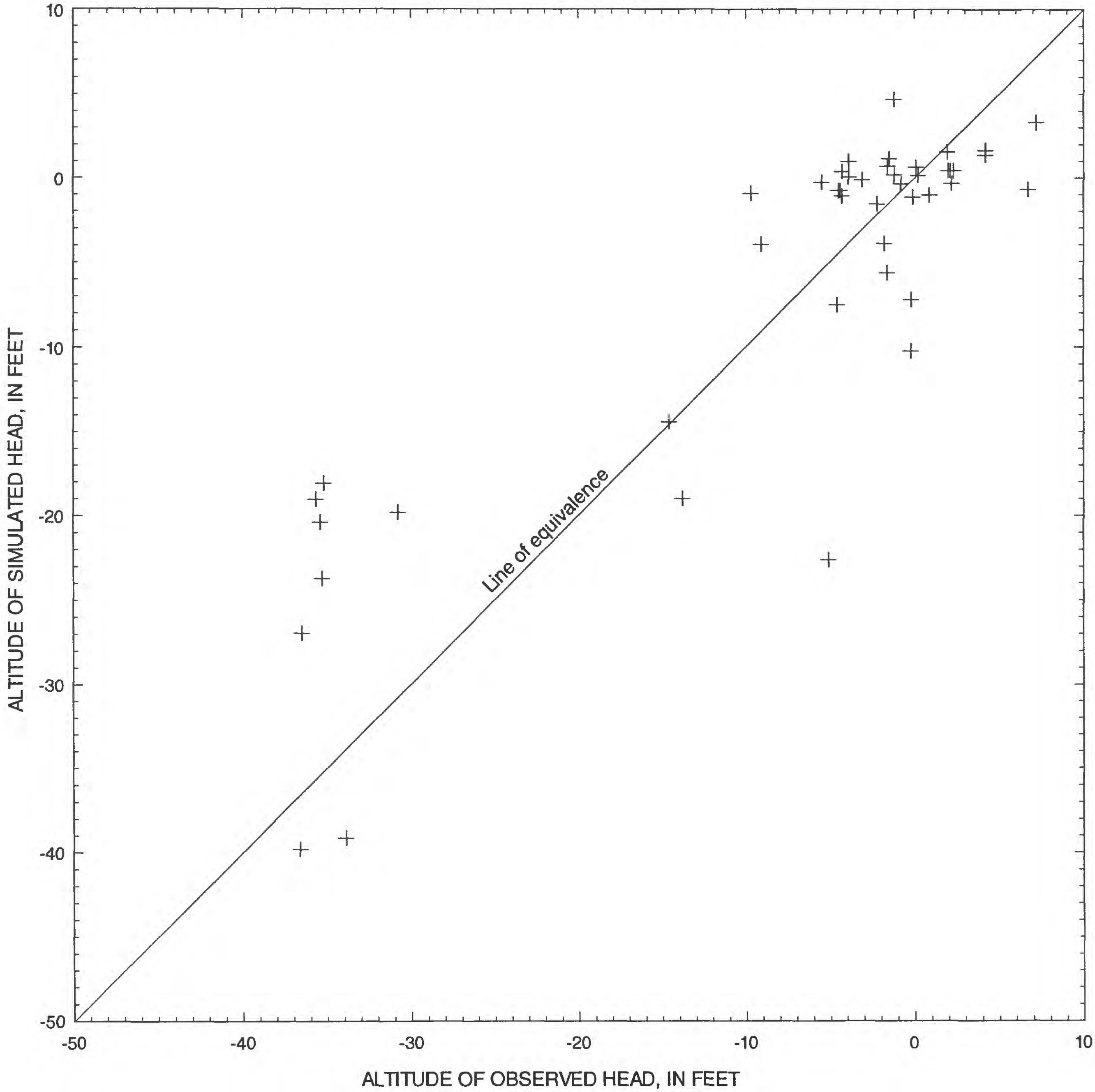


Figure 14.-- Relation between ground-water heads simulated by calibrated model and observed heads (Observed heads are from table 1).

Effects of Model Boundaries

The effects of the no-flow boundary conditions at the perimeter boundaries of the model on simulated discharges to dry docks and on ground-water heads was investigated by comparing simulations produced by the calibrated model with no-flow boundaries and simulations produced by a model with heads specified at the areal boundaries (both terrestrial and marine). The heads specified at these boundaries were set equal to heads simulated with a version of the calibrated model (with no-flow boundaries), which was modified by removing the dry-dock drains, shoreline bulkheads and sheet-pile cutoff walls. These features were removed by setting the altitudes of the dry-dock drains to sea level and the bulkhead coefficients to unity, and by removing the horizontal-flow barriers. Simulated flows across the boundaries of the model with these specified heads are larger than they would be in a model with correct (actual but unknown) boundary conditions, whereas the zero flows across the no-flow boundaries are smaller than the correct boundary flows. Therefore, dry-dock discharges and ground-water heads simulated by a model with correct boundary conditions should be between those simulated by the models with no-flow and specified-head boundary conditions.

The differences between total combined ground-water discharges to all the dry docks and to individual dry docks that are simulated by the models with no-flow and specified-head boundaries are less than 7 percent (table 4), which implies that the type of boundary conditions had little effect on simulated discharges to dry docks. (It was not possible to calculate separately the fresh and saline water discharges to the dry docks that are simulated by the model with specified-head boundaries.) Although the heads on the boundaries of the model with specified heads (not shown) are as much as 8 ft higher than those simulated by the model with no-flow boundaries, heads in the area of the shipyard that are simulated by the model with specified-head boundaries are only about 2 ft higher than corresponding heads simulated by the model with no-flow boundaries (fig. 15). The simulated flows at the specified-head boundaries are 3.5 ft^3/s into the model and 0.3 ft^3/s out of the model (table 5).

The effect of the assumed no-flow boundary condition on the model's bottom boundary could not be evaluated directly because there was very little simulated ground-water flow in the bottom layer of the model (layer 14), which is about 1,500 ft thick in many places. However, removing this layer from the model and specifying a no-flow boundary condition at the bottom of layer 13 (altitude -150 ft) had very little effect on either simulated discharges to dry docks or ground-water heads.

Table 5.--*Simulated volumetric budgets for calibrated model with no-flow boundaries and modified model with specified-head areal boundaries*

[Values in cubic feet per second; --, not applicable]

Component	Calibrated model with no-flow boundaries	Modified model with specified-head boundaries
Recharge from precipitation	4.1	4.1
Discharge to dry docks	8.6	9.0
Discharge to Puget Sound	1.3	1.7
Discharge from Puget Sound	5.7	4.0
Discharge from specified-head boundaries	--	3.5
Discharge to specified-head boundaries	--	0.3

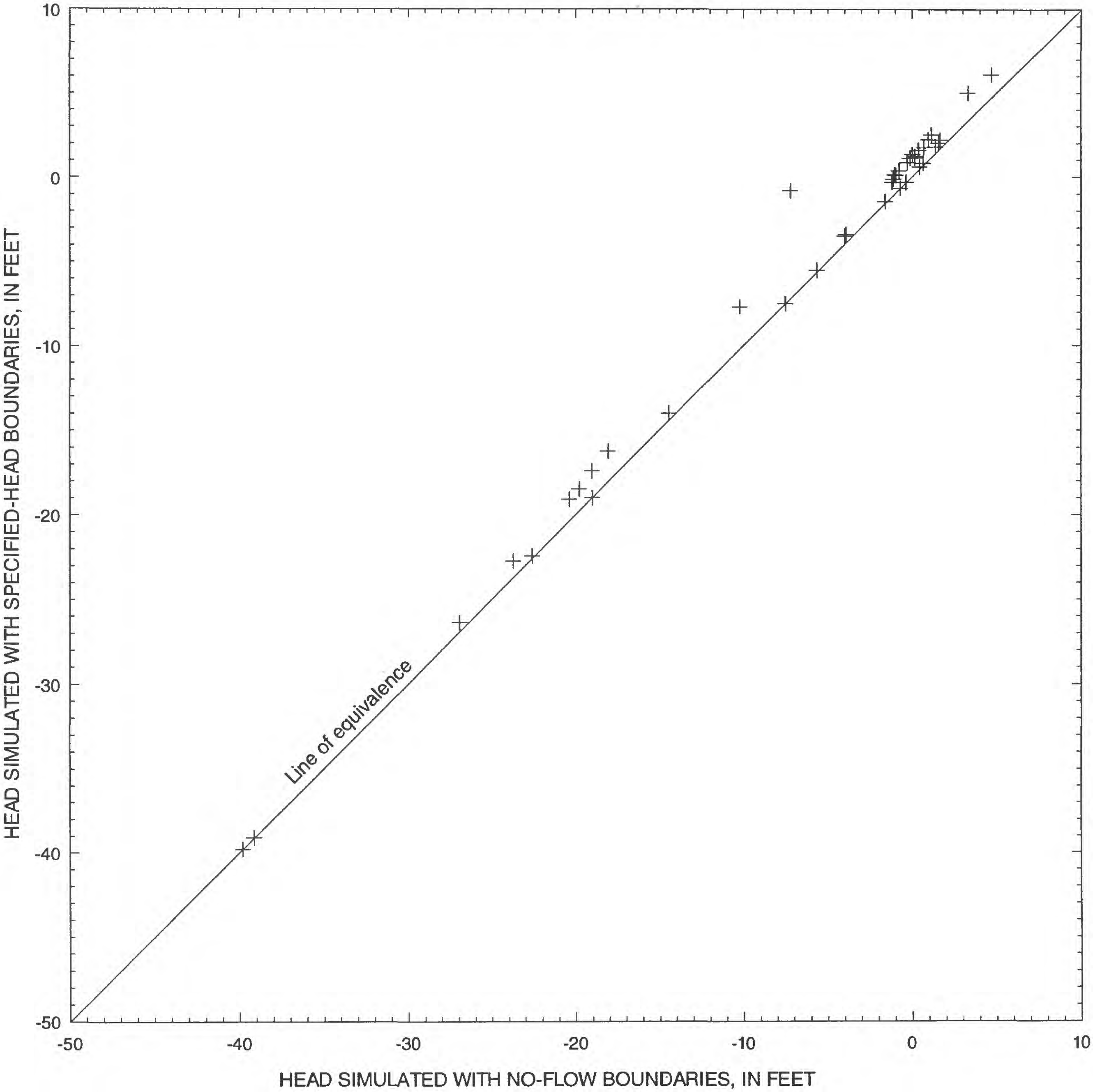


Figure 15.-- Relation between ground-water heads at selected observation wells at shipyard simulated by model with specified-head boundaries and those simulated by model with no-flow boundaries.

DISCHARGE LOCATIONS OF GROUND WATER FLOWING THROUGH THE SHIPYARD

Ground-water flows and heads that were simulated by the calibrated model with no-flow boundary conditions were used as input data to the set of programs MODPATH and MODPATH-PLOT (Pollock, 1994) to calculate and display the flow paths of ground water as it moves through the shipyard. Figure 16 is an example of the output from MODPATH and MODPATH-PLOT showing selected flow paths originating at an altitude of -20 ft (center of model layer 5). Output from these programs was used to construct maps showing discharge locations of hypothetical particles that originate at the centers of model cells in eight of the model layers beneath the shipyard and move with the ground-water (fig. 17). Altitudes of the centers of these cells range from 6 to -70 feet. Simulations indicate that nearly all ground water flowing through the shipyard discharges to the drainage systems of the dry docks.

Before the results shown on fig. 17 are discussed, a few words of caution and explanation are in order. First, the flow model used in this study is steady-state and does not simulate the reciprocating tidal exchange of water between Sinclair Inlet and the ground-water system near the shoreline. Consequently, although fig. 17 may show that particles originating very near the shore discharge to a dry dock, some of these particles probably discharge to Sinclair Inlet when the tide is low. Secondly, the accuracies of the positions of boundaries between zones that discharge to different locations depend on the accuracy of the flow model. Although the model simulated the total ground-water discharge to dry docks fairly well, the observed distribution of discharge among the dry docks was not simulated well (table 4). Consequently, the actual zones for discharge to DD-6 are probably larger than shown on fig. 17 and the zones for DD-1, 3, 4 and 5 are probably smaller than shown. Also, because no simulated discharge was permitted to DD-2, fig. 17 shows no zone for this dry dock even though one should exist. However, the zone for this dry dock is probably very small because the observed fresh-water discharge to DD-2 was only 0.02 ft^3/s. The reader should also be aware that when a particle is described as originating at a particular location, it is not intended to mean that that location is the source of water to the ground-water system. In most cases the water only passes through that location; nothing is implied about the source of the water.

Although ground water flowing through the west end of the shipyard at altitudes below about -30 ft discharges to DD- 6 (fig. 17d), ground water flowing at altitudes above about -20 ft discharges to Sinclair Inlet (fig. 17c). All dry docks receive some discharge of some ground water from altitudes above about -30 ft; however, ground water from altitudes -40 ft and below discharges only to the deeper dry docks. For example, ground water flowing at -40 ft discharges only to DD-1, 4, 5 and 6, but not to DD-3, the shallowest of the dry docks; and ground water at -70 ft discharges only to DD-4, 5 and 6. These results imply that most ground water that is transporting contaminants at the shipyard would discharge to the drainage system of one of the dry docks and would not discharge directly into Sinclair Inlet.

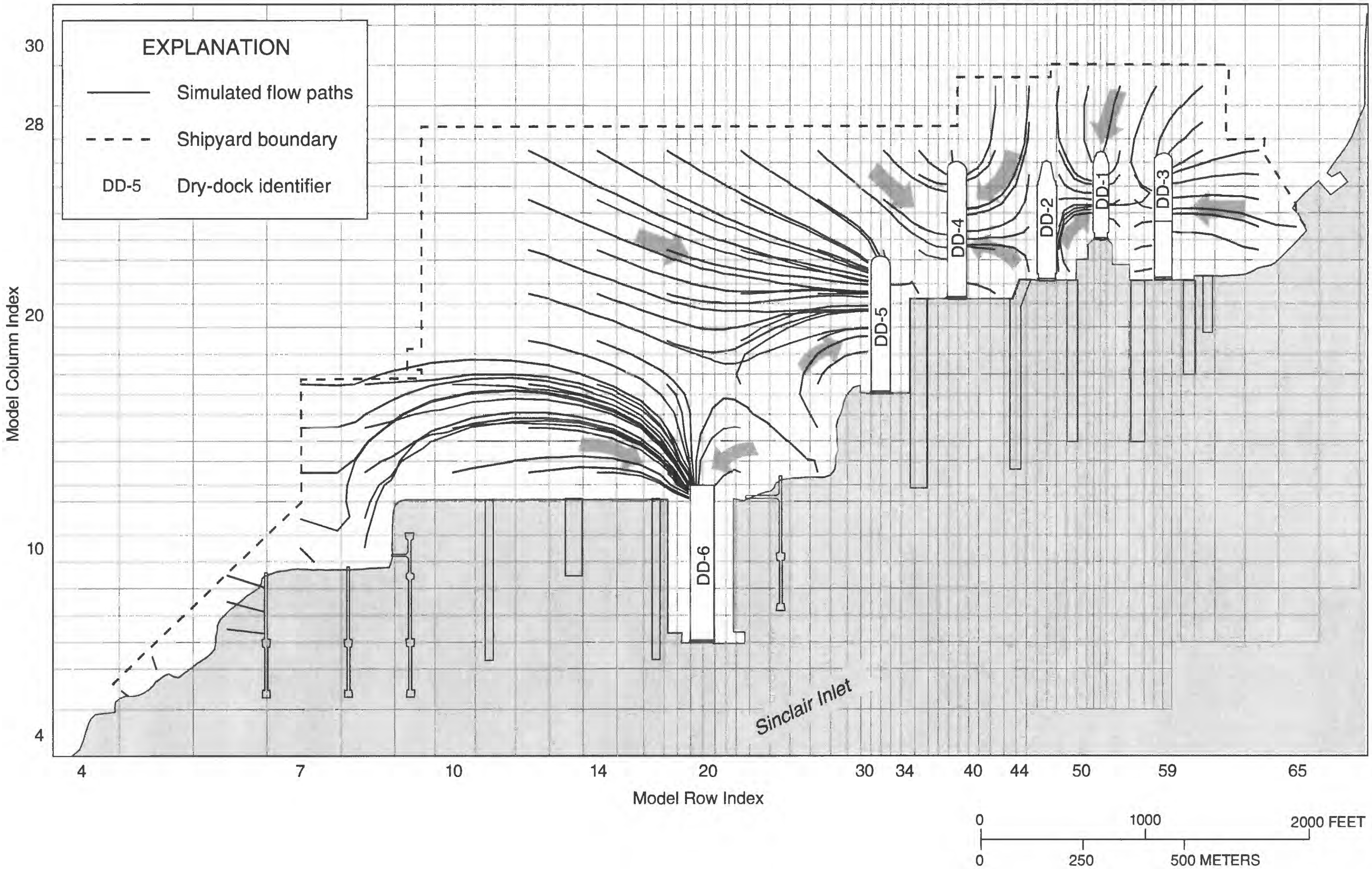


Figure 16.-- Simulated flow paths of selected particles originating beneath the shipyard at an elevation of -20 feet.

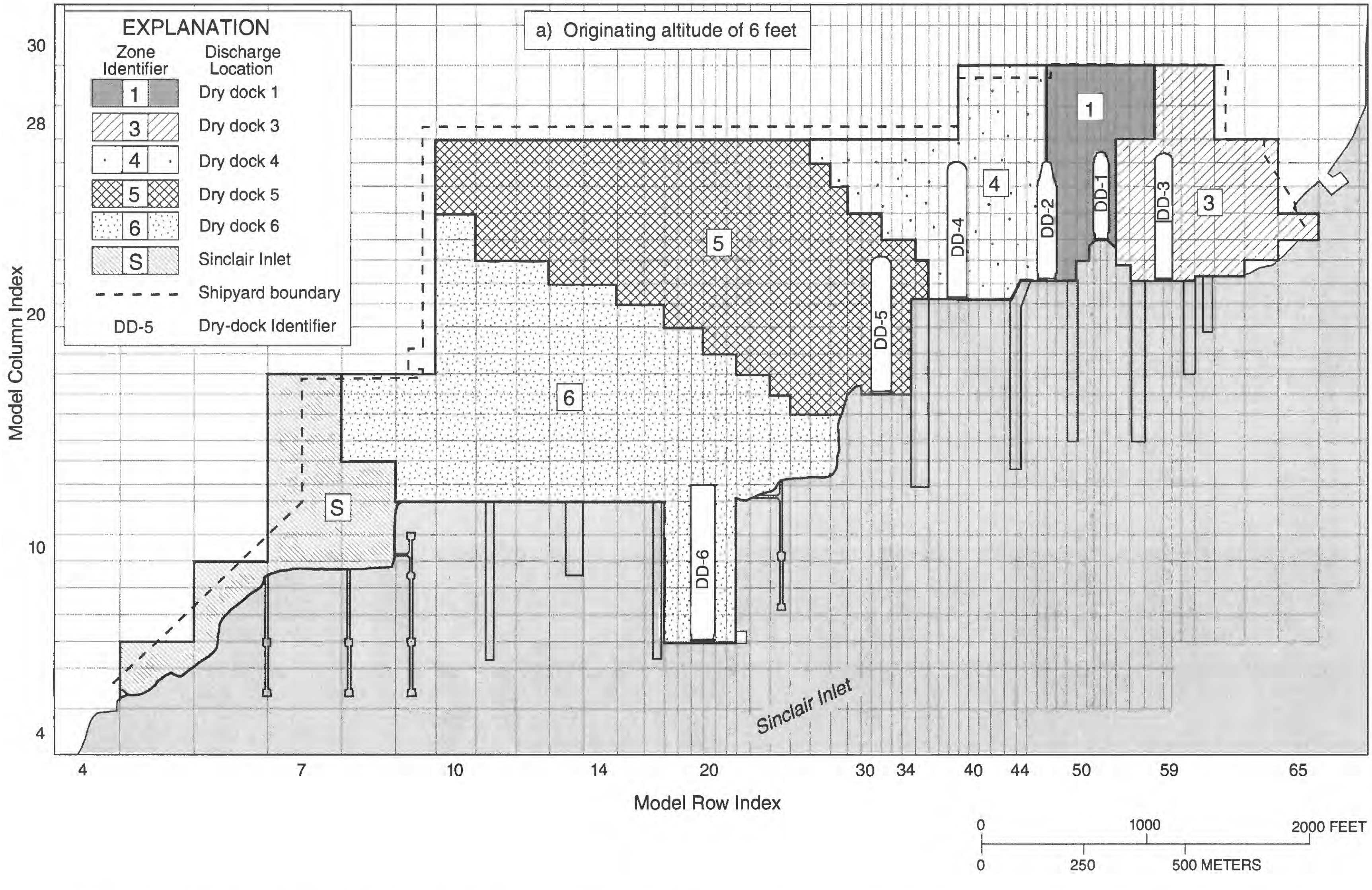
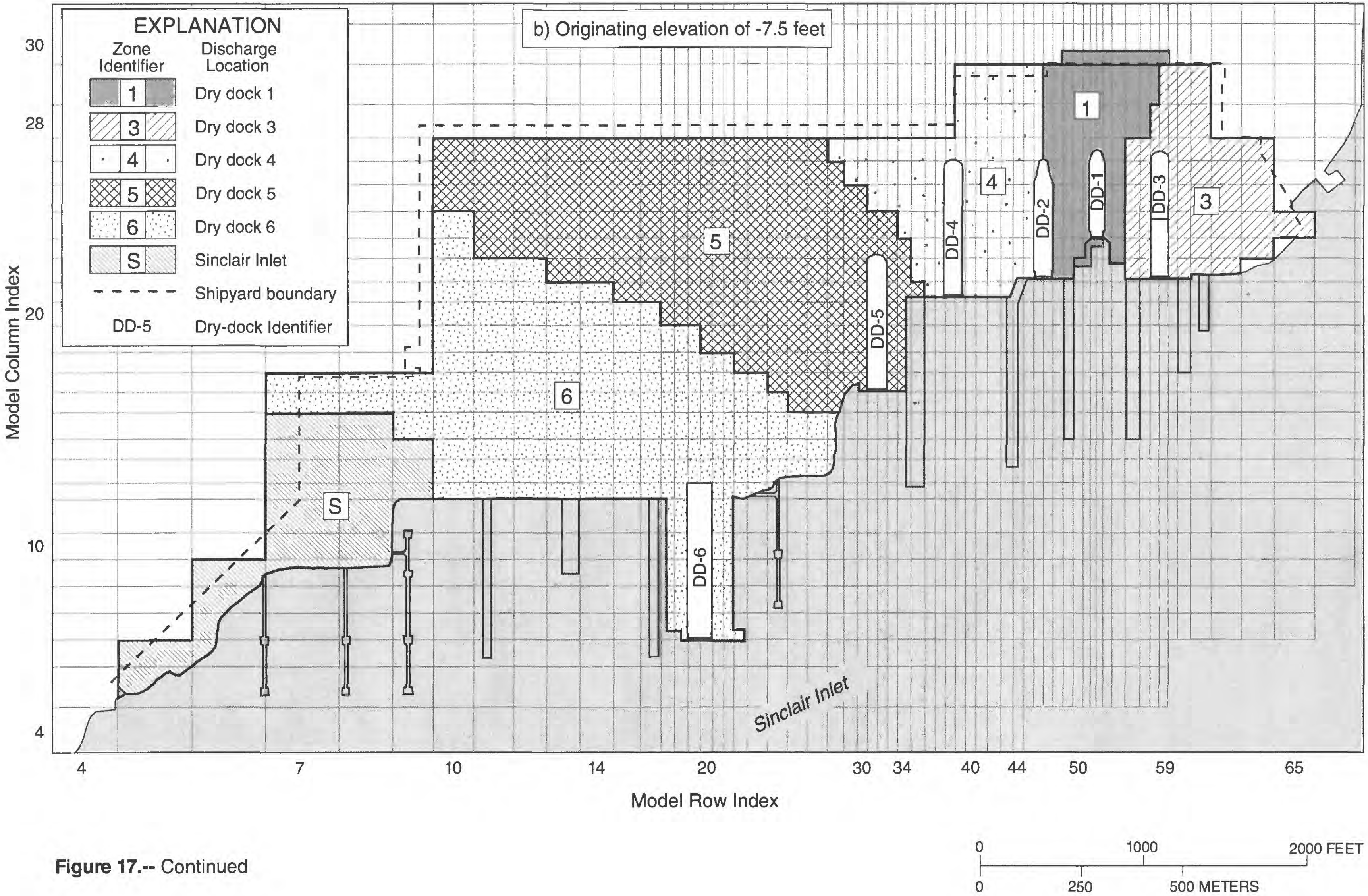


Figure 17.-- Discharge locations of particles originating in different areas and at different elevations beneath the shipyard. Zones designate areas with common discharge locations. Different maps show zones for particles originating at different elevations.



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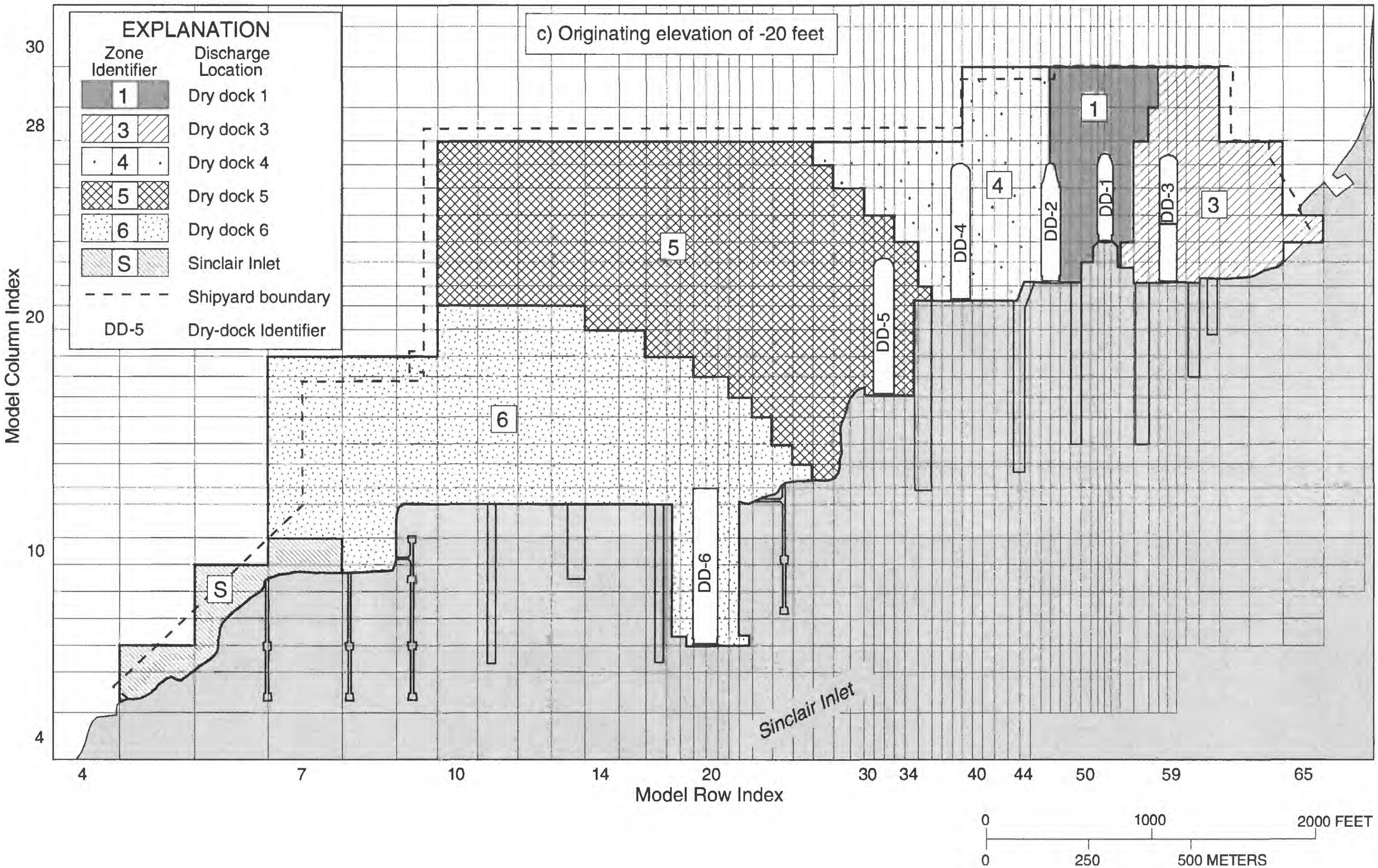

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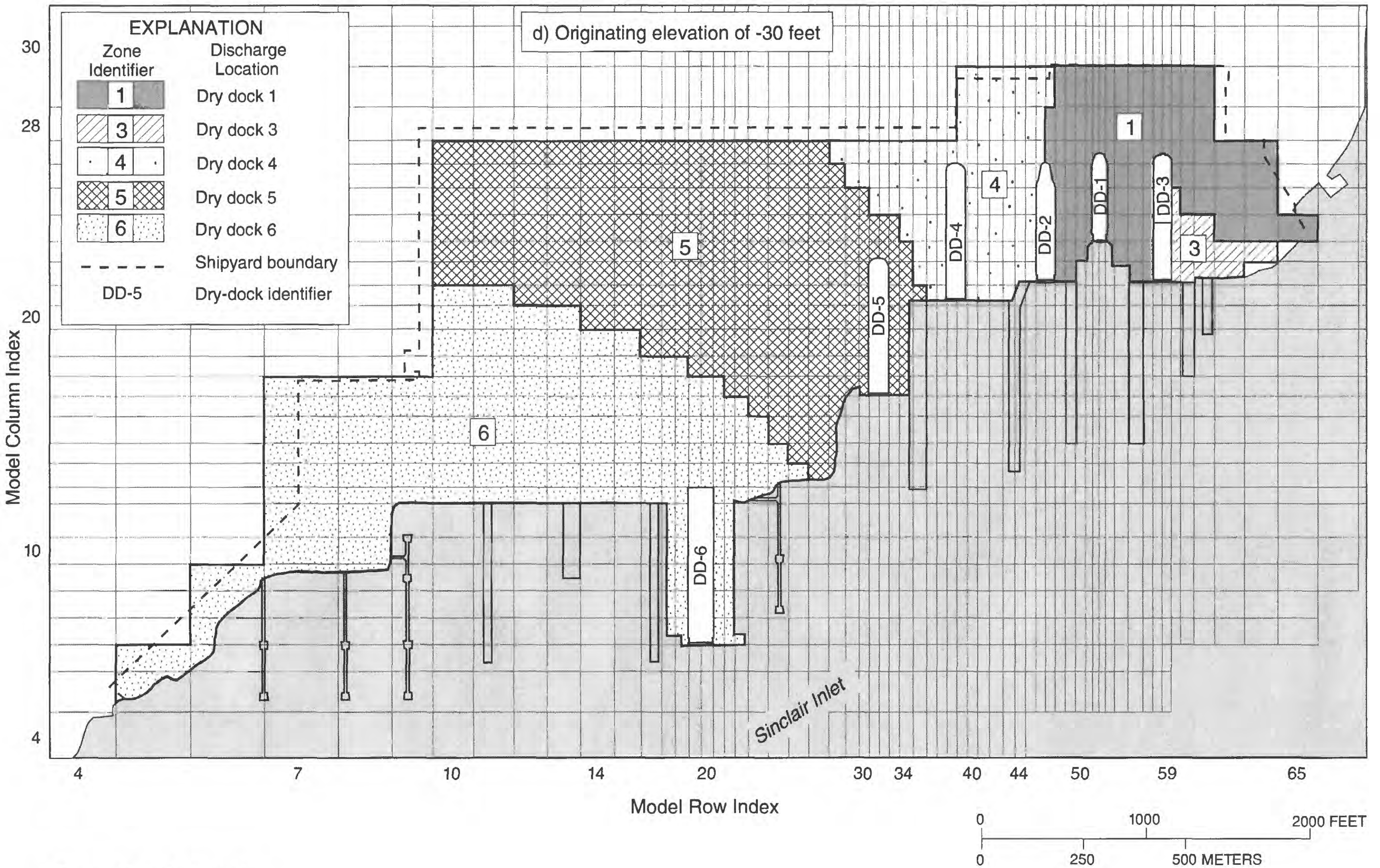
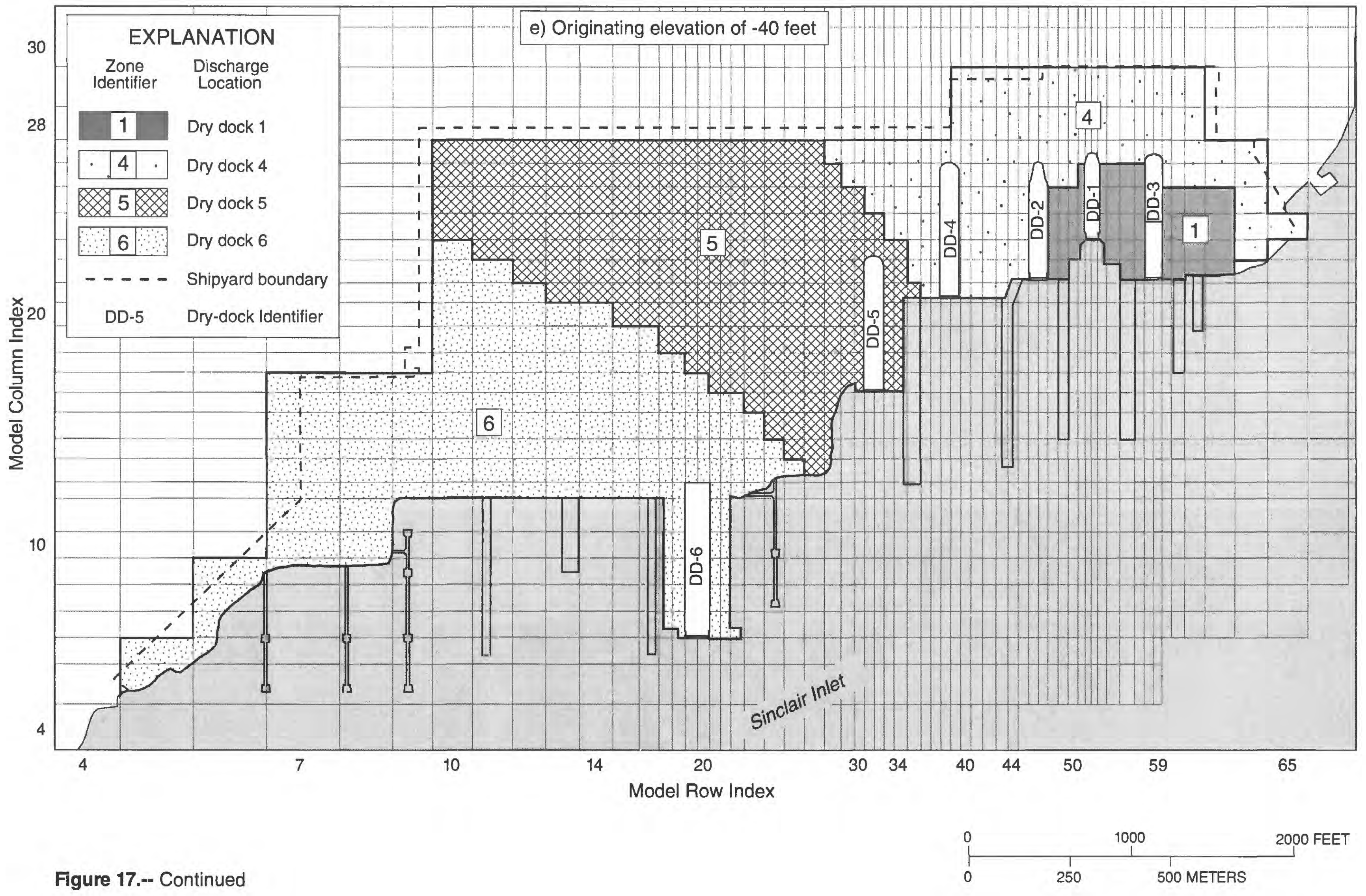


Figure 17.-- Continued



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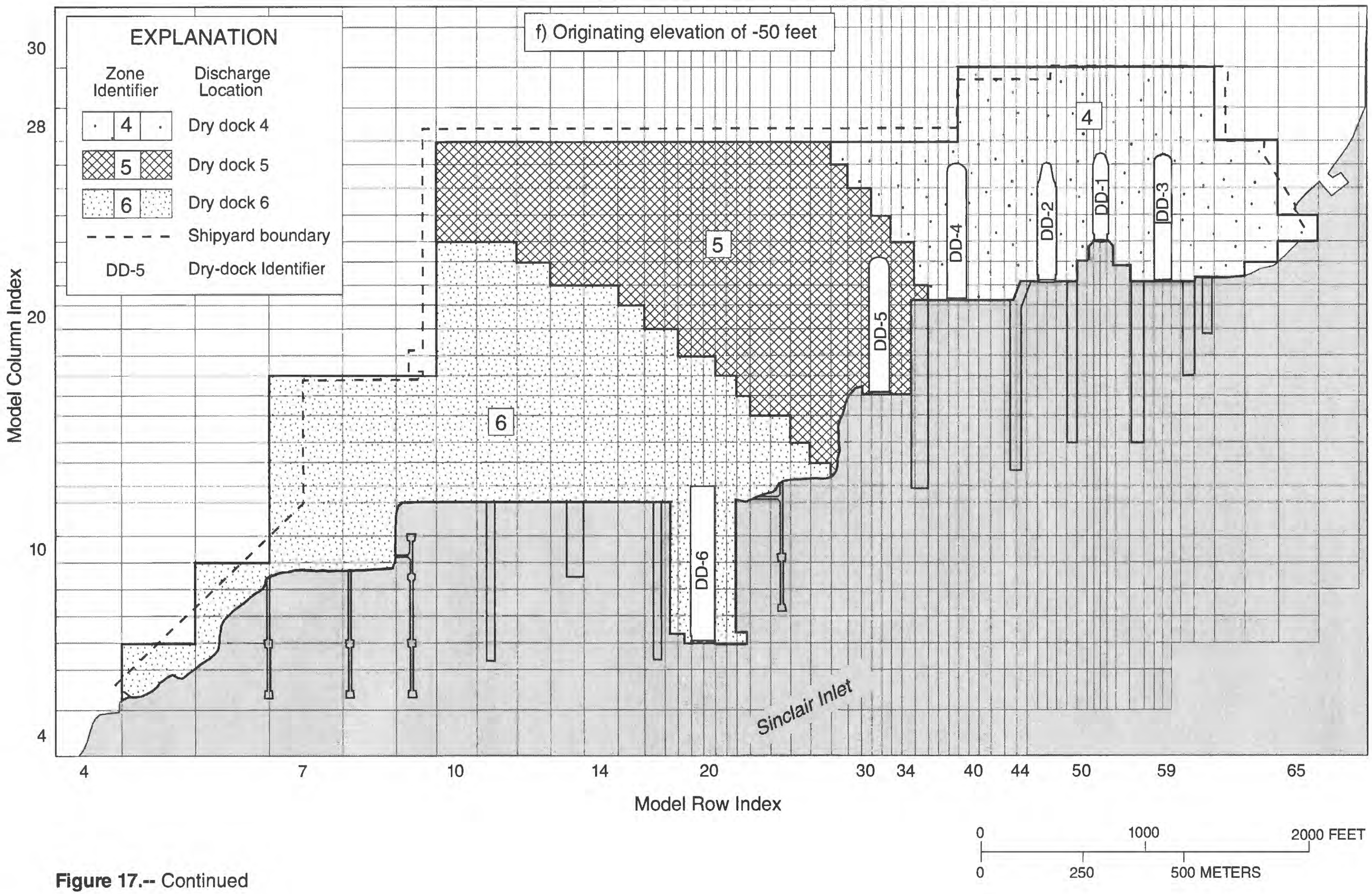

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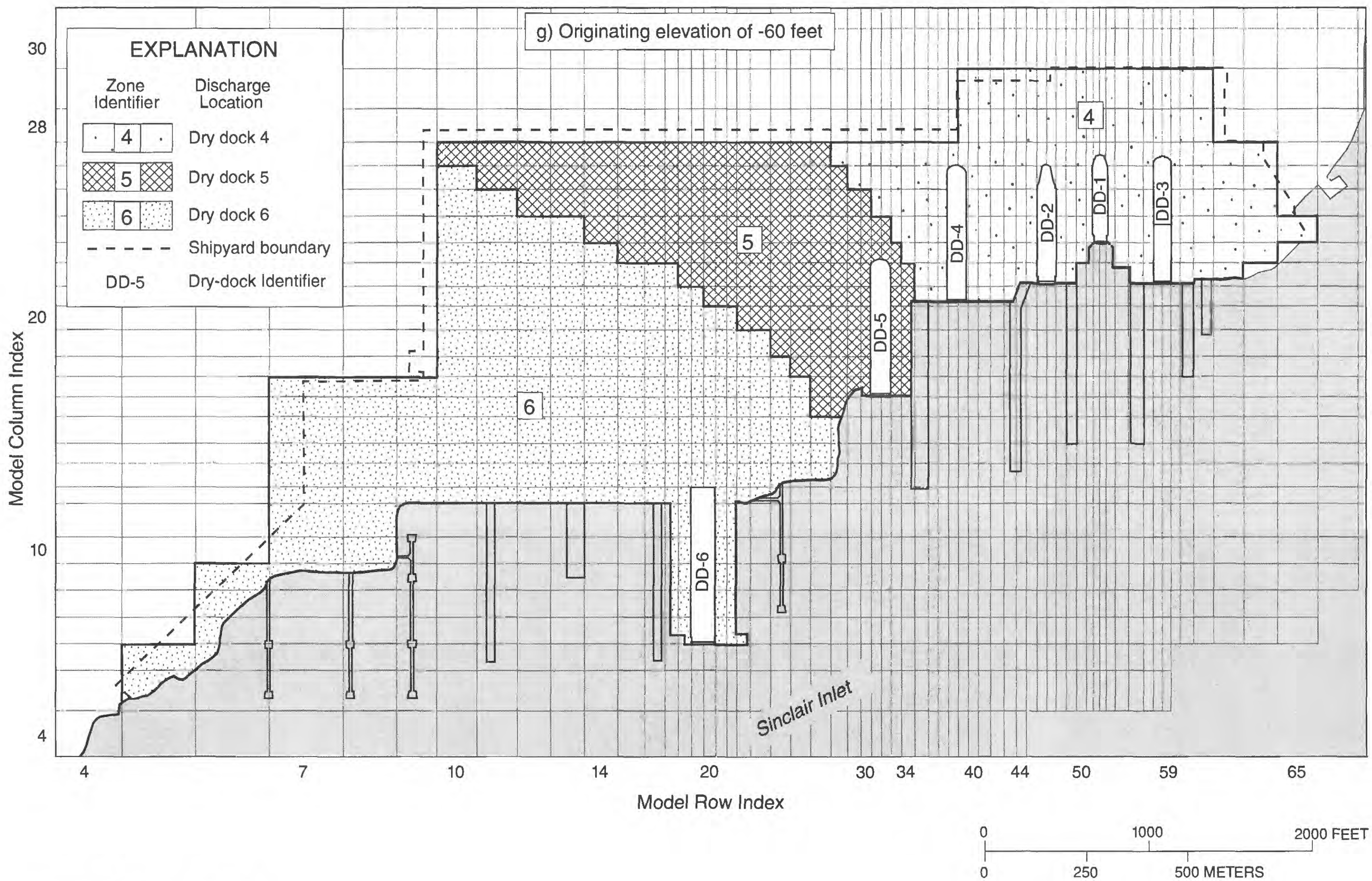

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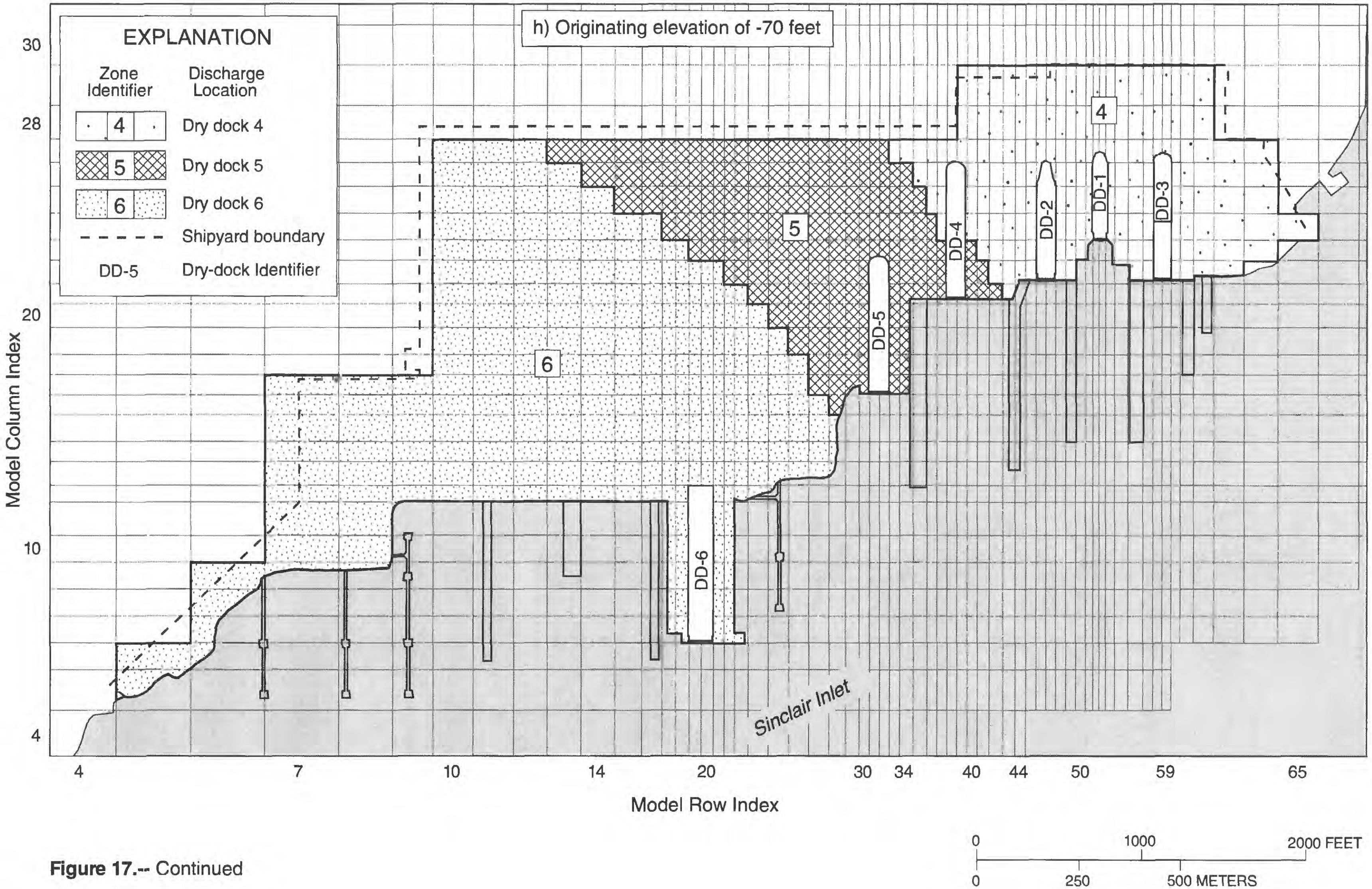

Figure 17.-- Continued

SUMMARY AND CONCLUSIONS

Puget Sound Naval Shipyard is located on the north shore of Sinclair Inlet of Puget Sound. Concentrations of some metals and organic compounds in some of the soil and ground water at the shipyard exceed regulatory limits, and there is concern that ground water may be transporting some of the contaminants from the shipyard into Sinclair Inlet. Consequently, the U.S. Navy and their consultants are conducting investigations to determine the transport and fate of contaminants beneath the shipyard. Information from these investigations will be used to decide if and where environmental remediation work is necessary and to plan the work. The purpose of the investigation described in this report was to obtain information on flow paths and discharge locations of ground water at and near the shipyard, and more specifically, to determine if ground-water from different locations beneath the shipyard discharges directly into Sinclair Inlet or to the drainage system of one of the shipyard's six dry docks.

A steady-state, multilayer numerical model for simulating the flow of ground water of uniform density was constructed of the shipyard and surrounding area. The model simulated ground-water discharge to the dry-dock drainage systems and to Sinclair Inlet and other parts of Puget Sound. The model also simulated the effects on ground-water flow of sheet-pile cutoff walls beneath the dry docks and of shoreline bulkheads. In the model the hydraulic characteristics of subsurface materials--fill beneath much of the shipyard and glacial and interglacial sediments beneath the fill and most of the surrounding area--were assumed to be uniform, both areally and with depth. Estimated fresh ground-water recharge to the modeled area (all from precipitation) was 4.1 cubic feet per second, which is only about one-third greater than measured fresh ground-water discharge to the dry docks (3.1 cubic feet per second).

The model was calibrated by adjusting values of horizontal and vertical hydraulic conductivities of subsurface materials and values of leakage coefficients for the sheet-pile cutoff walls and shoreline bulkheads to obtain agreement between simulated and observed ground-water levels in the shipyard, total fresh ground-water discharge to the dry docks, and total saline ground-water discharge to the dry docks. Values of horizontal and vertical hydraulic conductivities obtained by model calibration equaled 10^{-3} and 10^{-7} feet per second, respectively. The former value is probably representative of the top 50 feet of sediments at the shipyard, much of which is fill, but probably is not representative of the deeper sediments beneath the shipyard or the fine-grained glacial and interglacial sediments in the surrounding area. Values of leakage coefficients obtained by calibration indicate that the flow though the shoreline bulkheads and sheet-pile cutoff walls is about 2 percent of the flow that would occur if they were not there and if the hydraulic gradients were the same. Simulated ground-water levels were in fair agreement with measured water levels, and simulated total fresh and saline water discharges to the dry docks were in good agreement with observed discharges; however, the simulated distribution of ground-water discharge to the individual dry docks did not agree well with the observed distribution of discharge.

Simulated ground-water flow paths indicate that ground water flowing beneath nearly all but the western end of the shipyard discharges to the dry-dock drainage systems. Only shallow ground water beneath the western end of the shipyard discharges directly to Sinclair Inlet. This result implies that most transportable contaminants in ground water beneath the shipyard are transported to the dry-dock drainage systems and do not discharge directly into Sinclair Inlet.

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