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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

IMPACT OF CHANGES IN LAND USE ON THE GROUND-WATER SYSTEM IN THE SEQUIM-DUNGENESS PENINSULA, CLALLAM COUNTY, WASHINGTON

By B. W. Drost

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS
REPORT 83-4094

Prepared in cooperation with the
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UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

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METRIC CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
	2.540	centimeter (cm)
	0.0254	meter (m)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per day per foot [(ft/d)/ft)]	0.3048	meters per day per meter [(m/d)/m]
micromho per centimeter at 25° Celsius (umhos/cm at 25°C)	1.000	microsiemen per centimeter at 25° Celsius (uS/cm at 25°C)

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 "Mean Sea Level." NGVD of 1929 is referred to as sea level in this report.

GLOSSARY

Aquifer - A formation, group of formations, or part of a formation that contains sufficient permeable material to yield significant quantities of water to wells.

Artesian aquifer - An aquifer in which water levels in wells stand above the top of the aquifer.

Confining bed - A body of relatively impermeable material separating two aquifers.

Evapotranspiration - The process by which water is lost from the earth's surface to the atmosphere by evaporation from surface-water bodies and transpiration by plants.

Head - The altitude of a water level in a well tapping an aquifer.

Hydraulic conductivity - The volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient - The change in water level in wells tapping an aquifer per unit of distance in a given direction.

Specific capacity - The rate of discharge of water from a well divided by the drawdown of water level in the well.

Specific yield - The ratio of (1) the volume of water which an aquifer will yield by gravity to (2) the volume of the aquifer.

Storage coefficient - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in water levels in wells tapping the aquifer.

Transmissivity - The rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

IMPACT OF CHANGES IN LAND USE ON THE GROUND-WATER SYSTEM IN THE SEQUIM-DUNGENESS PENINSULA, CLALLAM COUNTY, WASHINGTON

By B. W. Drost

ABSTRACT

In the Sequim-Dungeness peninsula, Clallam County, Washington, leakage from irrigation ditches is the most important source of ground-water recharge. Possible future land-use changes could lead to termination of the irrigation system. This would result in lower heads throughout the ground-water system, that could lead to well failures, increased pumping costs, seawater intrusion, and water-quality degradation. A digital-computer model was developed to simulate three-dimensional ground-water flow in aquifers underlying the peninsula in order to assess the impact of termination of the irrigation system. After 10-20 years of no irrigation, the model predicts that the water level in the water-table aquifer would have average declines of about 20 feet, some areas would become completely unsaturated, several hundred wells could go dry or nearly so, and leakage from the Dungeness River would become the major source of ground-water recharge.

As of June 1980, ground-water quality in the study area has apparently not been affected by the use of on-site domestic sewage-disposal systems. The median nitrate-plus-nitrite (as N) concentration in the water-table aquifer was 0.35 milligrams per liter, and the maximum concentration was 2.5 milligrams per liter.

INTRODUCTION

Some of the oldest developed areas in western Washington are in Clallam County, but in recent years the pattern of development has undergone a dramatic change. Much of the land, especially in northeastern Clallam County, that was originally used for irrigated agriculture has been subdivided for residential use. This change in land and water use has caused changes in the stresses on the ground-water and surface-water systems. It has also increased the potential for contamination of the ground-water system by the increased use of on-site domestic sewage-disposal systems.

Purpose and Scope

In 1978, the U.S. Geological Survey, in cooperation with the State of Washington Department of Ecology and the Board of Clallam County Commissioners, began a study that would (1) make a general assessment of the water resources of the developed areas of the county, (2) identify present and potential water-resource problems in these areas, and (3) make in-depth analyses of selected problem areas. The first two items have been completed and documented in a forthcoming report by Drost.

This report deals exclusively with a selected problem area, the Sequim-Dungeness peninsula (fig. 1). In the only previous investigation of the ground-water resources of the study area, a reconnaissance-type study conducted during July-September 1960 (Noble, 1960), Noble concluded that, "An important secondary source of recharge (to the ground-water system) is directly from irrigation." This conclusion caused concern when land-use trends began to indicate a possible future decrease in irrigation. A decrease in recharge would lead to lower heads in the ground-water system, which could result in well failures, increased pumping costs, seawater intrusion, and degradation of water quality. The purpose of this study was to examine the effect of decreased irrigation and increasing use of septic systems on aquifers underlying the Sequim-Dungeness peninsula.

A computer model is used in this report to simulate three-dimensional ground-water flow in the aquifers and to estimate the possible future effects on the ground-water system of possible changes in land use and irrigation practices. The potential effects of these changes on ground-water quality are also discussed.

Most of the data used in constructing the model were collected by the U.S. Geological Survey, the State of Washington Department of Ecology (WDOE), and the Clallam County Departments of Health and Public Works, during the period September 1978 to September 1980. These data include (1) monthly water-level measurements in about 65 wells, (2) daily staff-gage readings at 10 surface-water sites, (3) a continuous record of discharge at one surface-water site, (4) monthly discharge measurements at 20 surface-water sites, (5) surveyed land-surface altitudes at about 75 sites, (6) drillers' records of about 1,400 wells, and (7) chemical analyses of about 170 ground- and surface-water samples collected during the period June 16-19, 1980. Most of these data are contained in a forthcoming report by Drost, and the remainder are available in the files of the U.S. Geological Survey, Tacoma, Washington. Additional data were obtained from a 1981 study by N. P. Dion and S. S. Sumioka (U.S. Geological Survey), Dion and Sumioka (1981), and from Grimstad and Carson (1981), Noble and Balmer (1980), and Walters (1971).

Description of the Study Area

The Sequim-Dungeness peninsula is an area of about 60 square miles in northwestern Washington (fig. 1). The peninsula extends into the Strait of Juan de Fuca to the north and is bounded on the south by the foothills of the Olympic Mountains.

The area has been extensively irrigated since about 1896 with water from the Dungeness River, which originates in the mountains to the south and flows through the middle of the area. Prior to irrigation, the area was sparsely vegetated and was subject to dry and barren summers (Keeting, 1976). As of 1960, the area was used primarily for agriculture, and supported a population of about 5,000 people. In the mid-1960's, land use in the area began shifting from agriculture to residential, resulting in population increases to about 7,000 in 1970 and 12,000 in 1980.

Acknowledgments

The cooperation and assistance provided by Mr. and Mrs. Norman Siebens in daily monitoring of the staff-gage network is gratefully acknowledged. Mr. Valier Stoican of Stoican Drilling Co., Inc., assisted the study by providing drillers' logs and location information on several hundred wells. Many local residents were especially helpful by providing access to their wells for water-level measurements and water-quality sampling.

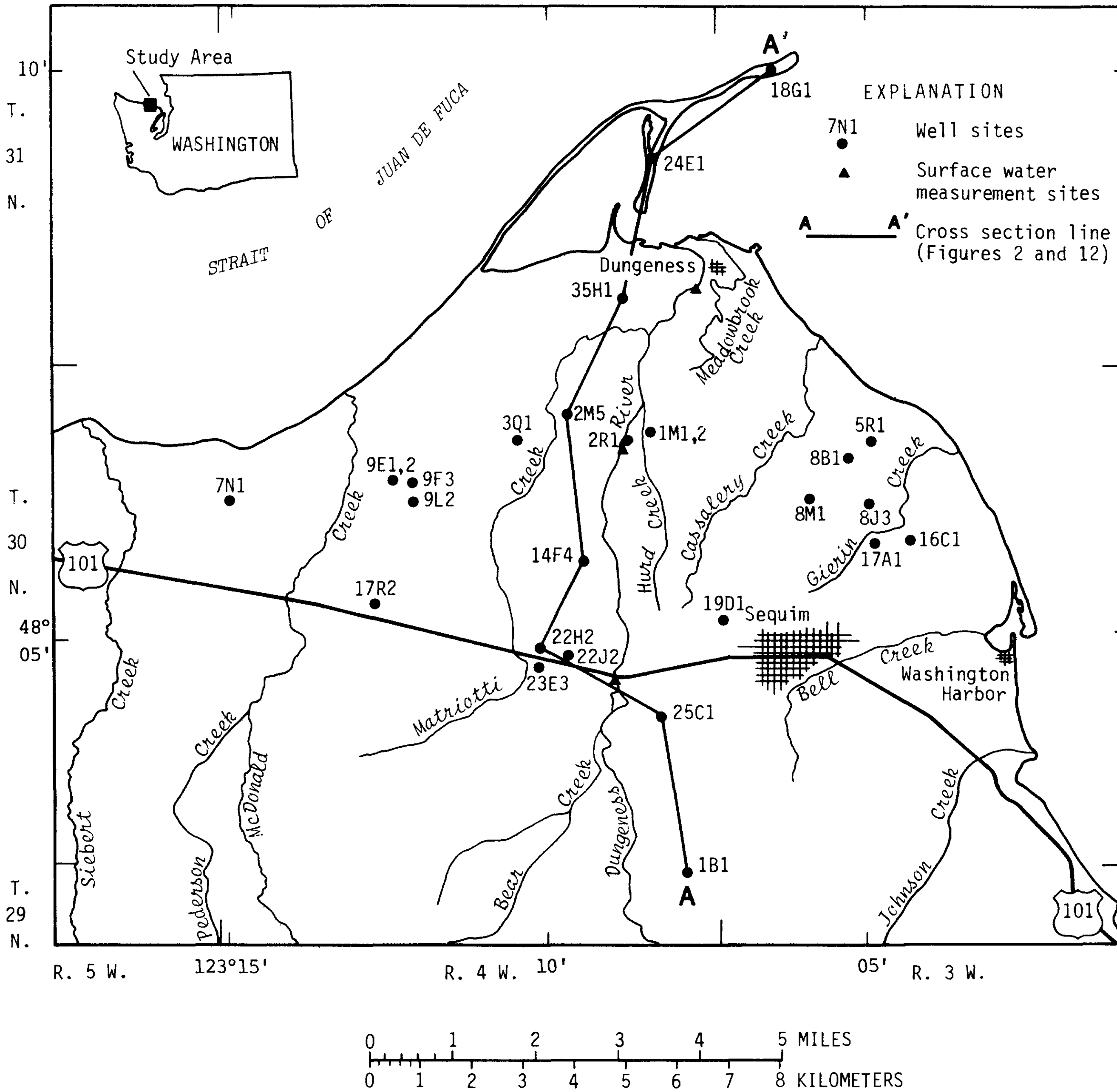
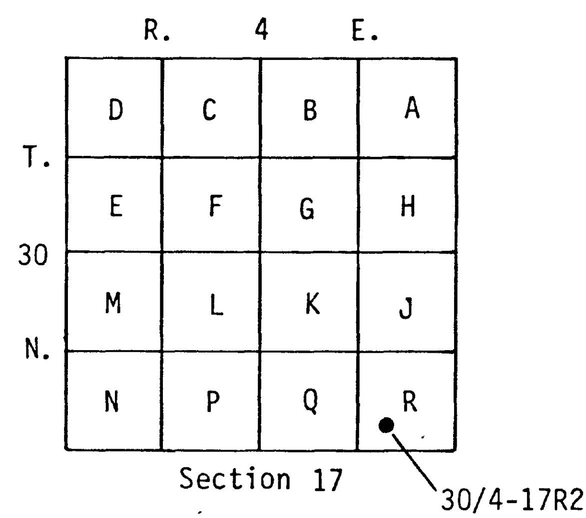


FIGURE 1.--Location of the study area.

Numbering System for Wells

Wells in Washington are assigned numbers that identify their location in a township, range, and section. Well number 30/4-17R2 indicates, successively, the township (T.30 N) and range (R.4 W.) north and west of the Willamette base line and meridian; the letters indicating north and west are omitted. The first number following the hyphen indicates the section (17) within the township, and the letter following the section gives the 40-acre subdivision of the section, as shown below. The number following the letter is the serial number of the well within the 40-acre subdivision.



HYDROGEOLOGY

Setting

The surficial sediments in the study area are mostly unconsolidated glacial, alluvial, and glaciomarine deposits (Othberg and Palmer, 1980a, b, and c). Mudstones, siltstones, and some sandstones are exposed at Bell Hill, just south of the study area (Tabor and Cady, 1978), and probably underlie the unconsolidated deposits beneath most of the study area. The consolidated rocks, when compared (using specific-capacity data) with the unconsolidated deposits, are impermeable and are treated as the base of the ground-water system in parts of the study area.

The unconsolidated deposits were divided into geohydrologic units on the basis of examination of more than 1,100 drillers' logs. Three aquifers and two confining beds were identified and are shown in figure 2. The aquifers are composed of sand and gravel, with some till, silt, and clay. In the upland regions where it directly overlies bedrock, the water-table aquifer is composed largely of till and clay, with minor amounts of sand and gravel.

The water-table aquifer includes at least seven geologic units identified by Othberg and Palmer (1980a, b, and c)—alluvium, older alluvium, Everson glaciomarine drift, Everson sand, Vashon recessional ice-contact and outwash deposits, Vashon till, and Vashon advance outwash, all of Quaternary age. The artesian aquifers apparently are not exposed in the study area, and were not described by Othberg and Palmer (1980a, b, and c).

The confining beds are composed of clay, silt, and till, with minor inclusions of sand in thin, discontinuous beds. The upper confining bed may correspond, at least in part, to the pre-Vashon silts and clays of Othberg and Palmer (1980a, b, and c), but the lower confining bed was not described in their report.

Data on the deeper unconsolidated materials were not sufficient to allow identification of individual units. There is at least one more aquifer within the deeper unconsolidated materials, and there may be several more. The deeper unconsolidated materials are treated as the base of the ground-water system in parts of the study area.

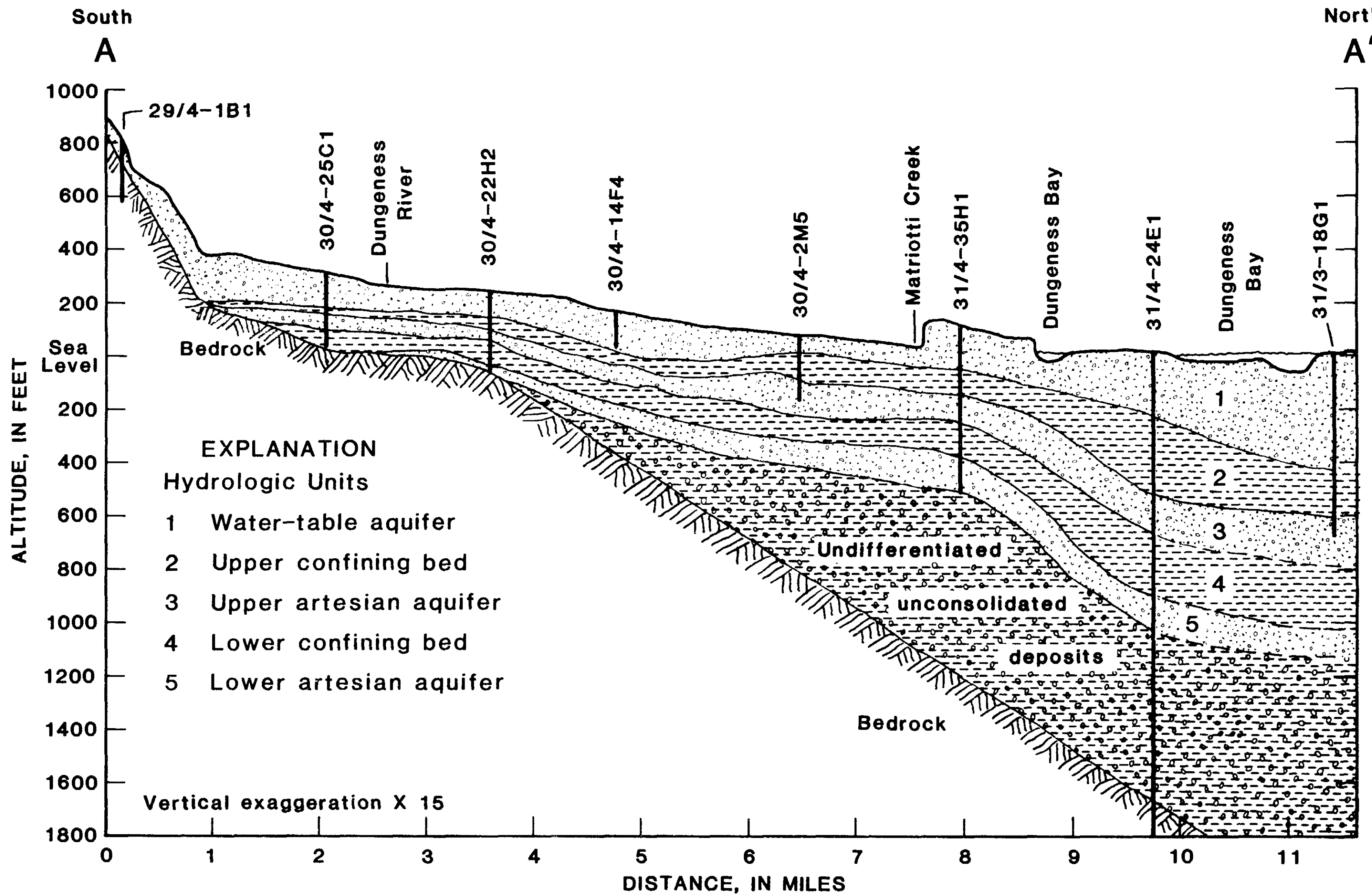


FIGURE 2.--Schematic cross section of the ground-water system of the study area.

Geometry of the Aquifers and Confining Beds

The water-table aquifer extends throughout the study area. The altitude of the bottom of this aquifer was determined from drillers' logs, and is shown in figure 3. The saturated thickness of the aquifer can be calculated by using this figure along with the altitude of the water table for March 1979 (fig. 4).

The upper confining bed underlies the water-table aquifer and overlies the upper artesian unit. The confining bed varies in thickness from about 1 foot to over 200 feet, but is between 25 and 75 feet thick throughout much of the study area (fig. 5).

The upper artesian aquifer is present in only part of the study area (fig. 6). Where present, its thickness ranges from a few feet to more than 100 feet and averages about 75 feet. In the foothill region in the southern part of the study area the upper artesian aquifer is absent and the water-table aquifer directly overlies bedrock or the upper confining bed. Only a few wells penetrate the entire thickness of the upper artesian aquifer; therefore, figure 6 shows only an approximation of the aquifer's actual thickness.

The lower confining bed is located between the upper and lower artesian aquifers. Very few wells penetrate the entire thickess of the confining bed. Figure 7 shows the approximate thickness of the bed.

The lower artesian aquifer covers a slightly smaller area than the upper artesian aquifer. The thickness of the lower artesian aquifer was not mapped because the existing data were insufficient.

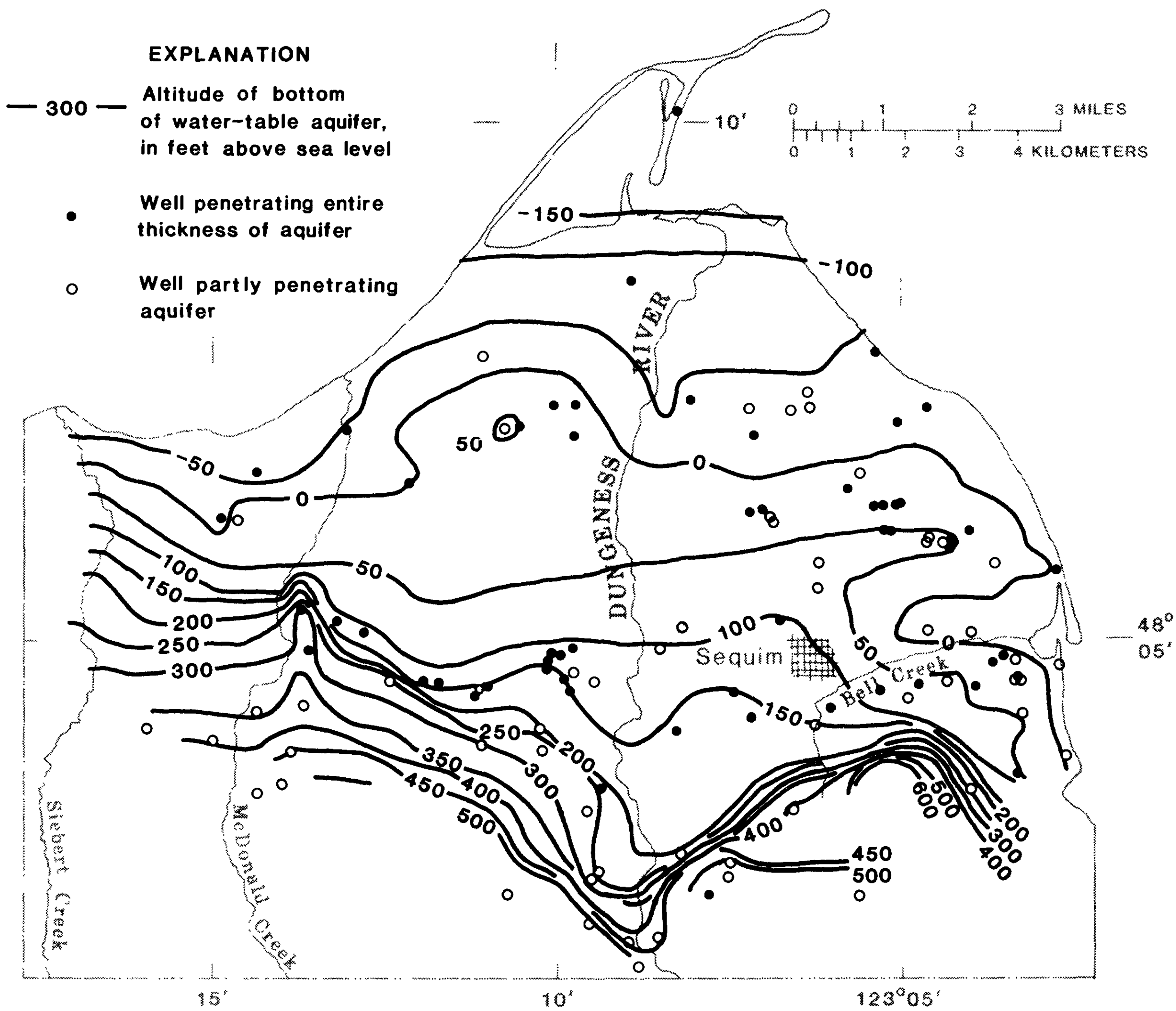


FIGURE 3.--Altitude of the bottom of the water-table aquifer.

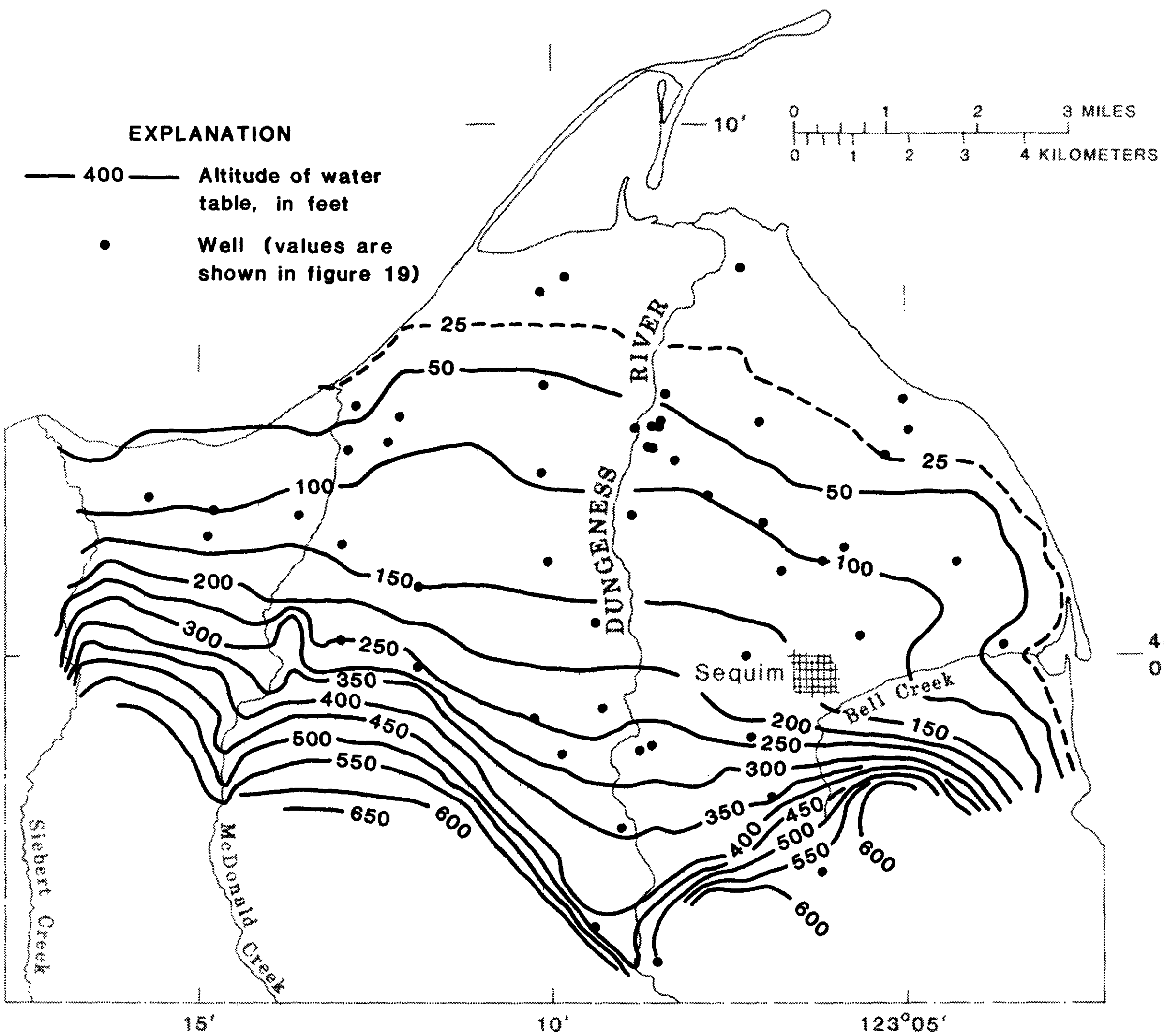


FIGURE 4.--Altitude of the water table in March 1979.

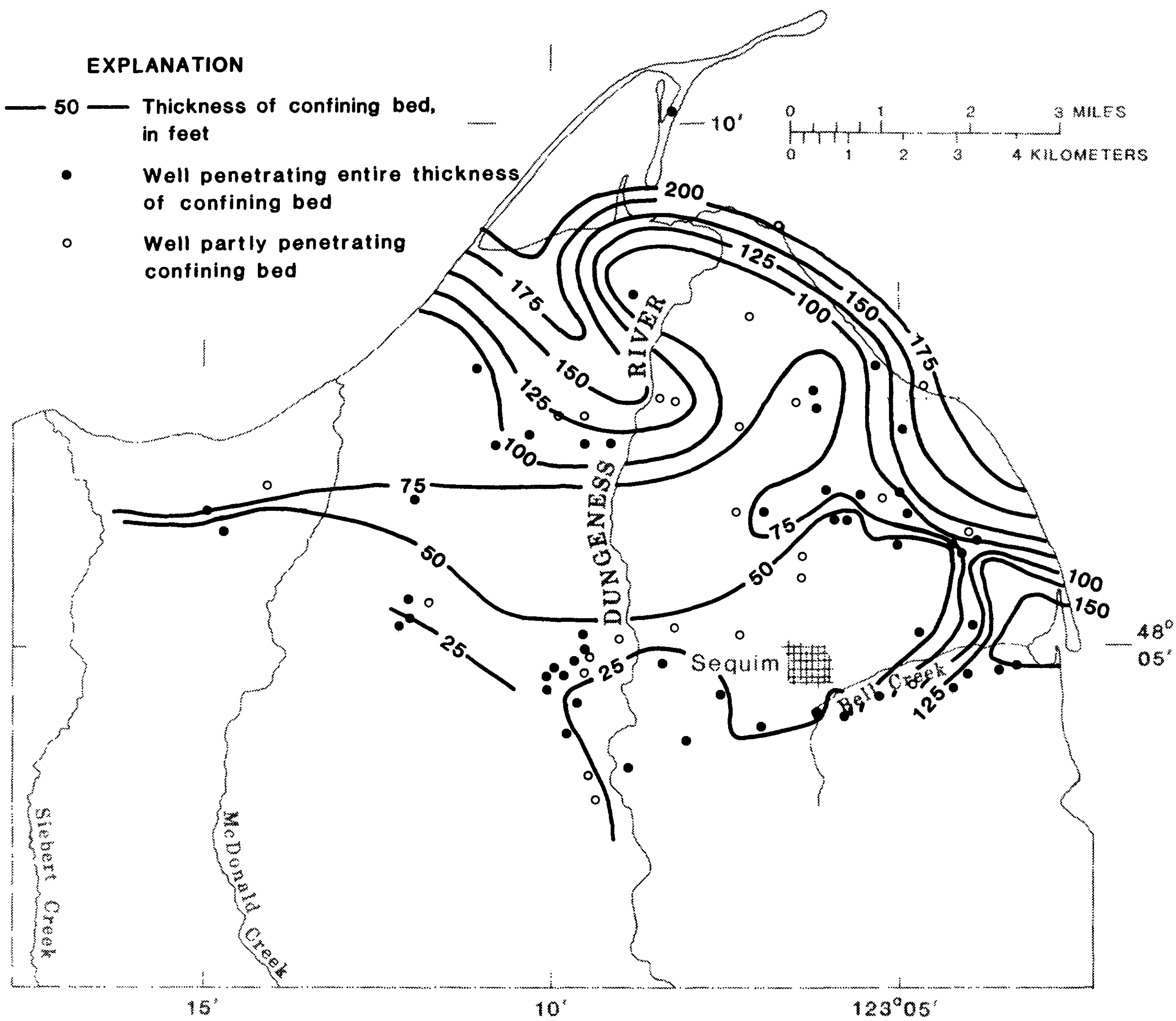


FIGURE 5.--Thickness of the upper confining bed.

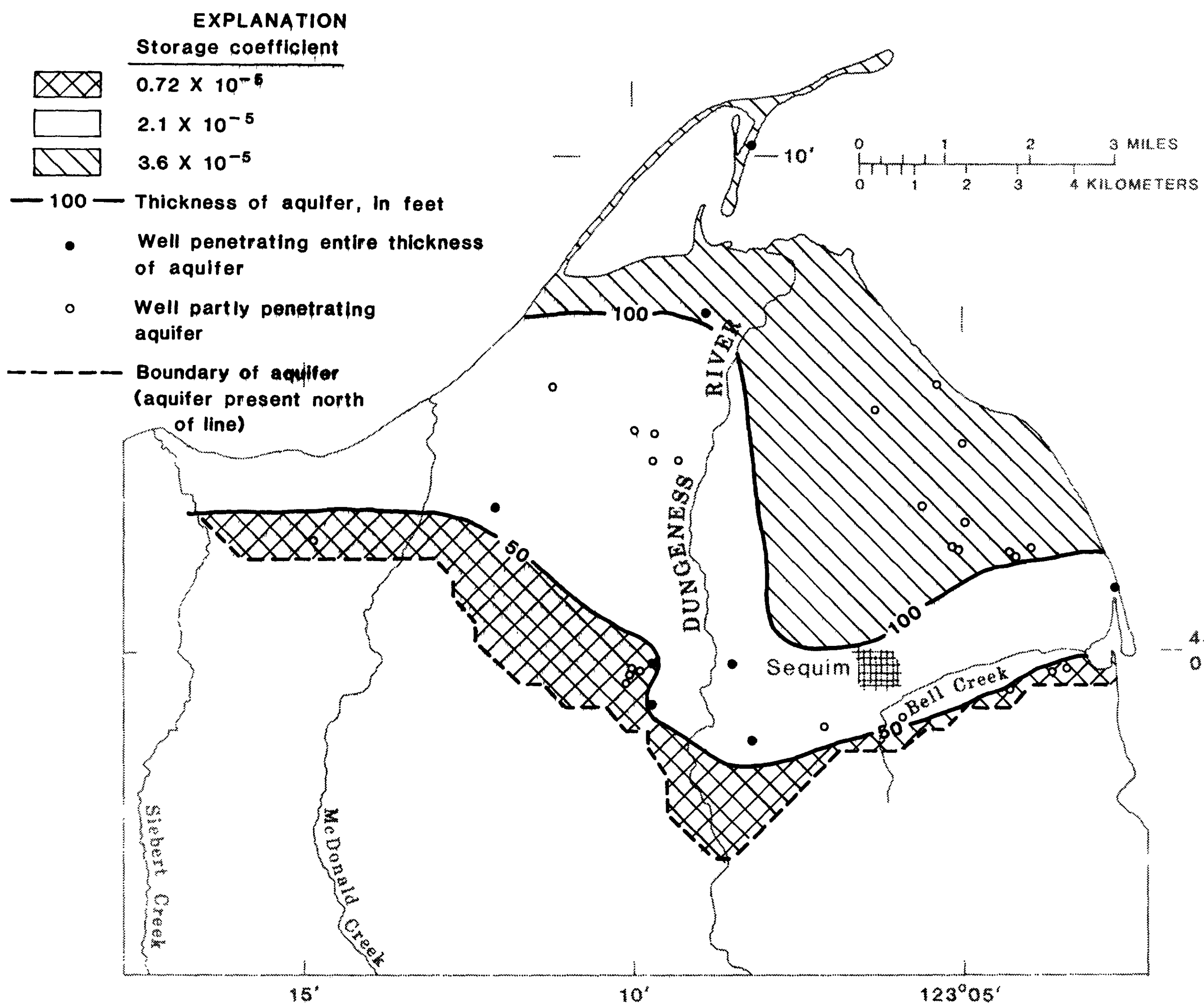


FIGURE 6.--Thickness of, extent of, and storage coefficient in the upper artesian aquifer.

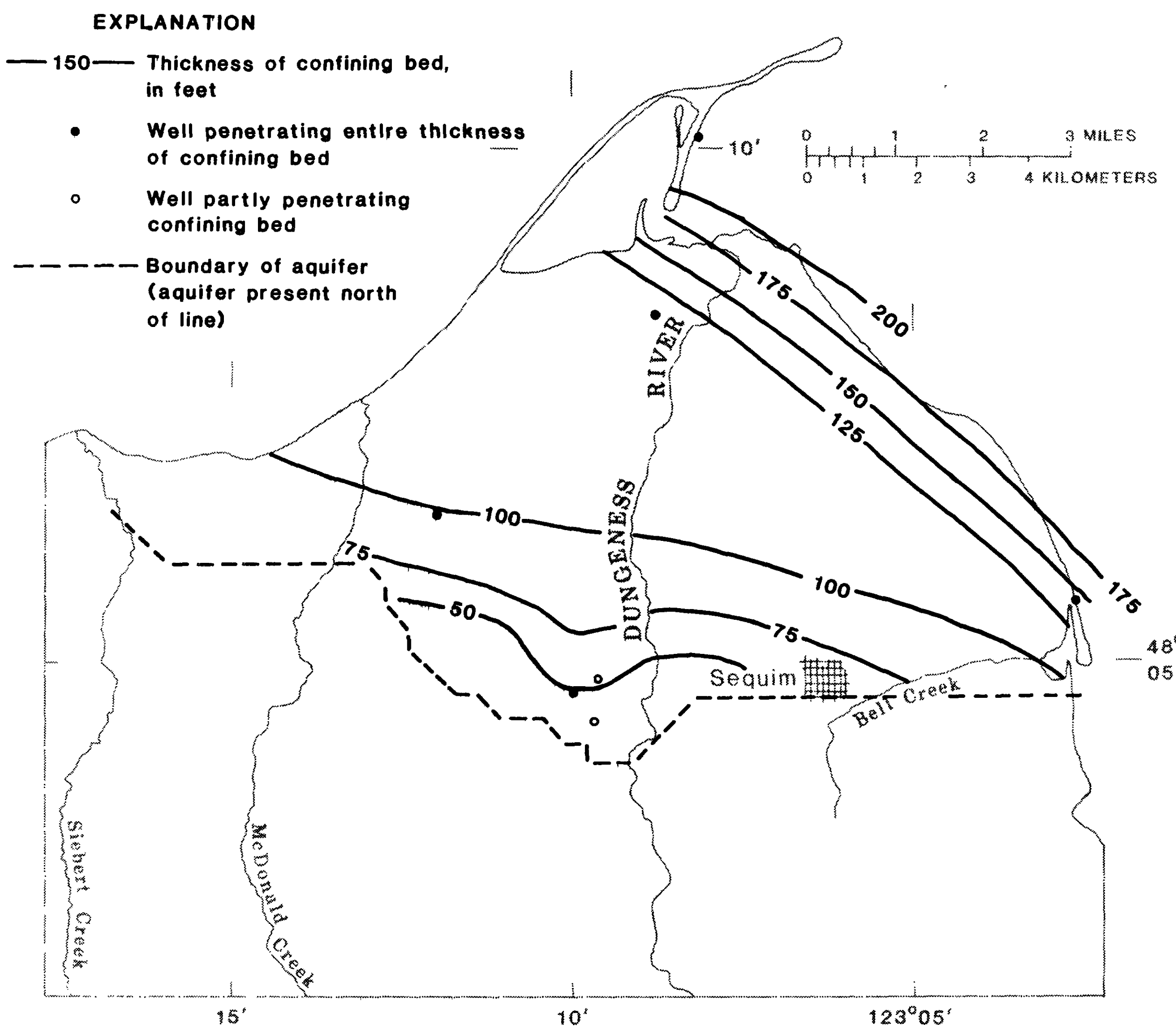


FIGURE 7.--Thickness of lower confining bed and extent of lower artesian aquifer.

Ground-Water Recharge from Precipitation

Average annual precipitation at the Sequim weather station is 16.1 inches (1919-79) and in the study area probably ranges from about 14 inches along the northeastern shoreline to 30 inches along the southern boundary. About 60 percent of the precipitation occurs from October to February in most years.

Potential evapotranspiration, calculated by a modified Blaney-Criddle technique (U.S. Department of Agriculture, 1970), is nearly twice the average precipitation. At the Sequim weather station the average annual potential evapotranspiration (1919-79) is 30.2 inches. This value is probably representative of the entire study area.

Actual evapotranspiration can be estimated by applying an assumed soil-moisture capacity (3 inches of water) to the monthly precipitation and potential evapotranspiration values. At the Sequim weather station, average annual evapotranspiration is 13.8 inches. Throughout the study area, it probably ranges from 12.7 inches (14-inches precipitation zone) to 18.8 inches (30-inches precipitation zone).

When precipitation exeeds potential evapotranspiration and the soil-moisture capacity is exceeded, the excess water is assumed to be ground-water recharge, because direct runoff is believed to be insignificant in the study area. Calculated average annual ground-water recharge ranges from 1.3 inches (14-inch precipitation zone) to about 11.2 inches (30-inch precipitation zone) and is 2.3 inches at the Sequim weather station.

Figure 8 shows the distribution of the calculated average annual ground-water recharge from precipitation. The zones are based on precipitation distribution calculated by the U.S. Weather Bureau (1965). The average recharge rate from precipitation to the study area was calculated to be about 15 ft^3/s.

All weather data used in the above calculations are from U.S. Weather Bureau (1920-65), U.S. Department of Commerce (1965-73), or U.S. National Oceanic and Atmospheric Administration (1974-79).

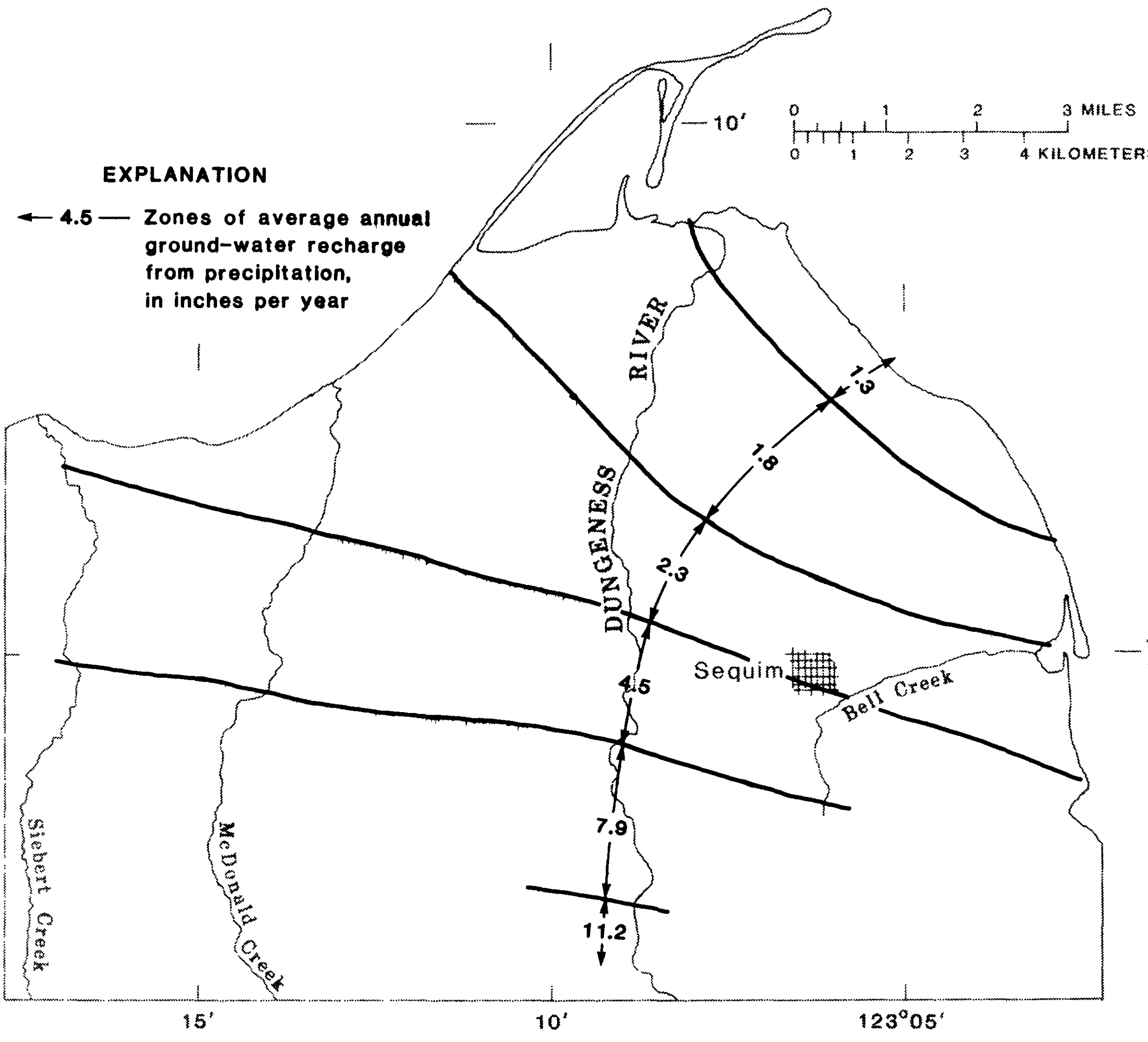


FIGURE 8.--Average annual ground-water recharge from precipitation.

Ground-Water Recharge from Irrigation Systems

Large quantities of water are continuously diverted from the Dungeness River. The water flows through a complex system of irrigation ditches belonging to nine irrigation companies and districts established between 1895 and 1921. The major ditches and their relationship to the area's surface-water system are shown in figure 9. There are also several times as many miles of secondary ditches and laterals that are not shown in figure 9. The water is used primarily for irrigation, but also for stock supply and fire protection in some areas, requiring year-round flow in most of the major ditches.

Water is also diverted from McDonald Creek by the Agnew Irrigation District at rates of about 20 ft^3/s during the irrigation season and about 5 ft^3/s during the nonirrigation season. Prior to this study, systematic discharge measurements had never been taken on the irrigation system. The average irrigation diversion from the Dungeness River during September 1978-August 1980 was about 67 ft^3/s (table 1). Average diversion was 100 ft^3/s during the irrigation season, April-September, and about 33 ft^3/s during the rest of the year.

The effect of ground-water recharge from irrigation systems can be observed in the relationship between flows in the irrigation ditches and water levels in the water-table aquifer. An example is given in figure 10, which shows the flow in the Independent Irrigation Ditch compared with the water level in well 30/3-19D1. (The well is 49 feet deep and within 100 feet of the ditch.)

An estimate of ground-water recharge from irrigation systems was made using the diversion data for the Dungeness River (table 1) and McDonald Creek, estimates of tail waters (water returned from ditches to surface-water bodies), and estimates of evapotranspiration. This resulted in an average rate of ground-water recharge of 70 ft^3/s. Figure 11 shows the relationship between estimated recharge and changes in water levels in the water-table aquifer during September 1978-September 1980. Water levels in the water-table aquifer show a definite response to increases in recharge from irrigation. Wells in the foothills, where irrigation systems have little or no effect, appear to respond primarily to increases in recharge from precipitation.

TABLE 1.--Irrigation diversions from the Dungeness River, September 1978-August 1980

Month	Diversions from the Dungeness River, in cubic feet per second									
	Irrigation district or company								Total irrigation diversion	Dungeness River above diversions[1]
	Dungeness Company	Agnew	Cline	Clallam	Eureka	Independent	Highlands	Sequim Prairie-Dungeness District		
1978										
Sept.	11	13	8.7	9.5	2.3	11	10	10[e]	76	340
Oct.	4.0	9.9	3.4	3.8	0	4.8	8.3	9.8	44	150
Nov.	3.9	6.3	5.7	5.1	0	5.4	8.5	9.1	44	190
Dec.	1.8	5.6	3.2	2.6	0	2.9	6.3	8.6	31	140
1979										
Jan.	2.1	5.2	2.1	2.2	0	10	7[e]	8.4	37	74
Feb.	4.0	1.5	0	3.2	0	6.4	7.3	9.1	32	180
Mar.	3.4	.93	0	2.7	0	4.4	11	7.1	30	350
Apr.	8.3	.08	2.7	6.2	16	7.6	12	8.4	47	220
May	18	6.4	16	15	5.9	15	21	29	130	500
June	20	18	16	16	5.3	16	25	34	150	460
July	17	19	14	13	4.3	15	24	34	140	300
Aug.	8.4	19	6.1	7.9	4.4	15	19	30	110	160
Sept.	8.3	11	7.0	7.0	3.3	9.9	15	15	76	170
Oct.	6.2	10	5.1	4.0	.72	5.9	7.4	12	51	240
Nov.	4.8	8.9	4.8	4.0	.94	2.2	7.5	15	48	170
Dec.	3.7	3.2	3.2	3.8	0	2.5	6.6	10	33	1,000
1980										
Jan.	1.3	1.7	1.5	3.0	0	0	7.2	2.9	18	420
Feb.	1.9	.91	0	1.8	0	1.1	7.4	2.1	15	520
Mar.	2.1	0	0	1.8	0	3.1	6.6	1.6	15	400
Apr.	5.2	5.0	3.0	5.0	1.9	7.8	7.6	22	58	480
May	15	12	13	12	3.4	13	12	29	110	600
June	12	13	7.8	7.8	2.5	9.8	12	17	82	740
July	13	15	10	12	2.5	9.3	14	20	96	550
Aug.	15	19	8.2	12	4.7	13	18	34	120	270
Maximum	20	19	16	16	5.9	16	25	34	150	1,000
Minimum	1.3	0	0	1.8	0	0	6.3	1.6	15	74
Mean	7.9	8.5	5.9	6.7	1.8	8.0	12	16	67	360

[e]Estimated

[1]USGS station number 12048000, Dungeness River near Sequim, Washington, 1.0 mile upstream from Canyon Creek.

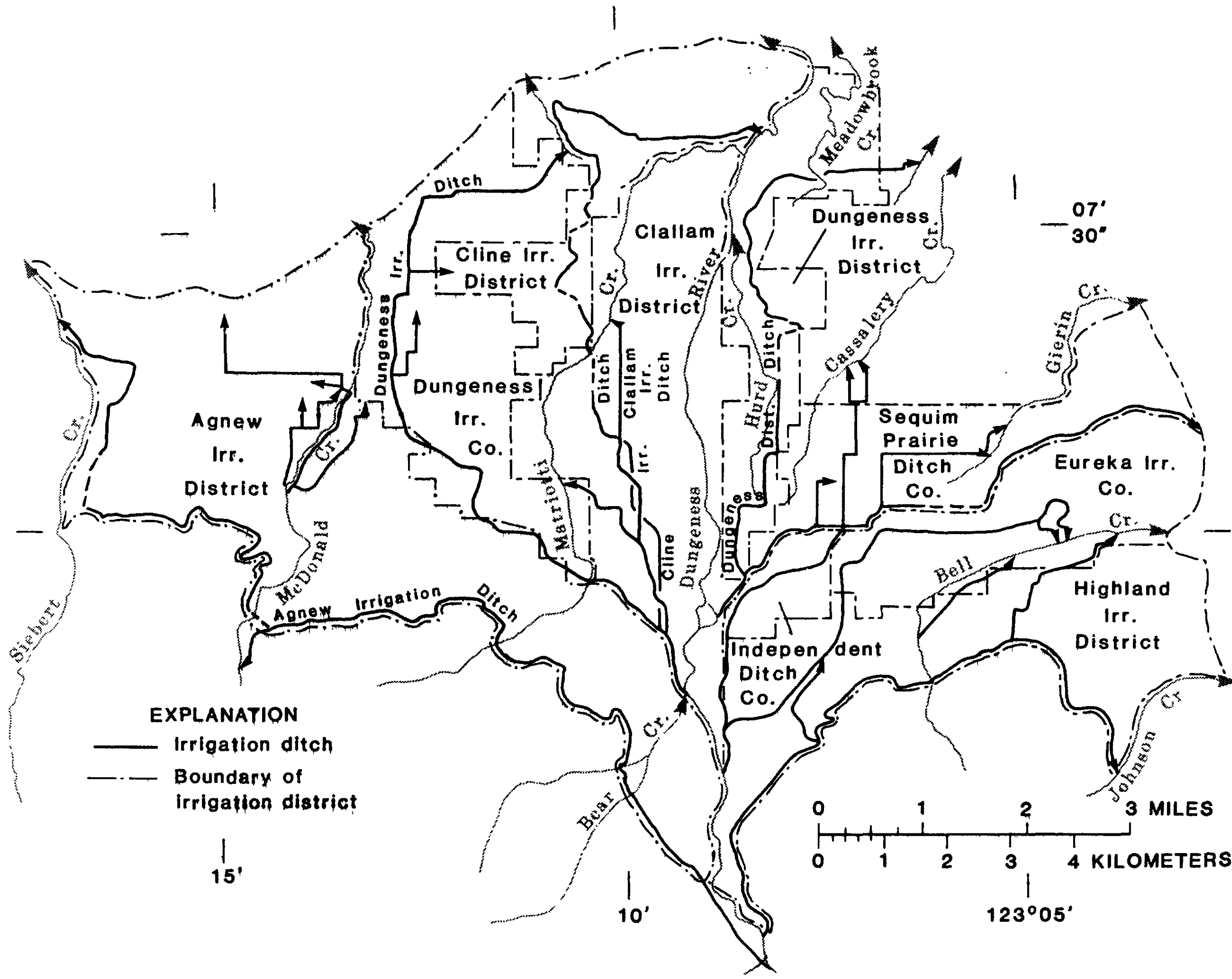


FIGURE 9.--Irrigation districts and major irrigation ditches.

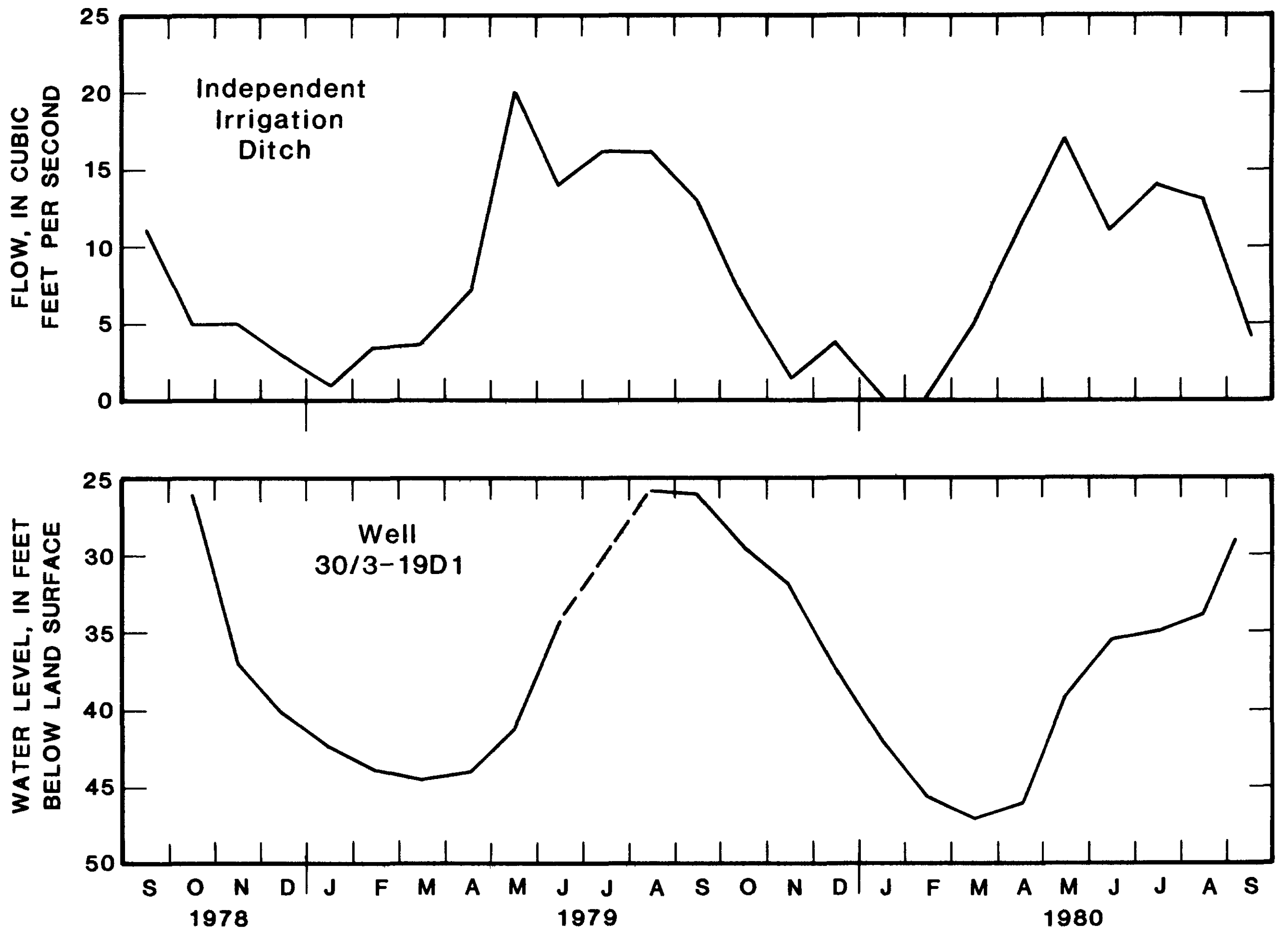


FIGURE 10.--Flow in the Independent Irrigation Ditch and water levels in well 30/3-19D1, September 1978-September 1980.

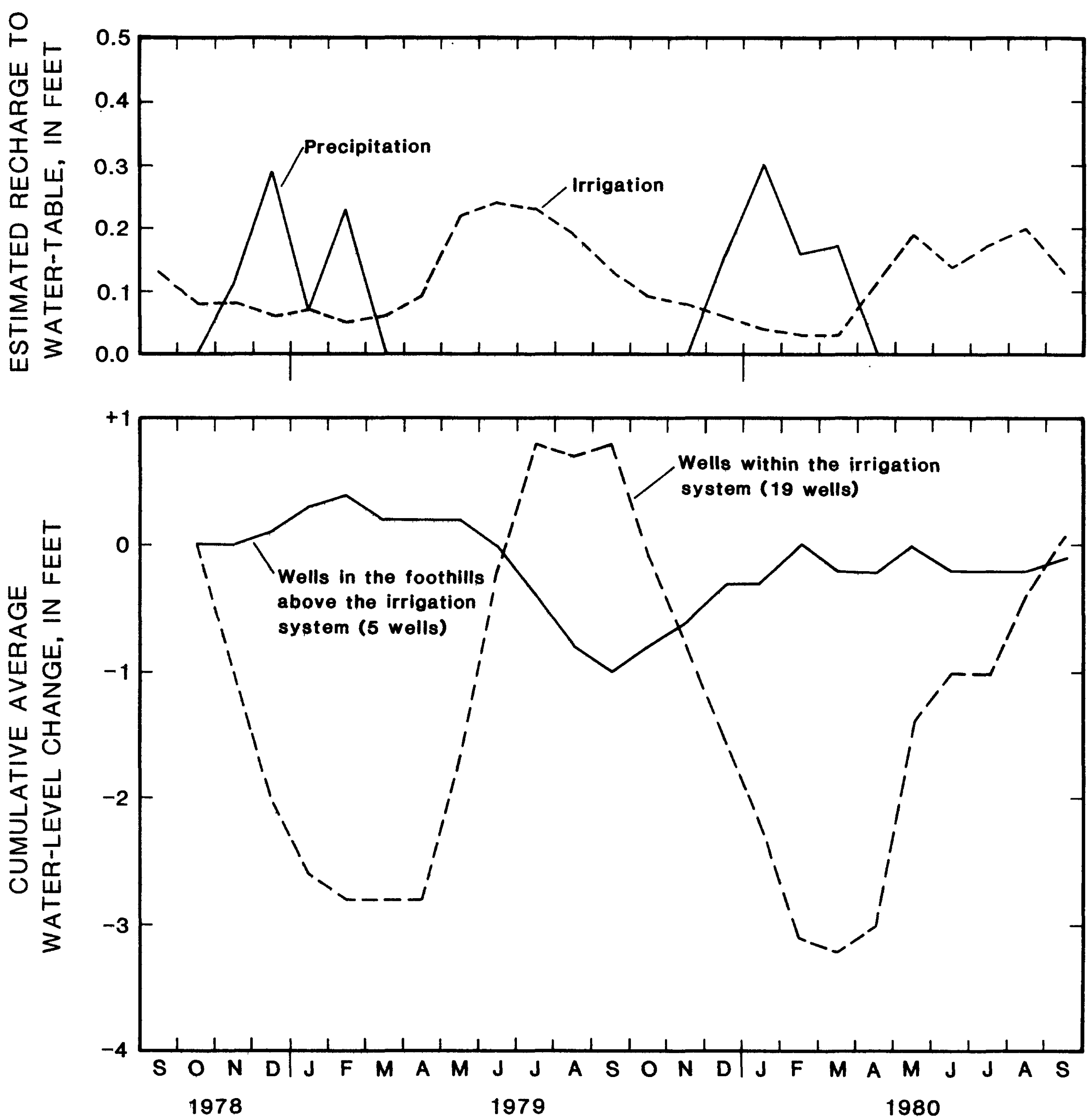


FIGURE 11.--Estimated irrigation and precipitation recharges and changes in water levels in the water-table aquifer.

Ground-Water Movement

General ground-water flow directions can be inferred from figure 4, which shows the configuration of the water table for March 1979. Ground-water movement is perpendicular to the water-table contours shown in figure 4. Although the altitude of the water table changes seasonally, the general pattern of flow remains generally constant.

In addition to lateral flow, there is also vertical flow in the ground-water system. Vertical flow occurs between aquifers through the confining beds. Figure 12 shows the general vertical flow directions in the study area. The diagram assumes that the relatively small amount of flow into and out of the bedrock and the undifferentiated unconsolidated deposits does not significantly affect the flow system.

Hydraulic Characteristics of the Aquifers

Knowledge of the hydraulic characteristics of the aquifers and confining beds is necessary in order to evaluate stresses on the ground-water flow system. These characteristics include hydraulic conductivity, transmissivity, specific yield, storage coefficient, and hydraulic connection between streams and the water-table aquifer.

Lateral Hydraulic Conductivity

Values of lateral hydraulic conductivity (fig. 13) were estimated for the water-table aquifer from specific-capacity data. The data were first adjusted, using the Jacob method (in Bentall, 1963), to account for partial penetration. Then transmissivity values were calculated using the Theis method (in Bentall, 1963). Transmissivity values were divided by saturated thickness to obtain values of lateral hydraulic conductivity.

These values of lateral hydraulic conductivity (calculated for about 500 wells) were plotted on a map of the area, and zones of lateral hydraulic conductivity were outlined. Within each zone, lateral hydraulic conductivity was made equal to the median of all the values in the zone.

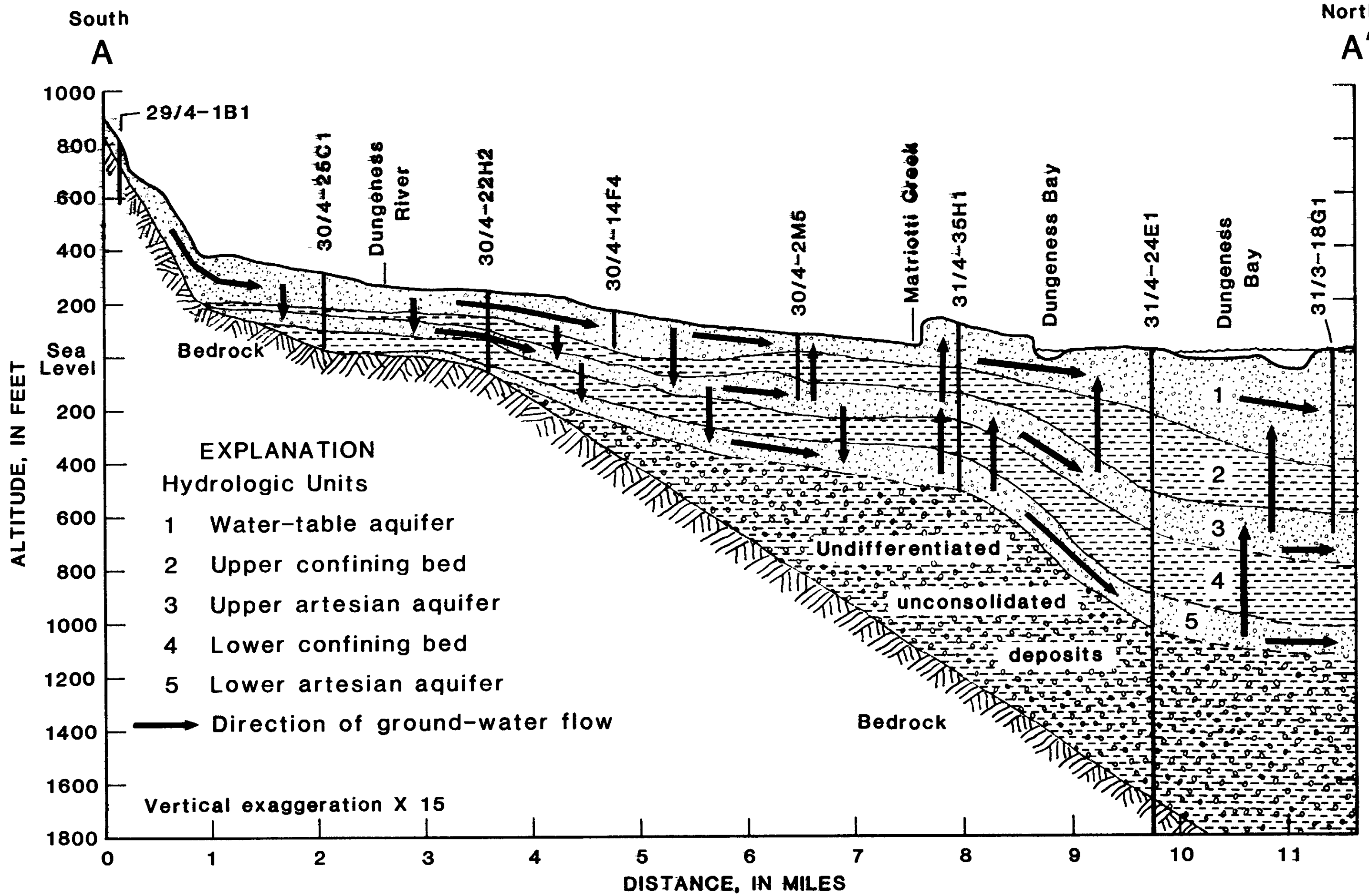


FIGURE 12.--Schematic cross section of the ground-water system and direction of flow.

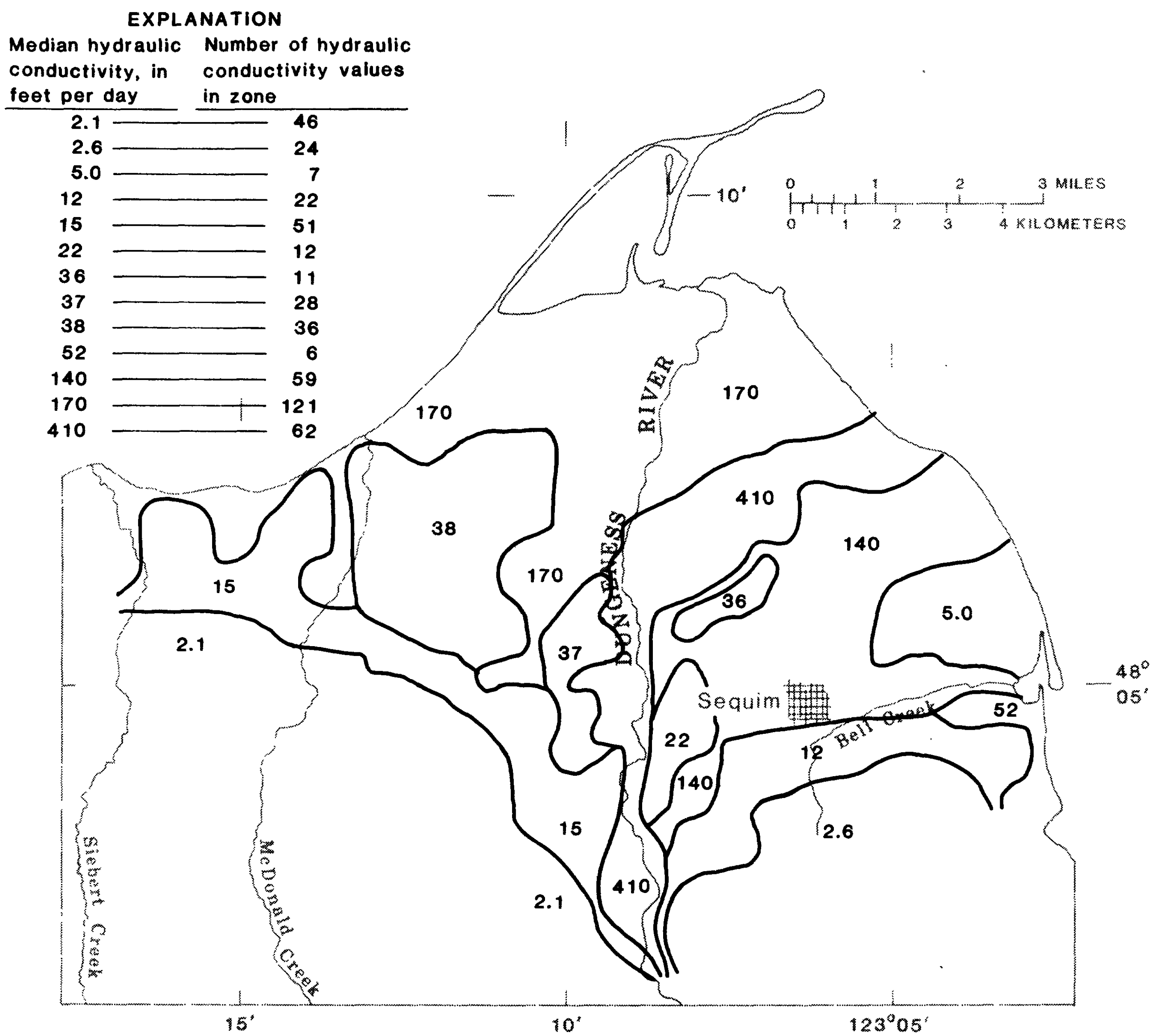


FIGURE 13.--Hydraulic conductivity in the water-table aquifer.

Transmissivity

Values of transmissivity were estimated for the upper artesian aquifer from specific-capacity data, and are shown in figure 14. The data were first adjusted, using the Jacob method (in Bentall, 1963), to account for partial penetration. Then transmissivity values were calculated using the Brown method (in Bentall, 1963).

The values of transmissivity (calculated for 46 sites in the upper artesian aquifer) were plotted on a map of the area, and zones of transmissivity were outlined. Within each zone, transmissivity was made equal to the median of all the values in the zone.

Data were available for only three sites in the lower artesian aquifer. The three transmissivity values were of the same order of magnitude as the respective transmissivity zones outlined in the upper artesian aquifer. Therefore, the transmissivity distribution in the lower artesian aquifer was assumed to be approximately the same as the upper artesian aquifer.

Specific Yield

The specific yield of the water-table aquifer was determined by using measured water-level changes from mid-March to mid-July 1979 (fig. 15). The change in volume of saturated material represented in the figure is an increase of 1,400 million ft^3.

Average inflow to the aquifer was estimated to be 95 ft^3/s from mid-March to mid-July 1979. Estimated outflow for the same period was about 80 ft^3/s. The difference in inflow and outflow resulted in an increase of 170 million ft^3 of water stored in the water-table aquifer.

The change in the volume of water stored, divided by the change in the volume of saturated material, indicated the average specific yield to be 12 percent.

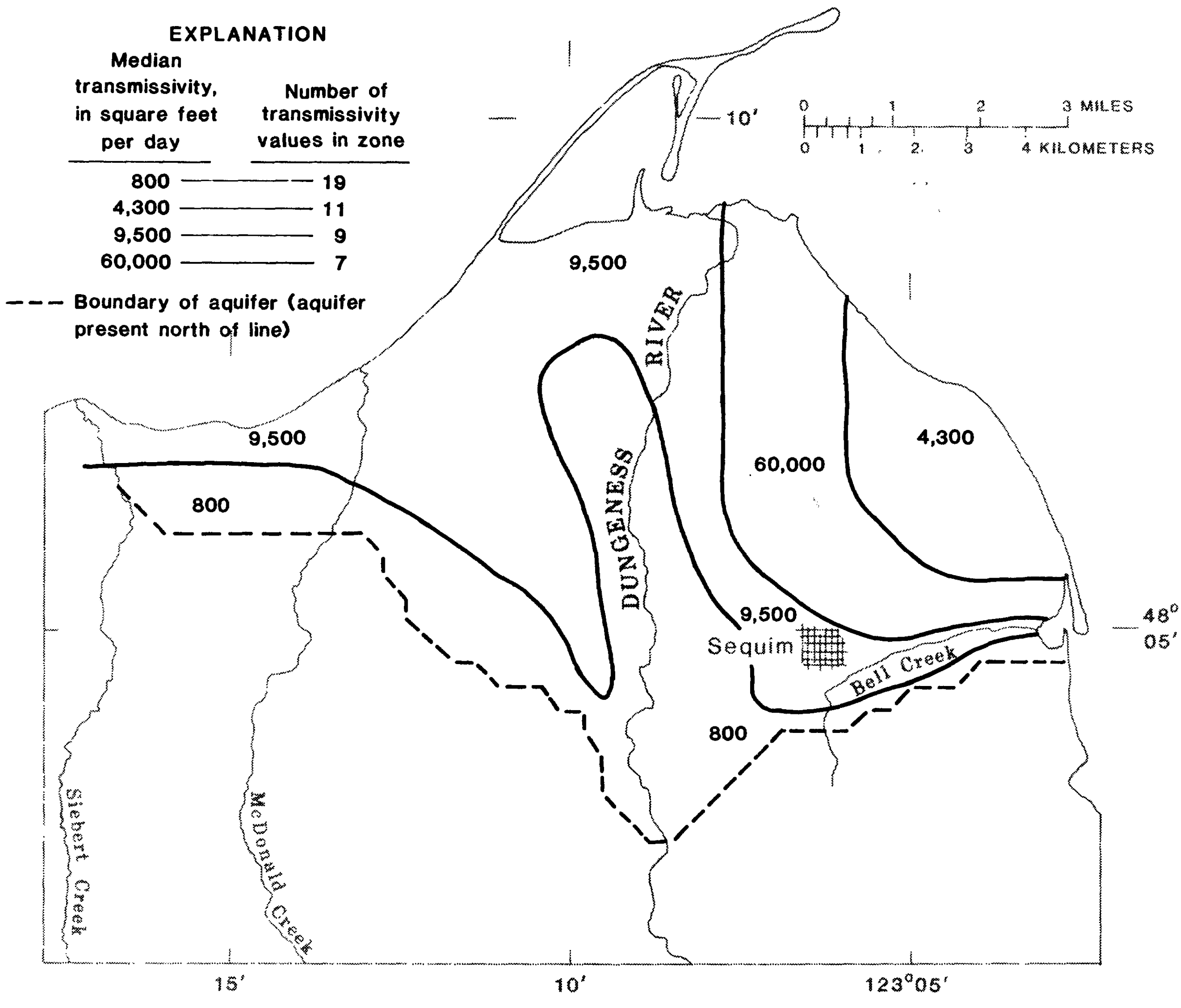


FIGURE 14.--Transmissivity in the upper artesian aquifer.

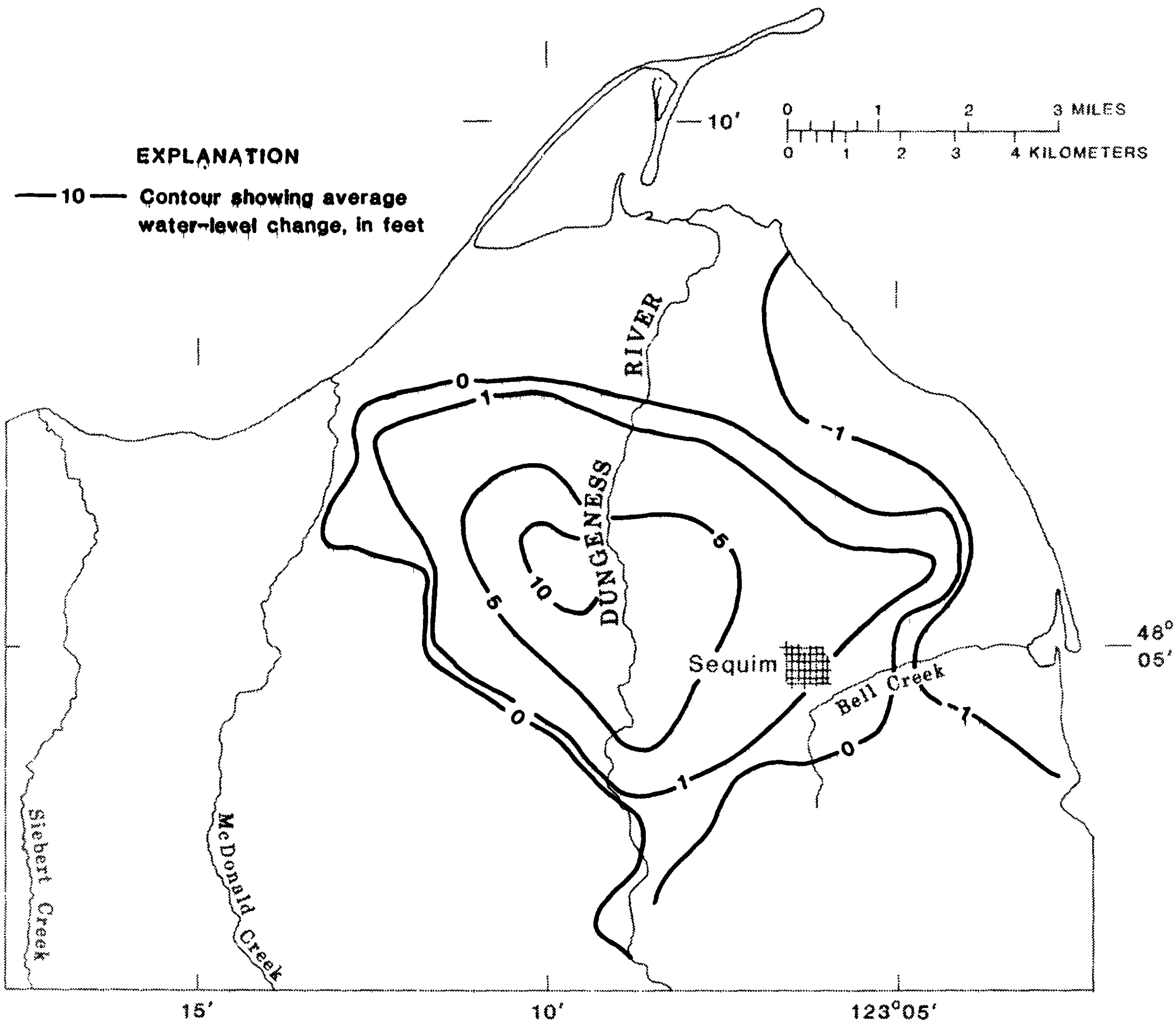


FIGURE 15.--Average water-level change in the water-table aquifer from mid-March to mid-July 1979.

Storage Coefficient

Storage coefficients for the artesian aquifers were estimated by using a calculation for the expansion of water and assuming that there was no compression of the aquifer and release of water from the confining beds. The formula is modified from Jacob (in Lohman, 1979):

$$S = \theta \gamma b \beta \ , \tag{1}$$

Where S = storage coefficient, θ = porosity, γ = specific weight per unit area (0.434 pound $inch^{-2}ft^{-1}$), b = aquifer thickness (feet), and β = reciprocal of the bulk modulus of elasticity of water ($3.3\times10^{-6} inch^2\ b^{-1}$).

Assuming a porosity of 0.2 and using thicknesses of the upper artesian unit from figure 6, three zones of storage coefficient were calculated. Aquifer thicknesses and corresponding storage coefficients are 25 feet and 7.2×10^{-6}, 75 feet and 2.1×10^{-5}, and 125 feet and 3.6×10^{-5} (fig. 6). The storage-coefficient distribution in the lower artesian aquifer was assumed to be the same as in the upper artesian aquifer.

Stream-Aquifer Connection

The Dungeness River loses water to and gains water from the water-table aquifer. Monthly discharge measurements were made at four sites on the Dungeness River from September 1978 through February 1980. The measured gains and losses were usually less than 10 percent of the total flow in the river. Because the discharge measurements themselves are probably accurate only to ± 5 percent, these directly measured gains and losses can be used only as a general indication of the stream-aquifer connection. Table 2 lists the measured gains and losses in the Dungeness River.

Creeks in the study area also lose water to and gain water from the water-table aquifer. Most of these creeks have mean flows of only a few cubic feet per second and probably exchange only small amounts of water with the aquifer.

TABLE 2.--Gains and losses in the Dungeness River

Site/Reach		Discharge, in cubic feet per second												
		1978				1979								
		9/12	10/12a	11/13	12/13a	1/16	2/15	3/15	4/16a	5/15	6/18	7/16	8/14a	9/11a
Dungeness River gage		445	155	162	153	68	193	358	245	480	325	301	172	203
- Agnew Irrigation Ditch		10	12	5.3	5.1	.0	0	1.4	0	0	18	20	19	12
+ Canyon Creek[a]		3.4	1.8	1.9	12	1.6	22	22	26	9.2	4.3	2.8	1.7	1.8
- Highland Irr. Ditch		7.6	7.6	8.5	8.1	12	9.4	10	12	23	27	26	19	13
-Independent Irr. Ditch[a]		11	5.0	5.0	2.3	5.0e	3.0	3.4	7.0	16	13	15	13	11
- Eureka Irr. Ditch		2.3	0	0	0	0	0	0	0	6.7	5.1	4.6	.9	5.0
+ Bear Creek[a]		.7	.2	0	.7	.4	1.3	1.5	.7	.0	.3	.5e	.5e	.5e
- Clallam Irr. Ditch		8.8	5.1	4.7	2.6	3.3	5.1	3.8	7.2	18	15	14	10	7.5
- Cline Irr. Ditch		7.2	4.3	4.6	4.1	2.2	0	0	0	25	16	14	8.5	8.5
- Dungeness Co. Irr. Ditch		9.8	5.9	4.4	1.4	2.8	7.0	5.9	13	23	20	19	11	11
- Sequim Prairie-Dungeness Dist. Irr. Ditch		16e	9.4	9.2	4.6	7.6	10	7.8	8.0	26	33	34	31	7.8
Dungeness River at Highway 101	Calculated	376	108	122	138	37	182	349	224	352	182	158	62	130
	Measured	461	104	126	129	73	203	345	209	342	186	150	52	140
Gain (+) or loss (-) from gage to Hwy 101		+85	-4	+4	-9	+36	+21	-4	-15	-10	+4	-8	-10	+10
Dungeness River at Woodcock Bridge		440	98	120	120	64	203	377	216	333	193	164	49	141
Gain (+) or loss (-) from Hwy 101 to Woodcock Bridge		-21	-6	-6	-9	-9	0	+32	+7	-9	+7	+14	-3	+1
+ Hurd Creek[a]		7.9	5.7	6.0	5.2	5.3	6.1	6.7	5.5	6.2	6.4	8.4	7.2	6.7
+ Matriotti Creek		11	11	11	15	12	16	13	12	17	19	20	11	15
Dungeness River at Dungeness	Calculated	459	115	137	140	81	225	397	234	356	218	192	67	163
	Measured	452	114	130	148	74	210	396	250	366	220	191	71	156
Gain (+) or loss (-) from Woodcock Bridge to Dungeness		-7	-1	-7	+8	-7	-15	-1	+16	+10	+2	-1	+4	-7
Net gain (+) or loss (-) from gage to Dungeness		+57	-11	-9	-10	+20	+6	+27	+8	-9	+13	+5	-9	+4

[a]Measurement dates on Canyon, Bear, and Hurd Creeks; 10/13/78, 12/14/78, 4/17/79, 8/17/79, and 9/17/79.
[e]Estimated

Ground-Water Quality

The Board of Clallam County Commissioners and the State of Washington Department of Ecology are concerned that the increased use of on-site domestic sewage-disposal systems (septic systems) in the study area may have caused pollution or may lead to future pollution of the ground water. Water-quality data existing prior to this study were not sufficient to allow a comparison with present water-quality data. Therefore, during this study, only a general assessment of the possible effects could be made.

During June 16-19, 1980, water samples were collected at 24 sites in irrigation systems, at 13 river and creek sites, and from 138 wells. These samples were analyzed for specific conductance and pH and for the following dissolved constituents: chloride, nitrate plus nitrite, and ammonia. Table 3 is a summary of the results of the analyses.

Some general observations can be made from table 3. Concentrations of chloride and ammonia, and values of specific conductance and pH all appear to increase with depth in the ground-water system. Nitrate-plus-nitrite concentrations apparently decrease with depth in the ground-water system. In terms of the constituents measured, water quality in the irrigation system shows little change from point of diversion from the Dungeness River to the end of the system.

The areal distribution of nitrate plus nitrite in the water-table aquifer is shown in figure 16. The distribution shows a possible correlation with density of septic systems, also shown in figure 16. However, other correlations with nitrate plus nitrite exist. For example, the greatest median concentration of nitrate plus nitrite is observed in the "older alluvium" of Othberg and Palmer (1980a, b, and c).

Other correlations between water quality and geologic units can be observed in the water-table aquifer in the June 1980 data (table 4). Median chloride and ammonia concentrations and specific conductance are significantly greater in the Everson glaciomarine drift than in any other geologic unit. The lowest median values for chloride, specific conductance, and pH are in the "alluvium."

An estimate of the amount of nitrogen added to the ground-water system by septic systems may prove useful for a gross qualitative look at the effects of septic systems on ground-water quality. The following calculation includes many assumptions and estimates and is intended only as an indication of the general magnitude of the rate at which nitrogen is added to ground water by septic systems:

9,000 People on septic systems (estimated from Clallam County Health Department records)
x 44 Gallons of water per day per person (Porter, 1980)

0.6 ft^3/s Total sewage into septic system

52 mg/L nitrogen in effluent from septic tanks to drain fields (Porter, 1980)
x 50 Pct reduction in nitrogen within drainfield (Porter, 1980)

26 mg/L nitrogen in seepage into ground-water system

Assuming complete mixing in ground-water system and average ground-water flow of 80 ft^3/s, average concentration of nitrogen in ground water from septic systems equals:

$$\frac{(0.6\ ft^3/s)\ (26\ mg/L)}{80\ ft^3/s} = 0.20\ mg/L$$

The median value of nitrate plus nitrite plus ammonia (probably the only significant forms of nitrogen present) in the samples collected from the water-table aquifer in June 1980 was 0.42 mg/L. It is likely that some nitrogen in the ground water comes from sources other than septic systems, including fertilizers (domestic and agricultural), dairy farms, and domestic animals.

The June 1980 data indicate that no obvious water-quality problem presently exists and the above estimate of the effect of septic systems shows no obvious danger from the present density of septic systems. However, the greatest value of the June 1980 data is as a baseline against which future measurements of water quality can be compared.

TABLE 3.--Summary of water quality, June 16-19, 1980

	Number of wells or sites	Median values, in milligrams per liter: Dissolved chloride (Cl)	Dissolved nitrate plus nitrite (N)	Dissolved Ammonia (N)	Specific conductance (micromhos)	pH
Ground water						
Water-table aquifer	125	3.9	0.35	0.01	261	7.6
Upper artesian aquifer	12	4.6	.24	.04	322	7.8
Lower artesian aquifer	1	5.3	.04	.31	353	8.0
Surface water						
Dungeness River	4	0.4	0.04	0.00	88	7.8
Inflowing creeks[1]	3	3.1	.15	.01	132	7.7
Outflowing creeks[2]	6	2.4	.47	.04	189	7.9
Irrigation system:						
All sites	24	.8	.02	.01	103	7.7
Inflow[3]	6	.6	.03	.00	90	7.6
Outflow[4]	9	.7	.02	.01	160	7.6

[1]Creeks with major source of discharge from the foothills south of the study area.

[2]Creeks with major source of discharge from the water-table aquifer. These creeks may also receive significant flow from the irrigation system.

[3]Measured near point of diversion from Dungeness River.

[4]Measured near end of system.

TABLE 4.--Correlation of water quality and geologic units in the water-table aquifer, June 16-19, 1980

Geologic unit (Othberg and Palmer, 1980a, b, and c)	Number of wells	Median values, in milligrams per liter: Dissolved chloride (Cl)	Dissolved nitrate plus nitrite (N)	Dissolved ammonia (N)	Specific conductance (micromhos)	pH
Alluvium	31	2.2	0.30	0.01	184	7.3
Older alluvium	29	2.7	.98	.01	256	7.7
Everson glaciomarine drift	10	12.	.15	.31	410	7.6
Everson sand	7	4.7	.19	.01	275	7.5
Vashon recessional ice-contact stratified gravels and fine-grained marine sediments	5	5.7	.47	.04	288	7.5

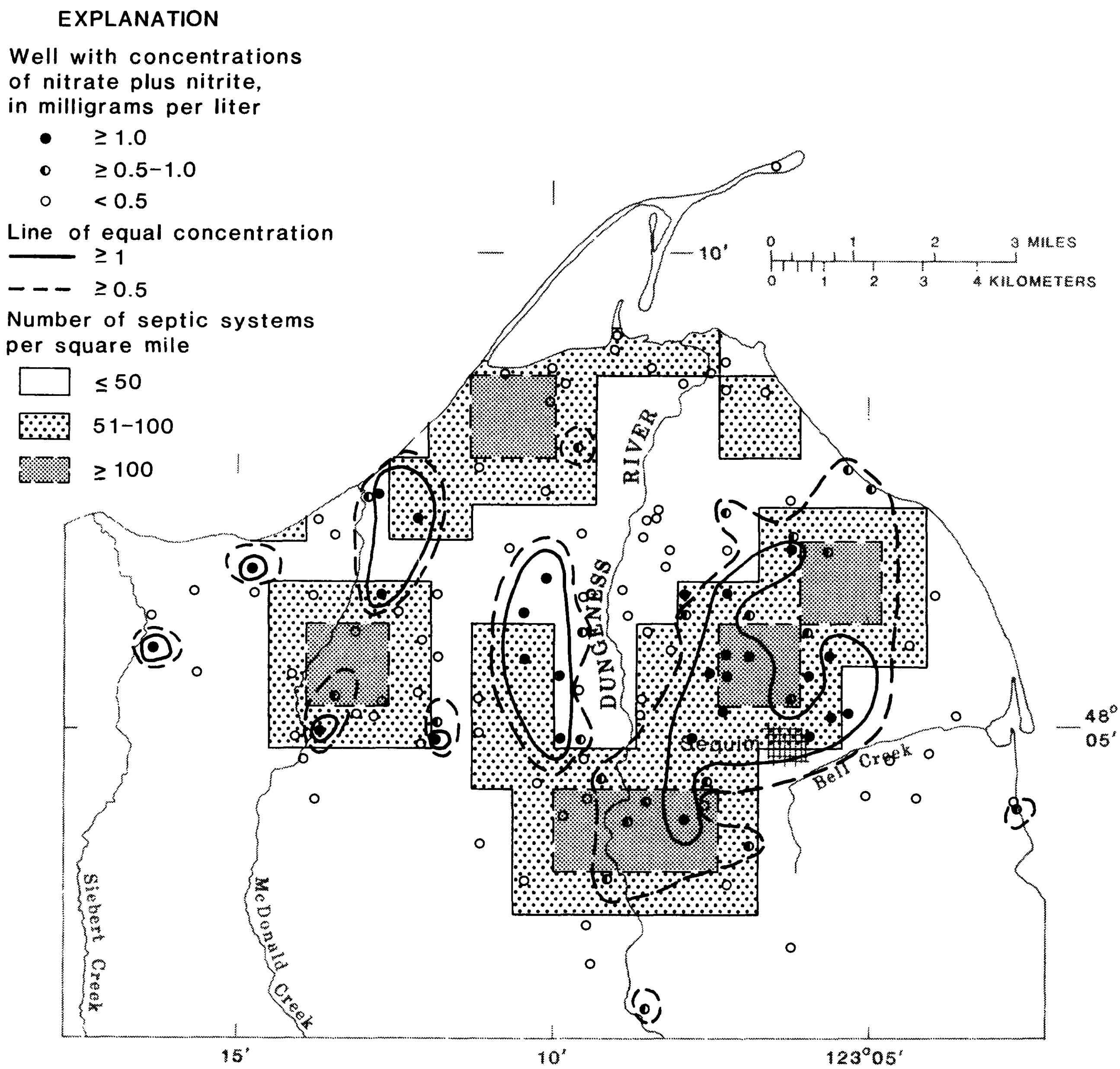


FIGURE 16.--Nitrate-plus-nitrite concentrations and septic-system densities in the water-table aquifer, June 16-19, 1980.

MODEL CONSTRUCTION, CALIBRATION, AND UTILIZATION

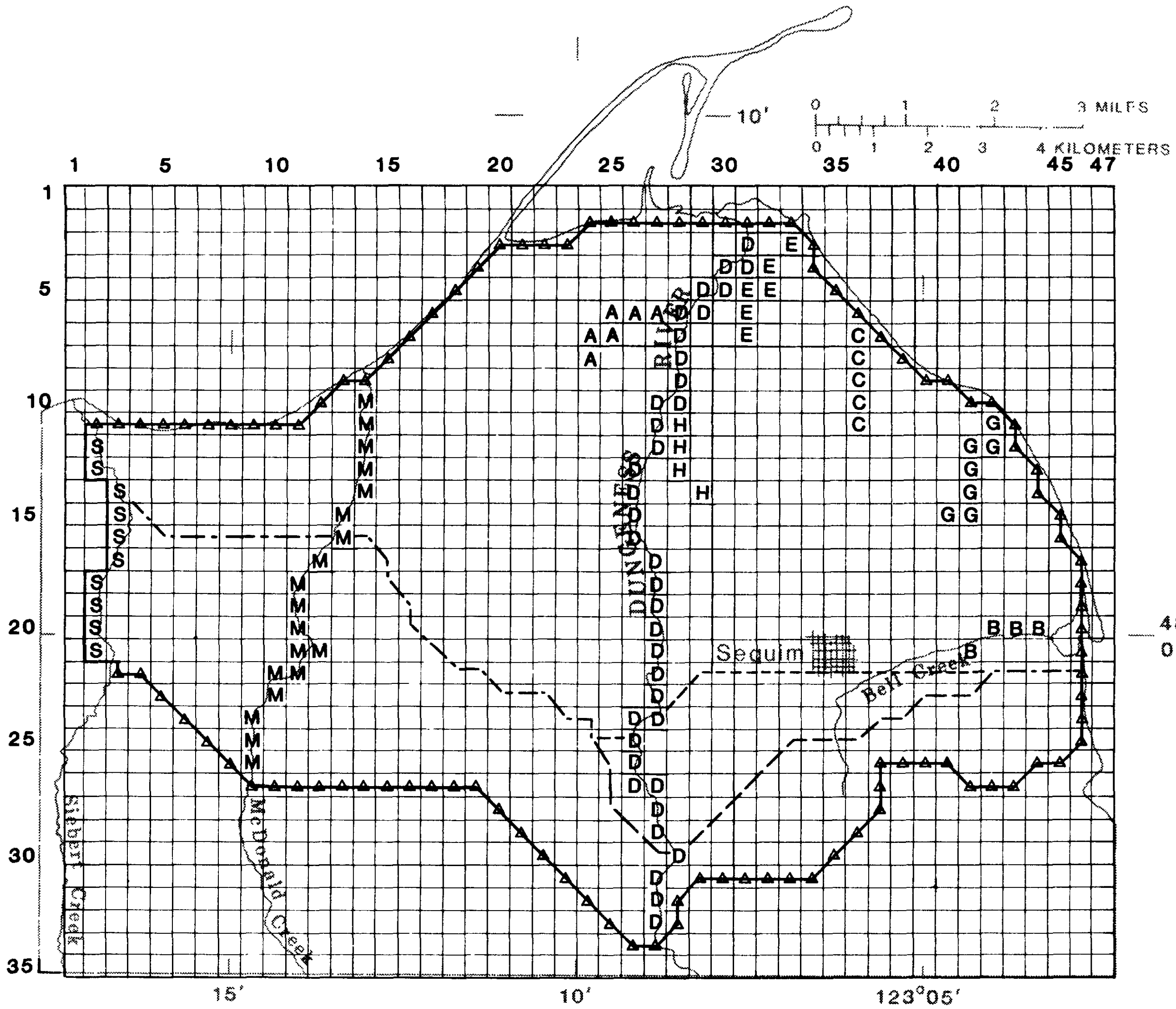
A three-dimensional digital ground-water-flow model was used to simulate the movement of ground water in three layers—the water-table, the upper artesian aquifer, and the lower artesian aquifer. The model simulates ground-water flow by solving a set of simultaneous-difference equations using the strongly implicit procedure (Trescott, 1975). Storage and horizontal components of flow in the confining beds were assumed to be insignificant, allowing vertical leakage through the confining beds to be incorporated into the vertical component of the anisotropic hydraulic conductivity of adjacent aquifers. Vertical flow within the aquifers is considered to be insignificant. All vertical flow in the model is through the confining beds. The hydraulic connection between streams and the water-table aquifer was simulated using additions to the Trescott model from S. P. Larson (written commun., 1976).

Model Boundaries

The boundaries of the model are shown in figure 17. The northern and eastern boundaries approximate the shoreline, where, during steady-state simulations, each node was assigned a specified head value (constant head) that was based on measured water levels. During some transient simulations these nodes were changed to constant flux (continuous rate of flow) nodes, based on flows calculated by steady-state simulations. The freshwater-saltwater interface is probably well offshore. The most seaward well, 31/3-18G1 (fig. 1), extends 657 feet below sea level and taps fresh water. No attempt was made to model the freshwater-saltwater interface.

The western boundary is along Siebert Creek, where each node is a river node in which the river level is held constant but the water level in the aquifer can change.

The southern boundary roughly approximates the 600-foot topographic contour. The water-table aquifer extends southward beyond the model boundary. The use of constant head nodes along the southern boundary that are based on measured water levels allows the model to calculate the ground-water inflow from the portion of the water-table aquifer outside of the model. The 600-foot level was selected as the farthest position southward where data were sufficient to accurately simulate the water-table aquifer. The base of the model is the bottom of the lower artesian aquifer or bedrock where the lower artesian aquifer is not present (fig. 2).



EXPLANATION

River nodes:

A–Matriotti Creek
B–Bell Creek
C–Cassalery Creek
D–Dungeness River
E–Meadowbrook Creek
G–Gierin Creek
H–Hurd Creek
M–McDonald Creek
S–Siebert Creek

– – – – Boundary of upper artesian aquifer

-------- Boundary of lower artesian aquifer

—·—·— Common boundary of upper and lower artesian aquifers

△ Constant head or constant flux node

FIGURE 17.--Grid network, boundary conditions, and river nodes used in the model.

Model Input

Mean annual recharge from precipitation applied at a continuous average rate of 15.2 ft^3/s (see calculation, p. 14) is used for both steady-state and transient simulations. The majority of recharge from precipitation occurs in the southern foothills of the modeled area. In the foothills, the low permeability of the materials above the water table (mostly till) slows infiltration of recharge from precipitation to the water-table aquifer. This results in recharge that is generally continuous, even though the periods of excess precipitation are restricted to several months each winter (fig. 11). Applying mean annual precipitation recharge at a constant rate in the steady-state simulations probably introduces slightly more recharge in the lowlands and slightly less recharge in the foothills than actually took place at the time simulated, March 1979.

The average rate of recharge during March 1979 from the irrigation system (32.3 ft^3/s) is calculated by subtracting estimated tail waters (2.4 ft^3/s) from measured diversions (34.7 ft^3/s). Evapotranspiration and consumptive uses are assumed to be insignificant. The areal distribution of the recharge is determined by calculating leakages along each main ditch and assigning the calculated rate of leakage to each grid block through which the main ditch passes. Any excess recharge in each irrigation district is assumed to be leakage from the numerous secondary ditches and laterals and was applied evenly over the entire district. The method of calculating leakage from the main ditches is as follows:

$$Q_L = \frac{k_D \ (h_D - h_A) \ A}{m} \qquad (2)$$

where Q_L = rate of leakage from irrigation ditch to water-table aquifer, L^3/T; K_D = vertical hydraulic conductivity of the bed of the ditch, L/T; m = thickness of the bed of the ditch, L; h_D = elevation of water surface in ditch, L; h_A = elevation of head in aquifer, L, or if h_A is below the bottom of the bed of the ditch, then the elevation of the bottom of the bed of the ditch is used; A = area of bed of ditch (wetted perimeter), L^2.

The ratio K_D/m is called the leakage coefficient. This parameter probably varies from ditch to ditch and within each ditch. However, a single value for the leakage coefficient, 1 (ft/day)/ft, is assumed for all locations, and produces values of leakage that fit the leakage rates calculated from the diversion measurements and estimates of tail waters (table 5).

As seen in table 5, the majority of leakage fom the irrigation system occurs from the ditch system and not from water actually spread on the fields. During the height of the irrigation season, a greater proportion of the recharge probably occurs as leakage from excess water applied to fields, but it probably still represents a small portion of the total leakage.

The leakage between the water-table aquifer and the Dungeness River and eight creeks is calculated by the model using equation 2 (p. 36) substituting parameters for the river or creeks in place of the ditch parameters. The altitude of the river bed of the Dungeness was obtained from a flood study by the U.S. Department of Housing and Urban Development (1980). The river-bed elevations of the creeks were obtained from 1:24,000-scale U.S. Geological Survey topographic maps. The area of the bed and the depth of water for each river node were obtained from the data collected during March 1979 at the measurement site nearest each node along the river and creeks.

The leakage coefficient for the river nodes was initially assumed to be 1 (ft/day)/ft. During calibration of the steady-state model various leakage coefficients from 0.1 to 100 (ft/day)/ft were tried. The results of these trial runs were compared to measured values of water-table elevation and estimated leakage from the Dungeness River (fig. 18). The value of leakage coefficient that gave the best agreement with measured heads and estimated leakage was 2.0 (ft/day)/ft. This value is used for all steady-state and transient simulations.

All parts of the Dungeness River and Siebert and McDonald Creeks which pass through the modeled area are represented by river nodes. The six other creeks are represented by river nodes only along their lowermost 1-1 1/2 miles. These creeks receive almost all of their flow from ground water and the irrigation system along the portions represented in the model.

The constant heads used in the model were estimated from water levels measured in March 1979. For the water-table aquifer, the large number of available measured heads (fig. 4) results in constant head values that are quite accurate. For the artesian aquifers, relatively few values of head are available along the coastline. Constant-head boundaries in the artesian aquifers were assigned on the basis of the few available measured heads, and were adjusted during model calibration.

Figure 3, showing the altitude of the bottom of the water-table aquifer, was constructed using driller's logs. These data were entered into the model. An average value was used for the area enclosed by each grid block.

Values of hydraulic conductivity, transmissivity, specific yield, and storage coefficients that were used in the model were calculated by methods discussed on pages 21-27, and are shown in figures 6 and 13-15. The distribution of transmissivity and storage co-efficient were assumed to be the same for both artesian aquifers.

Vertical leakage through the confining beds was simulated by estimating a vertical leakage coefficient that was based on the vertical hydraulic conductivity and the length of the flow path (confining bed thickness). Vertical leakage is computed as the product of the head difference between adjacent layers and the vertical leakage coefficient. Thicknesses of the confining beds were determined from drillers' log and are shown in figures 5 and 7. The vertical hydraulic conductivity of the confining beds used in the model is 5×10^{-3} ft/day. This value was determined during model calibration as the one yielding the best simulation of heads in all three aquifers. The value fits the range given by Johnson (1963) for laboratory samples of clay to silt size (1×10^{-5} to 1 ft/day).

In March 1979, pumpage from the ground-water system was insignificant. Total pumpage, essentially all for domestic use, was estimated to be about 2 ft^3/s. Most of this water was pumped from individual domestic wells and small public-supply systems (20 homes or less). Public supply for Sequim was obtained from a modified infiltration gallery along the Dungeness River upstream of the model's southern boundary. The only significant pumpage for March (≥ 0.05 ft^3/s within a single grid block) was for the Sunland Development (estimated at 0.13 ft^3/s), and was obtained from one well tapping the upper artesian aquifer. This is the only well represented in the steady-state simulations. For the transient simulations, pumping (annual average rate) is greater, but is still insignificant when compared with the average rate of flow in the ground-water system. Total pumpage in the transient simulations was 1.6 ft^3/s (table 6).

TABLE 5.--Ground-water recharge from the irrigation system, March 1979

[All values in cubic feet per second]

Irrigator	Mean diversion from Dungeness (March 1979)	Tail waters (estimate)	Ground-water recharge: Total leakage	Main ditch leakage[e]: Upstream half of ditch	Main ditch leakage[e]: Downstream half of ditch	Secondary leakage (from smaller ditches and fields)
Dungeness Irrigation Company	3.4	0.1	3.3	2.2,	1.1	0
Agnew Irrigation District	1.4[a] 5.2[b]	0 0	1.4 5.2	0.9, 5.2[f]	0.5	0 0
Cline Irrigation District	0	0	0	0		0
Clallam Irrigation District	2.7	.1	2.6	1.1,	.6	0.9
Eureka Irrigation Company	0	0	0	0		0
Independent Ditch Company	1.9[c]	0	1.9	.9,	.5	0.5
Highland Irrigation District	10.5	1.6	8.9	6.0,	2.9	0
Sequim Prairie Ditch Company	7.8[d]	.5	7.3	2.6, .7[g]	1.3	2.7
Dungeness Irrigation District	1.8[d]	.1	1.7	1.1,	.6	0
Totals	34.7	2.4	32.3	28.2		4.1

[a]Includes 0.5 ft^3/s estimated inflow to main ditch from surface-water.

[b]Estimated diversion from McDonald Creek.

[c]Actual diversion equals 4.4 ft^3/s; approximtely 2.5 ft^3/s is dumped into Sequim Prairie Ditch

[d]Sequim Prairie and Dungeness District share a common diversion equal to 7.1 ft^3/s; assume one-fourth to Dungess District (1.8 ft^3/s) and three-fourths to Sequim Prairie (5.3 ft^3/s); Sequim Prairie also receives 2.5 ft^3/s from Independent Ditch.

[e]Leakages were calculated in two parts: upstream half of ditch calculated using full wetted perimeter at point of diversion, downstream half of ditch calculated using one-half wetted perimeter.

[f]Leakage from McDonald Creek diversion applied equally over part of Agnew ditch system carrying the diversion.

[g]Value calculated for 1 1/2 miles of ditch upstream of inflow from Sequim Prairie Ditch. Remaining values for remainder of ditch.

TABLE 6.--Estimated average pumping rates used in model simulations

Well location	Aquifer tapped	Use of water	Estimated average pumping rate (ft^3/s)	Method of estimating pumping rate
30/3-5R	Upper artesian	Irrigation	0.08	Assume 5 inches per year applied to irrigated area.
-8B	Water-table	--do.--	.07	--Do.--
-8J	Upper artesian	--do.--	.02	--Do.--
-8M	--Do.--	Public supply	.13	Assume 250 homes times 2.5 people per home times 130 gallons per day per person
30/4-1M	Water-table	Aquiculture	1.00	Assume half of maximum rate allowed by water-right permit and half of pumped water leaks back to water-table aquifer through holding ponds.
-2R	--Do.--	Irrigation	.08	Assume 5 inches per year applied to irrigated area.
-3Q	Upper artesian	--do.--	.07	--Do.--
-9L	Lower artesian	--do.--	.05	--Do.--
-9E	Water-table	--do.--	.05	--Do.--
-9F	--Do.--	--do.--	.05	--Do.--

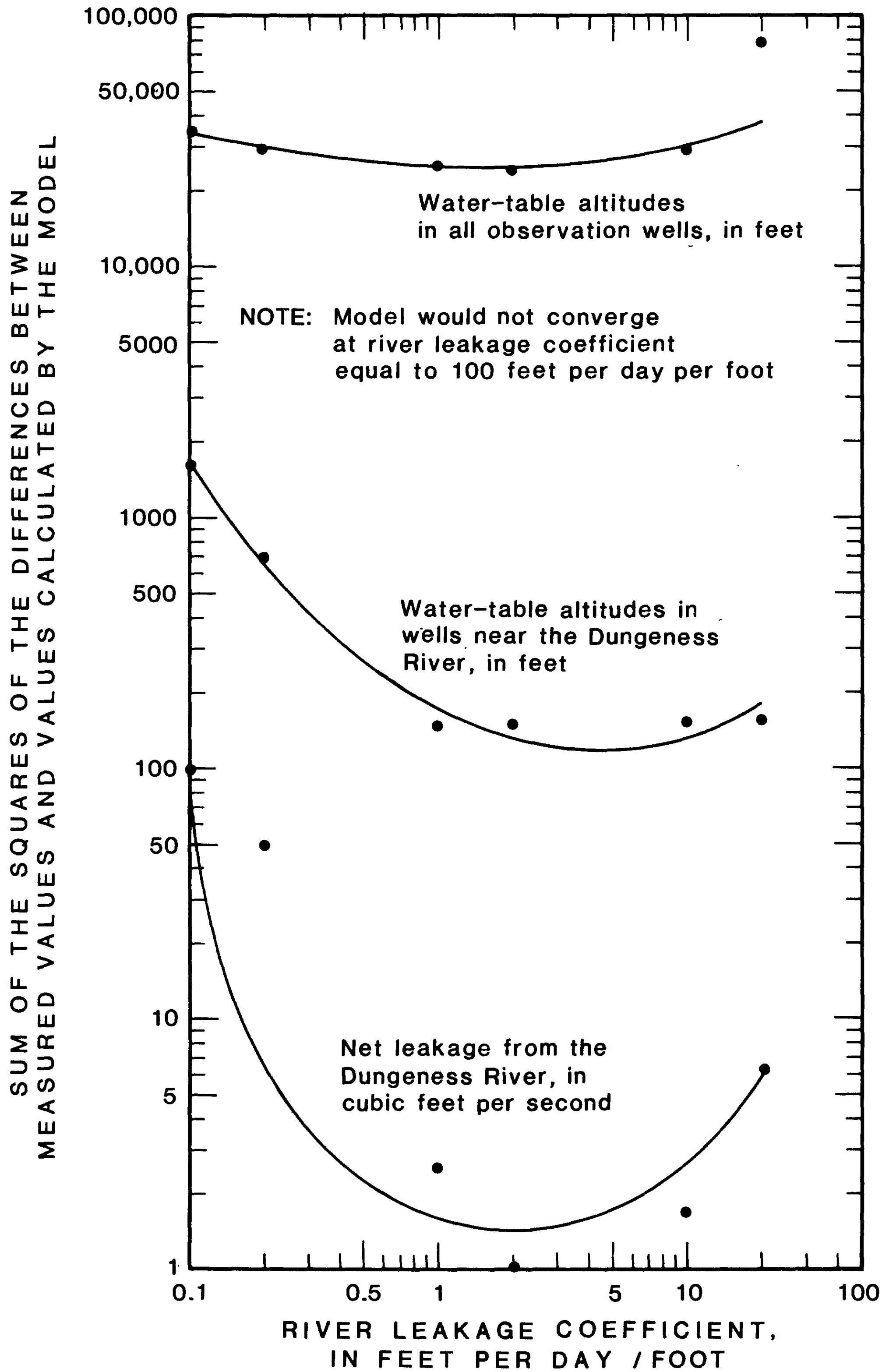


FIGURE 18.--Comparison of measured water-table altitudes and Dungeness River leakage to values computed by the model using various river-leakage coefficients.

Steady-State Simulation

Average conditions existing during March 20-31, 1979, were used for steady-state calibration of the model. This period was selected for calibration because (1) water levels were generally stable (fig. 11); (2) flow in the Dungeness River was generally constant; (3) precipitation was insignificant (0.12 inch); (4) evapotranspiration was minimal; and (5) essentially all irrigation water was restricted to the major ditch systems (no field irrigation).

Calibration was accomplished by holding all model input constant except hydraulic conductivity of the water-table aquifer, transmissivity, vertical leakage coefficients, and river leakage coefficients. Hydraulic conductivity in the water-table aquifer and transmissivity in the artesian aquifers were adjusted only by changing the boundaries of the zones of conductivity and transmissivity, resulting in the final distributions as shown in figures 13 and 14. In all cases, the value assigned to a zone of hydraulic conductivity or transmissivity is the median value derived from all specific-capacity tests in that zone and was not modified during calibration. The model proved to be insensitive to the value of vertical leakage coefficient, showing significant head changes only when the tested value differed by two orders of magnitude or more (from the final value used, 5×10^{-3}ft/day). The river-leakage-coefficient value was adjusted during calibration (fig. 18) to obtain the best reproduction of heads in the water-table aquifer and measured leakage in the Dungeness River.

The reliability of the calibration can be checked by comparing measured heads and river leakages with heads and leakages calculated by the model. Comparisons of measured and calculated heads are shown in figure 19 (water-table aquifer) and table 7 (upper artesian aquifer). No measured water levels were available for the lower artesian aquifer. Well 30/4-9L2, open to the undifferentiated deposits beneath the lower artesian aquifer, had a water-level altitude of 54.1 feet in March 1979, which was probably slightly less than the water-level altitude in the upper artesian aquifer at the same site. The model-calculated water-level altitude was 58.1 feet.

Average measured river leakage from the Dungeness River gage to Dungeness (near the mouth of the river) for March 20-31, 1979, was 20 ft^3/s. Leakage calculated by the model was 19 ft^3/s. The measured leakage includes approximately 1 1/4 miles of river not simulated in the model but believed to be insignificant in regard to the total leakage.

Meadowbrook Creek (the only outflowing creek not significantly affected by irrigation tail waters) had a measured discharge of 5.2 ft^3/s on March 16, 1979. Basically all flow in Meadowbrook Creek is from leakage from the water-table aquifer. Leakage from the aquifer to the creek was calculated to be 5.0 ft^3/s by the model.

The water budget of the ground-water system for the modeled area, as calculated in the steady-state calibration, is shown in figure 20. Total calculated flow through the ground-water system is 82 ft^3/s, including 32.2 ft^3/s, or about 40 percent of the total flow, from irrigation leakage. During the prime irrigation season (April-September) irrigation leakage probably represents an even greater percentage of the total flow (see fig. 11).

TABLE 7.--Comparison of measured and model-calculated water-level altitudes in the upper artesian aquifer, March 1979

Well No.	March 1979 water-level altitude, in feet (1) Measured	March 1979 water-level altitude, in feet (2) Calculated by model	Percent difference $\frac{(2)-(1)}{(1)} \times 100$
30/3-8J3	42.1	43.0	+2
-8M1	42.2	48.8	+16
-16C1	37.4	41.8	+12
-17A1	44.7	49.0	+10
30/4-3Q1	100.4	67.3	-33
-7N1	68.7	62.8	-9
-22J2	152.1	145.4	-4
-23E3	118.1	138.8	+18
-25C1	271.4	269.1	-1

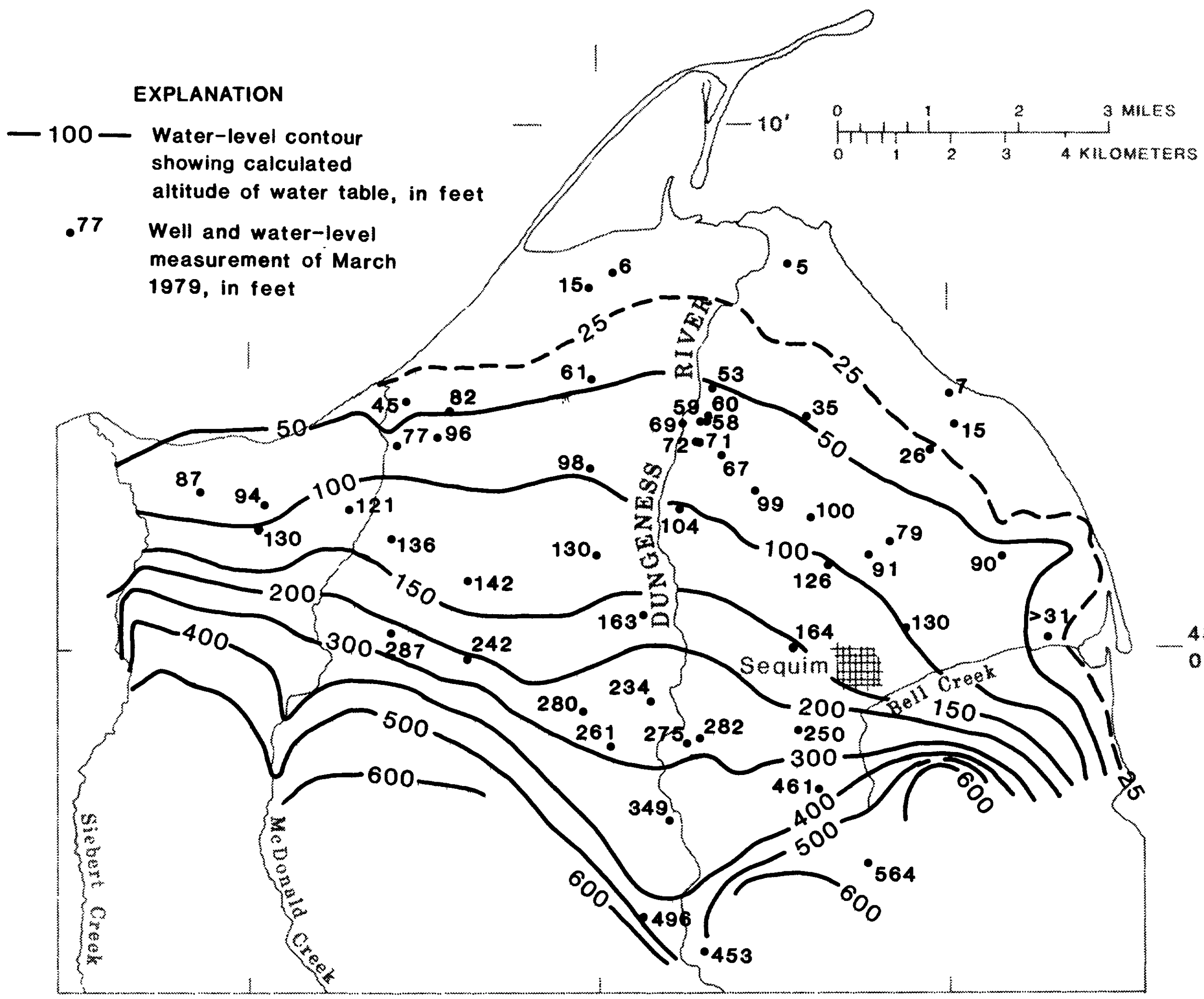


FIGURE 19.--Comparison of measured and model-calculated water-level altitude in the water-table aquifer, March 1979.

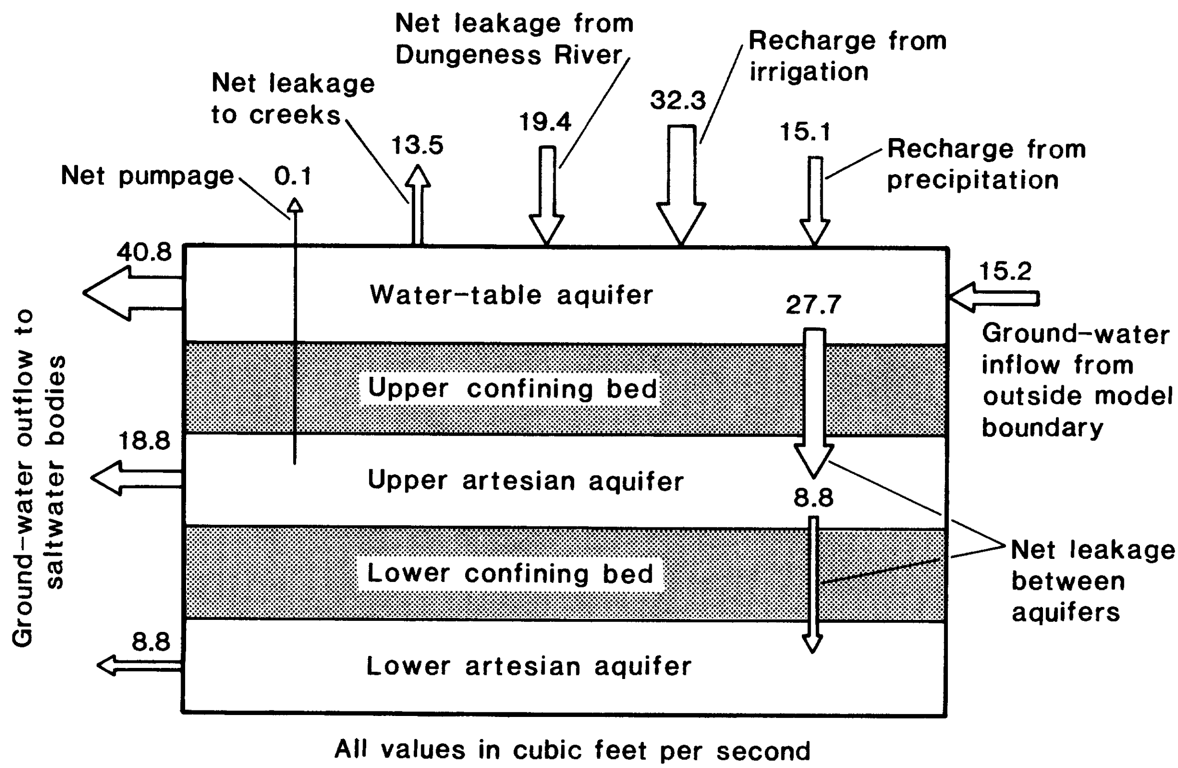


FIGURE 20.--Ground-water budget for March 1979, calculated by steady-state model.

Transient Simulation

The present trend in land use in the study area may lead to eventual abandonment of the irrigation system. This would cause ground-water conditions to return gradually to conditions similar to those existing before construction of the irrigation system. Because data are not available for the period prior to irrigation, a transient model was constructed to show the potential effects of no recharge from irrigation.

Seasonal fluctuations of the ground-water system were considered to be of secondary interest and importance. It was assumed that the gross changes caused by termination of the irrigation system would be at least several times greater than the seasonal fluctuation of water levels (presently about 4 feet, fig. 11).

The transient model uses basically the same input as the steady-state model, except that no recharge from irrigation systems is included in the transient model, and the storage coefficient is added. Starting heads and flow rates in the transient model are the heads and flow rates calculated by the steady-state model.

The transient model was run using two different sets of boundary conditions. One set (constant-head condition) uses exactly the same boundaries as in the steady-state model. In the other set (constant-flux condition) the constant-head boundary along the coastline was changed to a constant rate of outflow as calculated by the steady-state model. The constant-head condition leads to simulations in which calculated drawdowns are generally somewhat less than what would probably occur, while the constant-flux condition produces calculated drawdowns that are generally somewhat greater than what would probably occur.

According to the model, an abrupt termination of the irrigation system would cause water levels to decline significantly, reaching a new equilibrium in 10 to 20 years (fig. 21).

Figure 21 represents the decline in water level (drawdown) at a point in the water-table aquifer where the calculated drawdowns are greatest. All transient simulations were run for 20-year periods to be certain that the effects caused by no recharge from irrigation would stabilize.

Calculated drawdowns caused by termination of the irrigation system are shown for each aquifer in figures 22-27 for various combinations of boundary conditions and river leakage. For each aquifer, the calculated drawdowns are more severe for the constant-flux condition than for the constant-head condition. Actual drawdown would lie somewhere between the two extremes. The greatest impact is in the water-table aquifer where drawdowns would probably average about 20 feet, indicating that some parts of the aquifer could be completely unsaturated and several hundred wells could be dry or nearly so. The artesian aquifers would be less severely impacted with probable average drawdown of about 10 feet. The artesian aquifers would be completely saturated, but the lowered heads would result in greater pumping costs.

Some potential for seawater intrusion could result from termination of the irrigation system. In two small coastal areas (fig. 23) and in a much larger coastal area (fig. 29), calculated heads in the water-table aquifer, using constant-flux conditions, are below sea level. Actual heads in these areas would probably be slightly above sea level. Any significant pumping could then lead to further inland movement of seawater.

Calculated changes that could occur in the ground-water budget due to termination of the irrigation system are shown in table 8. Total flow through the ground-water system could be reduced by 15-30 percent. Net leakage from the Dungeness River could increase by 40-80 percent. The creeks, which have a net inflow from the ground-water system in the steady-state model, could have a net loss to the ground-water system. This could mean that most of the small creeks would be dry or nearly dry most of the time.

The calculated drawdowns in the water-table (figs. 22 and 23) and the calculated changes in the ground-water budget (table 8) indicate that the Dungeness River would be an important factor if the irrigation system were terminated. The calculated drawdowns are very small near the Dungeness River, showing that the increased leakage from the river would serve to replace some of the lost irrigation recharge. Accurate simulation of leakage from the Dungeness River is obviously a prerequisite for accurate simulation of the ground-water system. Because the river-leakage coefficient was not determined independent of the model, the model was run using leakage coefficients one order of magnitude greater than and less than the "ideal" coefficient of 2.0 (ft/day)/ft (fig. 18).

The effects of changing the river-leakage coefficent can be seen in table 9 and figures 28 and 29. Increasing the coefficient by a factor of 10 does not significantly change the computed drawdowns. However, decreasing the coefficient by a factor of ten drastically increases drawdown. The high and "ideal" values of river leakage coefficient (which assume ratios of vertical hydraulic conductivity of the river bed to the horizontal hydraulic conductivity of the underlying aquifer that are about 1/20 and 1/200) are reasonable values to expect in nature. The low value (which assumes a ratio of about 1/2,000) is probably not likely to occur naturally.

TABLE 8.--Comparison of calculated ground-water budgets from steady-state model and transient model after 20 years of no irrigation, with river leakage coefficient of 2.0 cubic feet per day per foot

Ground-water flow	Calculated flow rate, in cubic feet per second		
		Transient model	
	Steady-state model	Constant-head condition	Constant-flux condition
Inflow (all to water-table aquifer)			
Ground water (from uplands)	15.2	16.2	15.7
Precipitation recharge[1]	15.1	15.0	14.7
Irrigation recharge	32.3	--	--
Dungeness River net leakage	19.4	27.1	34.2
Net leakage from creeks	--	1.1	5.1
Total	82.0	59.4	69.7
Net flow between aquifers			
Water-table to upper artesian	27.7	21.9	27.9
Upper artesian to lower artesian	8.8	7.7	8.8
Outflow			
Net leakage to creeks	13.5	--	--
Net pumpage			
Water-table aquifer	--	1.2	1.2
Upper artesian aquifer	0.1	0.3	0.3
Lower artesian aquifer[2]	--	.0	.0
Ground water (all at shorelines)			
Water-table aquifer	40.8	36.4	40.8
Upper artesian aquifer	18.8	13.9	18.8
Lower artesian aquifer	8.8	7.7	8.8
Total	82.0	59.5	69.9
Change in storage (inflow-outflow)	--	-0.1	-0.2

[1]Precipitation recharge in all three cases is input as 15.1 cubic feet per second. In transient model, when a node goes dry the precipitaion recharge at that site is changed to zero.

[2]Pumping rate input to the transient model is actually 0.05 cubic feet per second; the 0.0 results from rounding off.

TABLE 9.--Comparison of drawdowns and selected ground-water flow rates computed by the model using various river leakage coefficients.

River leakage Coefficient[1]	Shoreline boundary condition	Drawdown, in feet, after 20 years of no irrigation, computed by model[4] (ft)										Calculated flow rate, in cubic feet per second		
		Water table aquifer[2]				Upper artesian aquifer[3]			Lower Artesian aquifer[3]					
		Node				Node			Node					
		3,25	13,27	19,32	26,34	3,25	13,27	29,28	3,25	13,17	24,26	Net leakage from Dungeness River	Net leakage from creeks	Net ground-water flow
0.2	Constant-flux	24.00	16.04	31.00 (dry)	56.99	37.81	36.21	9.59	39.27	38.79	30.30	23.6	0.9	55.1
2.0	Constant-flux	2.52	.74	17.56	54.47	17.90	17.28	1.01	19.42	19.32	12.71	34.2	5.1	69.7
2.0	Constant head	.03	.52	17.22	54.88	.13	2.84	.99	.06	1.26	3.60	27.1	1.1	59.4
20.0	Constant head	.00	1.00	16.53	54.76	.10	2.45	.00	.05	1.05	2.83	32.1	-2.1	61.7

[1]Equals vertical hydraulic conductivity of the river bed divided by the thickness of the river bed, in feet per day per foot.

[2]Nodes are located; near shoreline, near Dungeness River, near center of aquifer (relatively unaffected by Dungeness River), and in upland area, respectively.

[3]Nodes are located; near shoreline, near center of aquifer, and at farthest upland extent of aquifer, respectively.

[4]For leakage coefficient of 0.2, drawdown and flow rates are computed after 10 years of no irrigation. The model would not compute beyond 10 years because of an excess number of dry nodes.

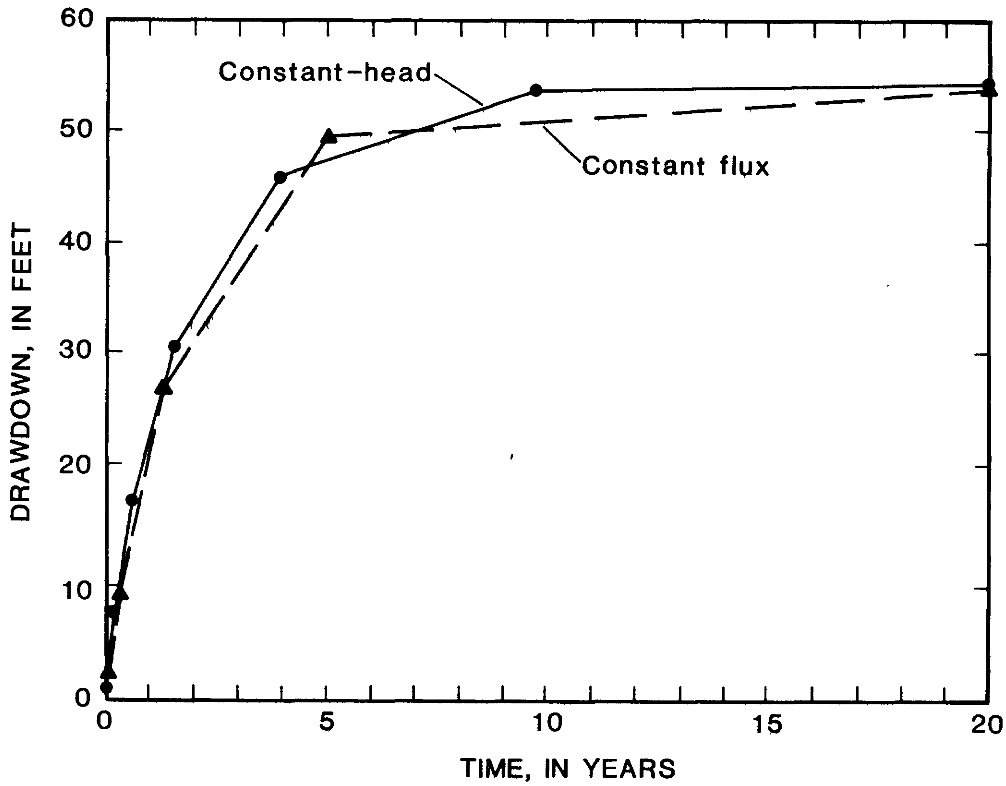


FIGURE 21.--Drawdown at node 26,34 in the water-table aquifer, computed by the model assuming no irrigation and river leakage coefficient of 2.0 feet per day per foot.

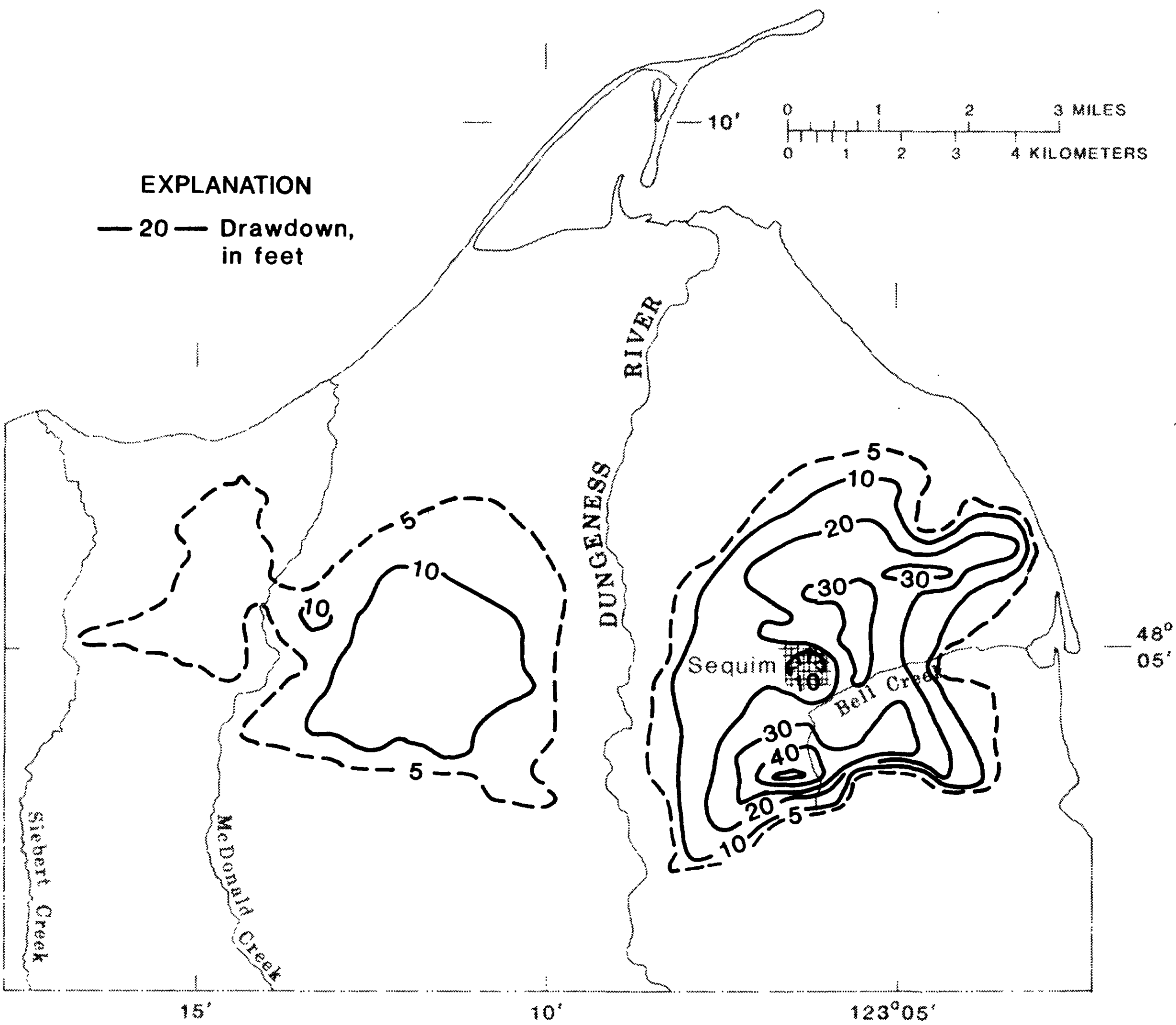


FIGURE 22.--Drawdown after 20 years of no irrigation, calculated by the model using river leakage coefficient of 2.0 feet per day per foot and constant-head conditions in the water-table aquifer.

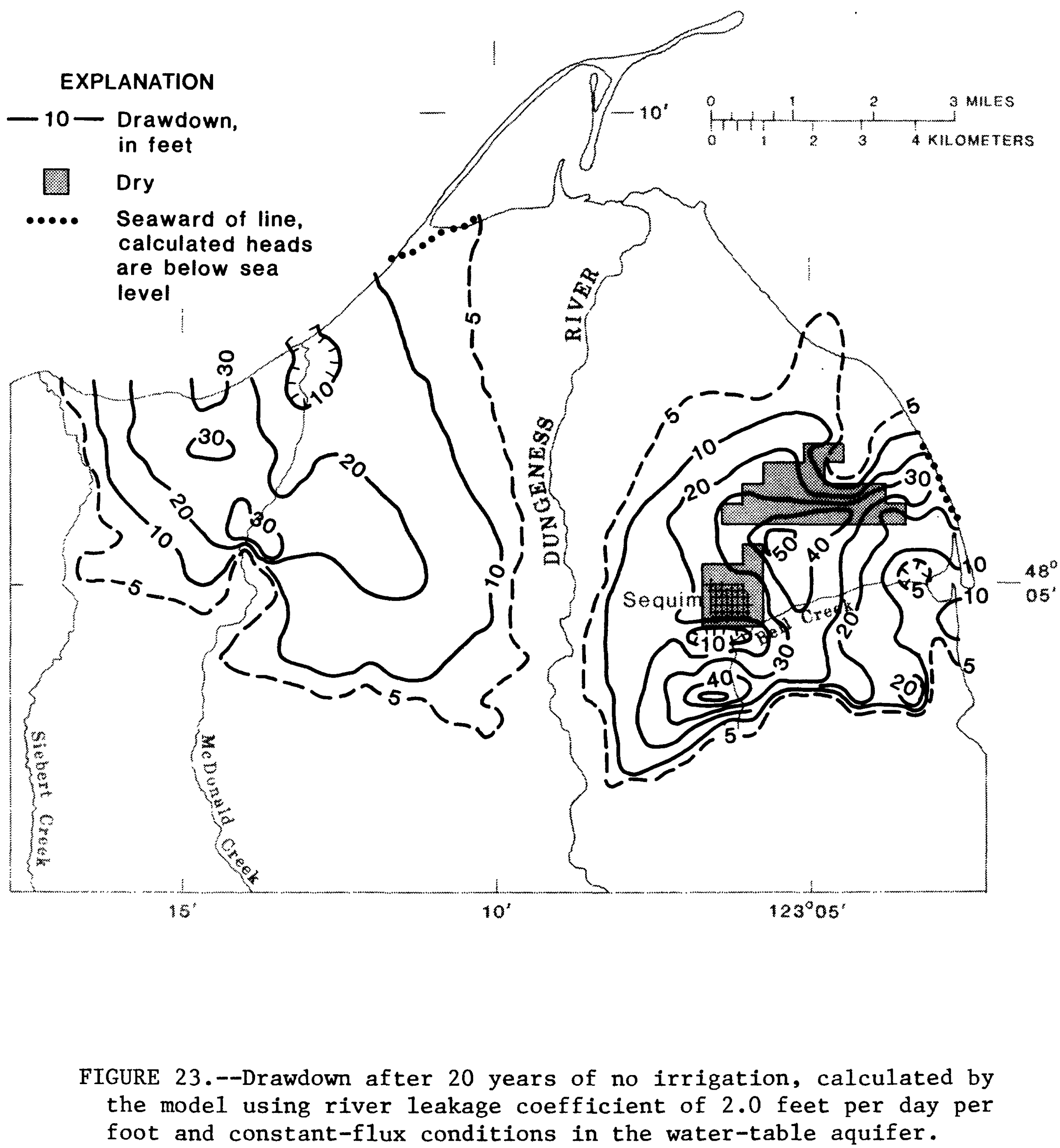


FIGURE 23.--Drawdown after 20 years of no irrigation, calculated by the model using river leakage coefficient of 2.0 feet per day per foot and constant-flux conditions in the water-table aquifer.

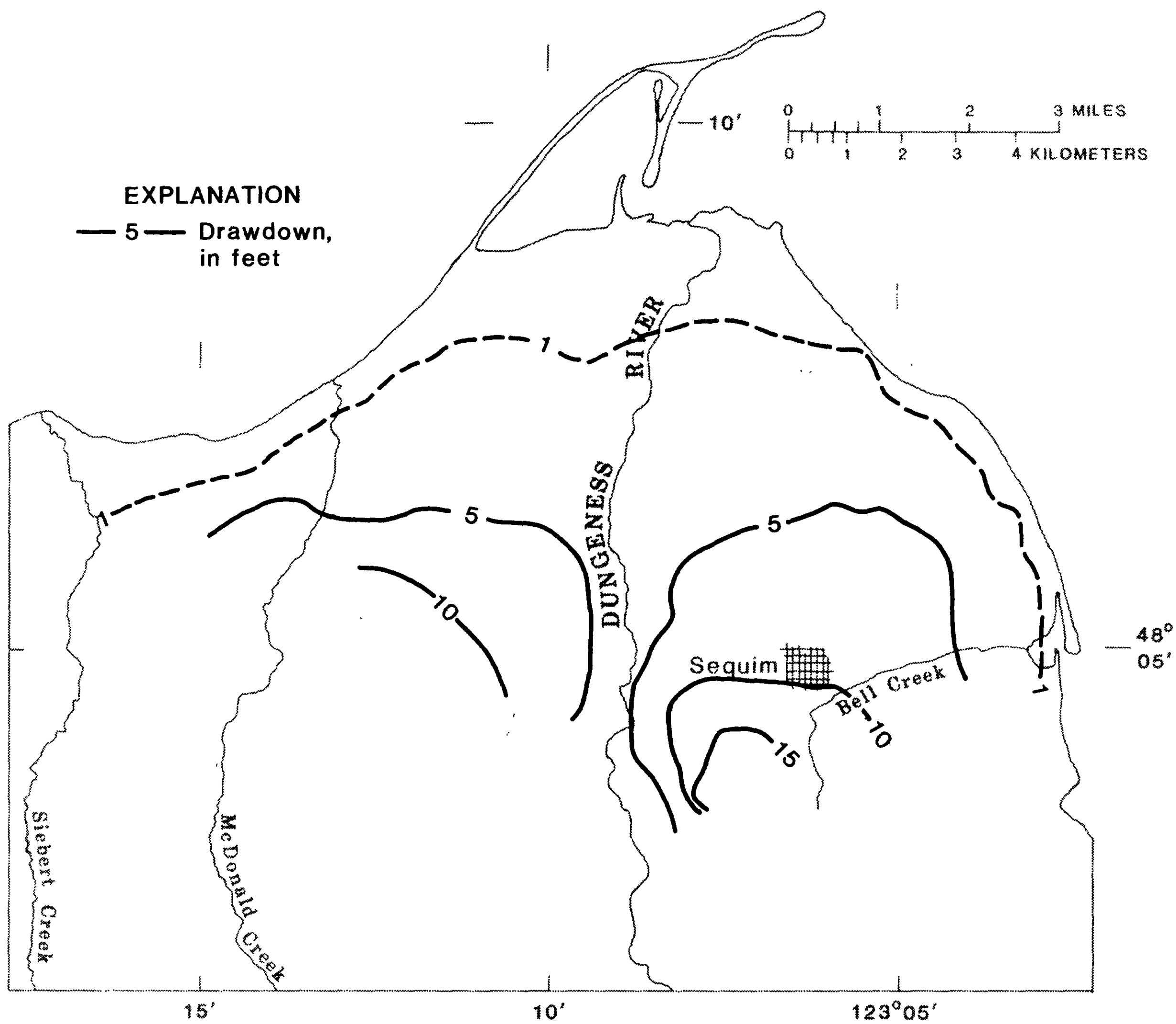


FIGURE 24.--Drawdown after 20 years of no irrigation, calculated by the model using river leakage coefficient of 2.0 feet per day per foot and constant-head conditions in the upper artesian aquifer.

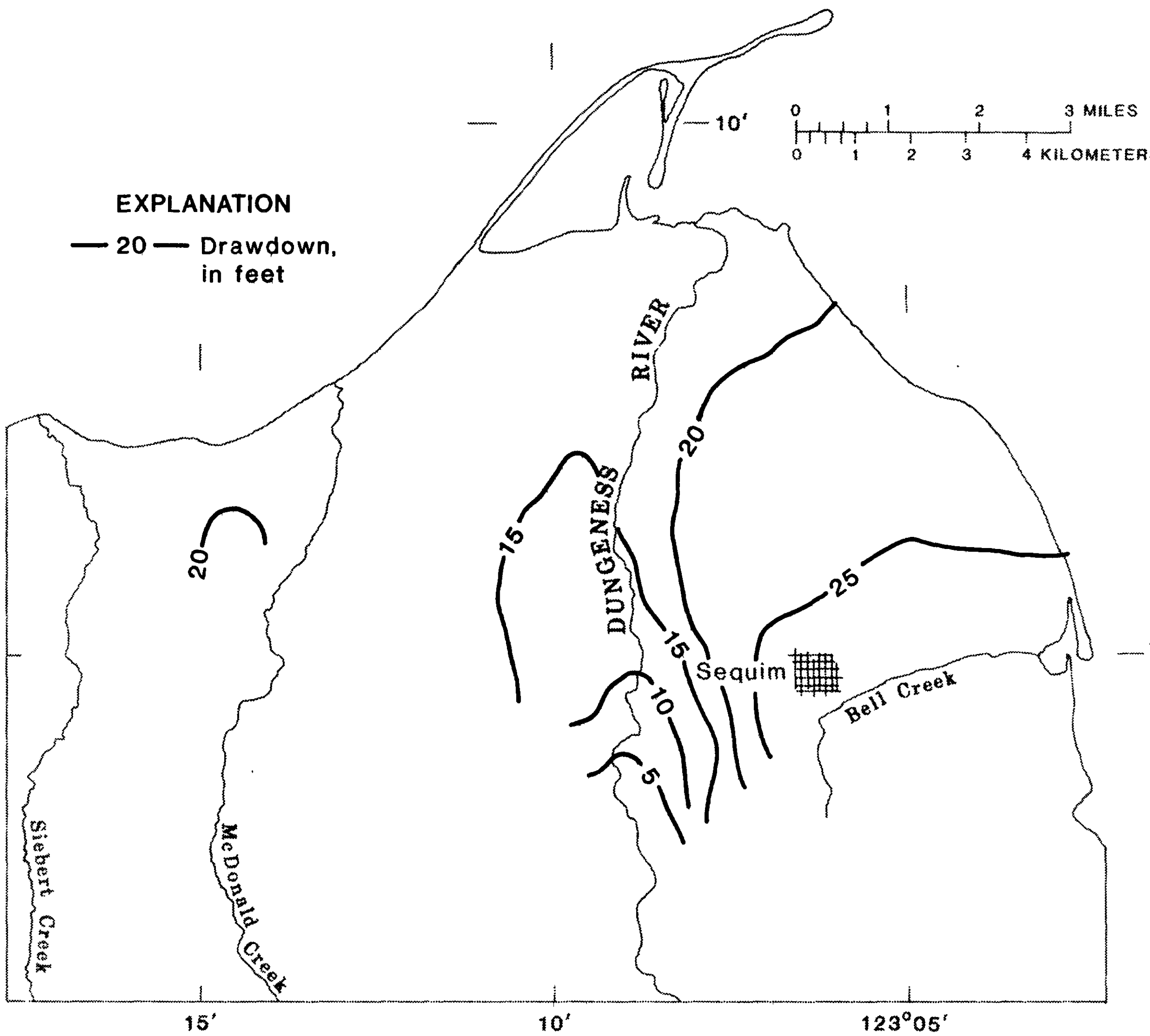


FIGURE 25.--Drawdown after 20 years of no irrigation, calculated by the model using river leakage coefficient of 2.0 feet per day per foot and constant-flux conditions in the upper artesian aquifer.

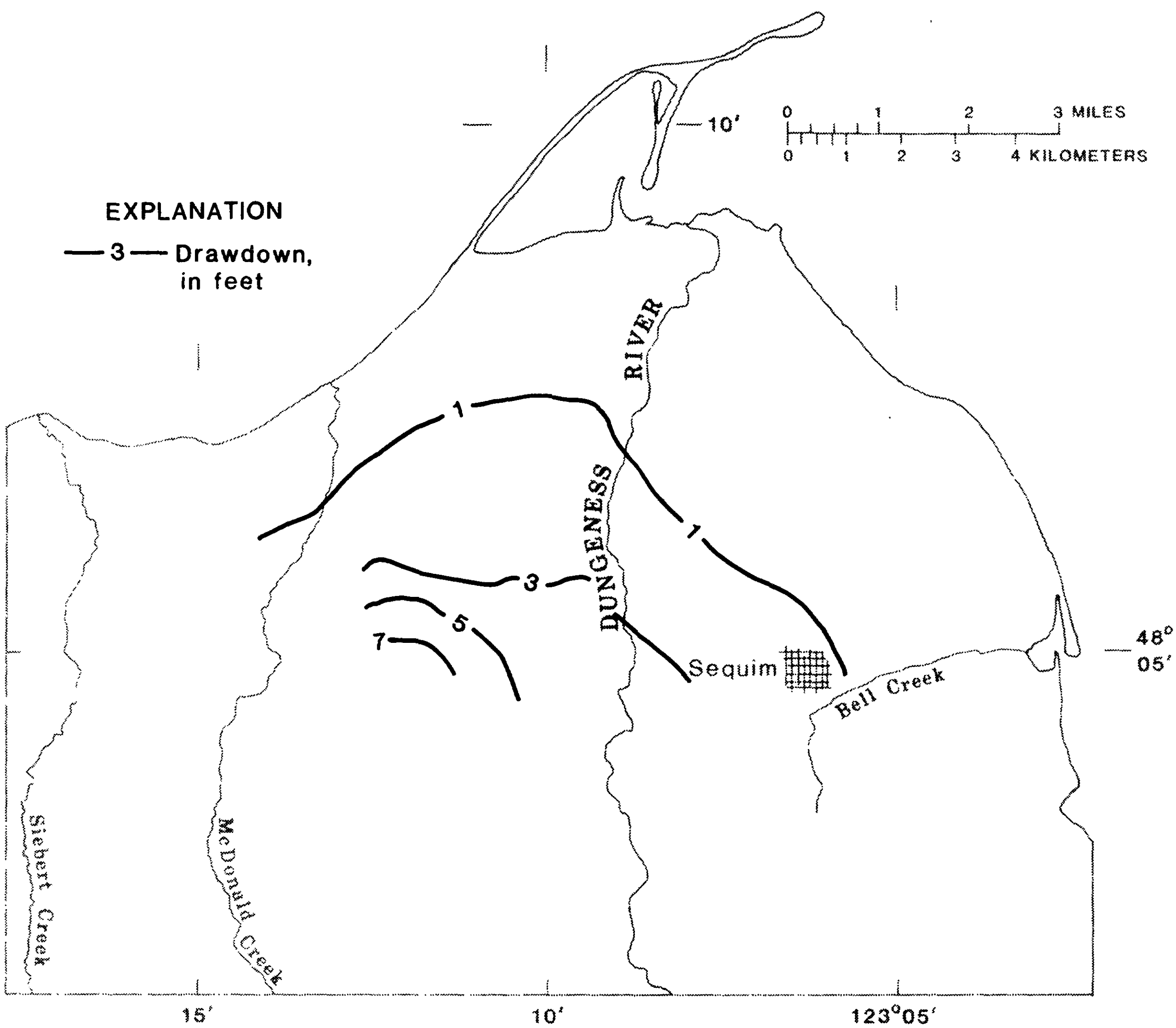


FIGURE 26.--Drawdown after 20 years of no irrigation, calculated by the model using river leakage coefficient of 2.0 feet per day per foot and constant-head conditions in the lower artesian aquifer.

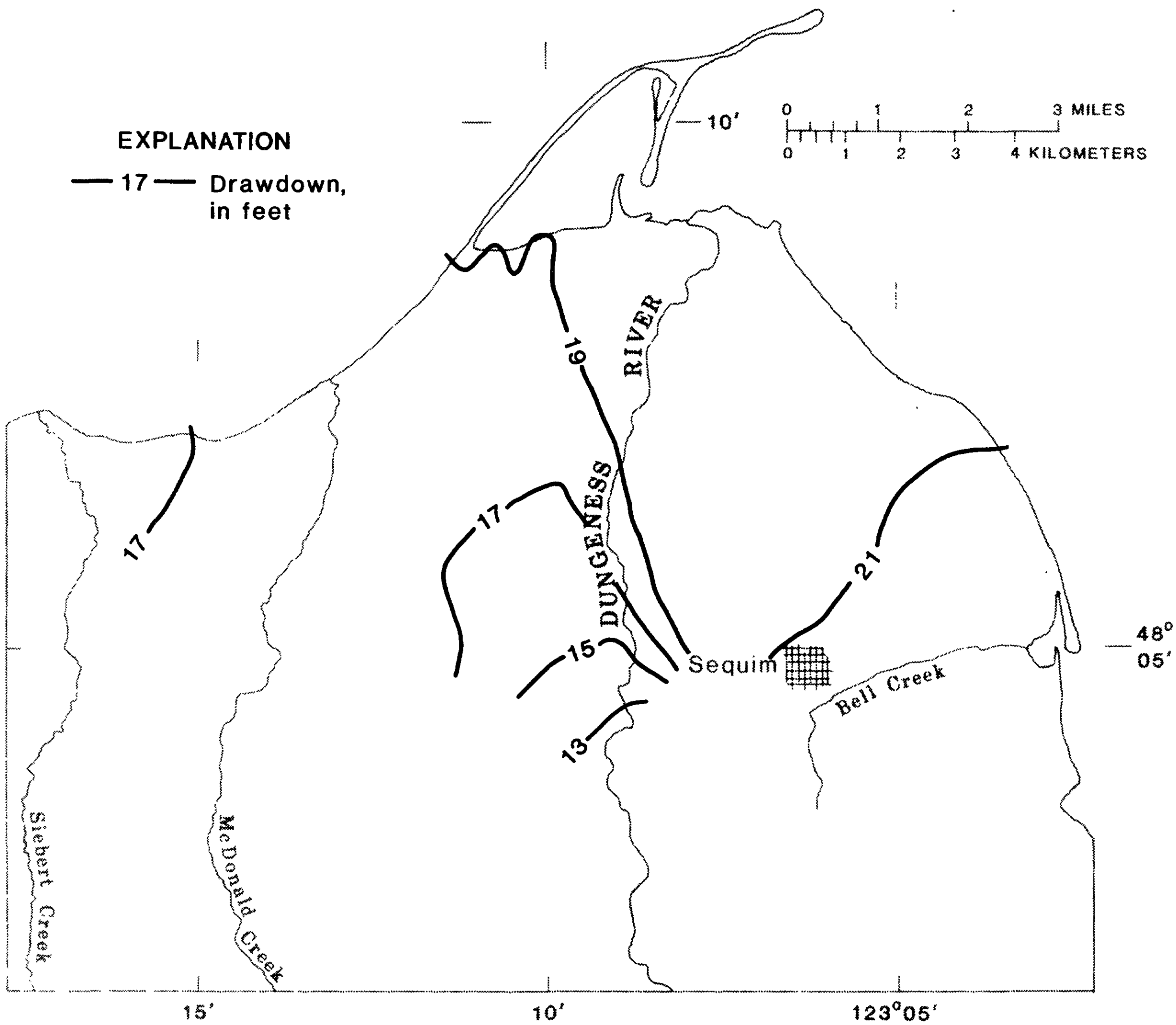


FIGURE 27.--Drawdown after 20 years of no irrigation, calculated by the model using river leakage coefficient of 2.0 feet per day per foot and constant-flux conditions in the lower artesian aquifer.

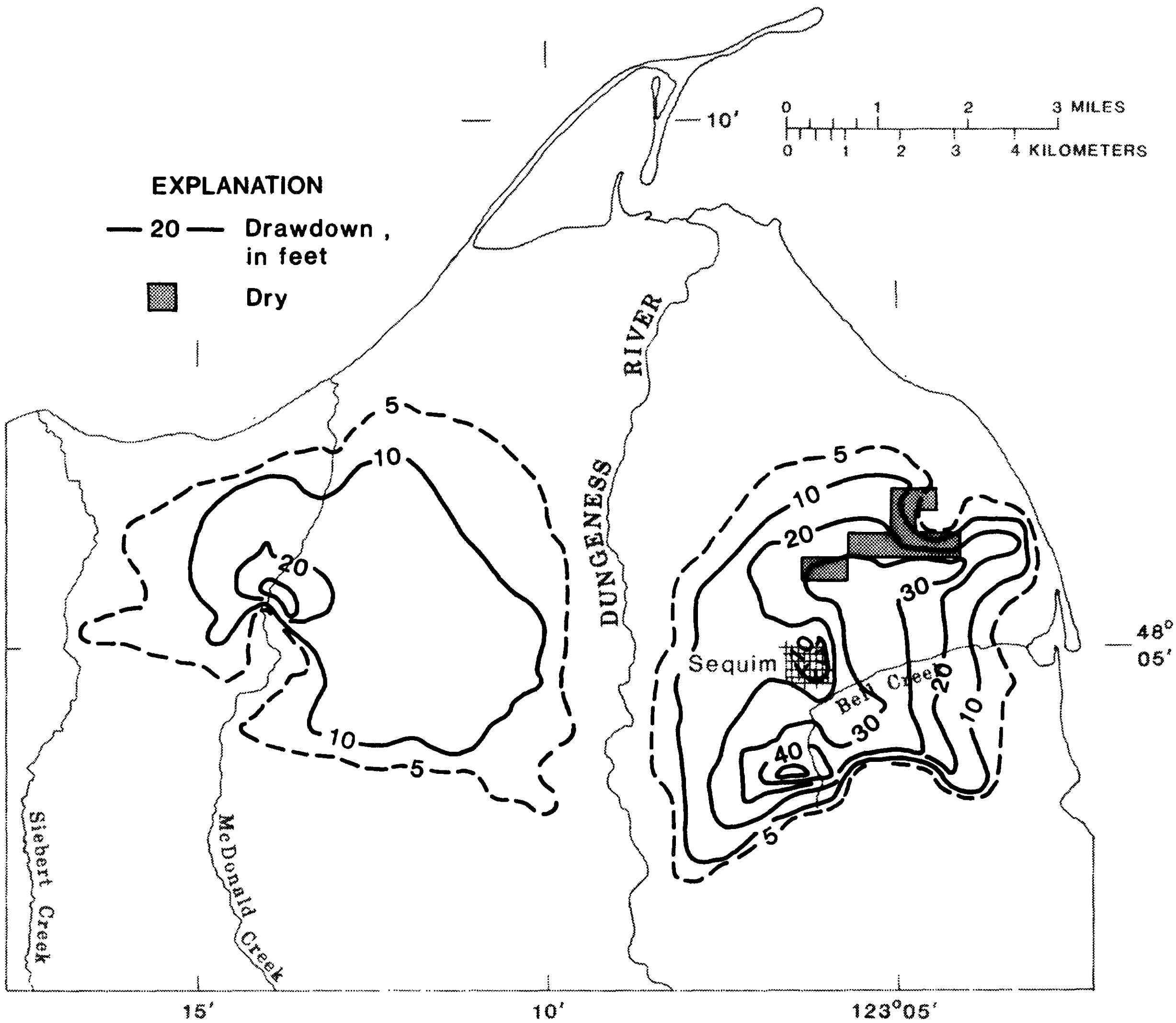


FIGURE 28.--Drawdown in the water-table aquifer calculated by the model after 20 years of no irrigation, using constant-head conditions and river leakage coefficient of 20 feet per day per foot.

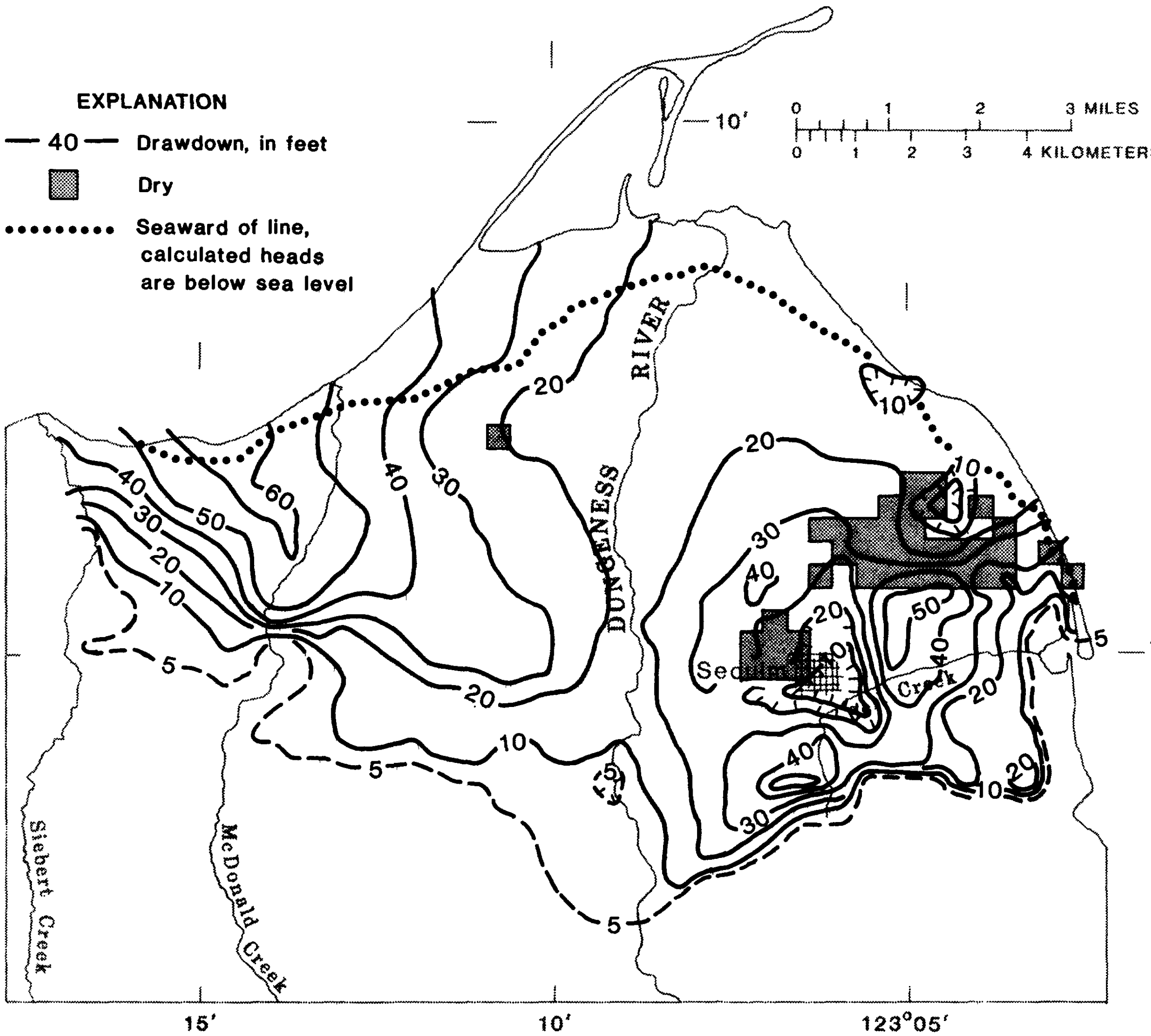


FIGURE 29.--Drawdown in the water-table aquifer calculated by the model after 10 years of no irrigation, using constant-flux conditions and river leakage coefficient of 0.2 foot per day per foot.

SUMMARY AND CONCLUSIONS

1. The digital model described in this report simulated the ground-water flow system within the accuracy of the input data.

2. The model confirms that leakage from the irrigation system is the largest source of recharge to the ground-water system. The leakage occurs primarily from the ditch system, not from water actually applied to fields.

3. Termination of the irrigation system would lead to lower heads throughout the ground-water system. The ground-water levels in the water-table aquifer could have average declines of about 20 feet, and some areas could become completely unsaturated. Several hundred wells could go dry.

4. Ground-water quality, as of June 1980, has apparently not been greatly affected by the use of on-site domestic sewage-disposal systems. The potential for future contamination cannot be assessed with the data presently available.

Future studies should include the following.

1. Ground-water levels and rates of irrigation diversion would need to be monitored in order to assess the impact of any changes in land use.

2. Flow in the Dungeness River would need to be monitored, at least at the gage and at Dungeness. This information would be required to properly interpret any changes observed in number 1 (above).

3. Water quality would need to be tested periodically and compared with the baseline data (June 1980) presented in this report.

4. If a significant increase in development of the artesian aquifers occurs, the new data could be used to update the model and test its ability to accurately simulate flow in these aquifers.

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