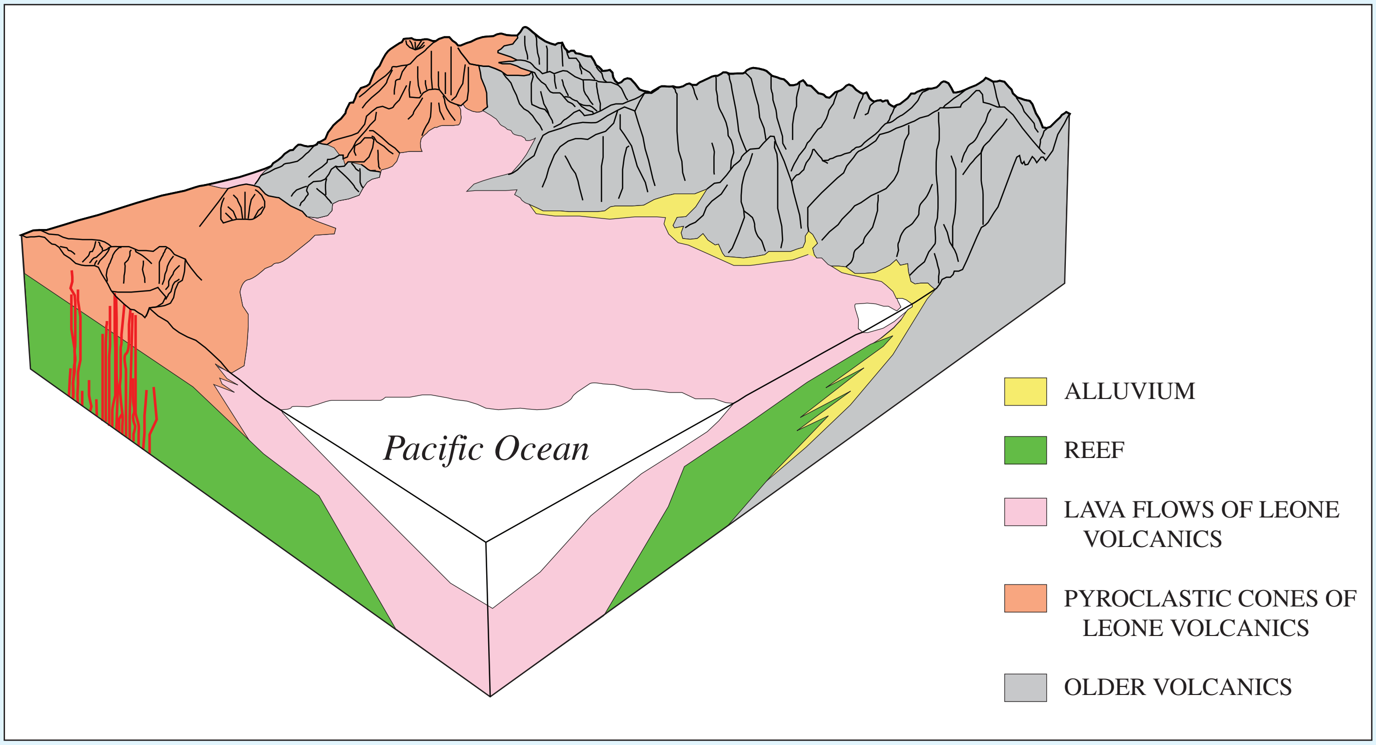
Prepared in cooperation with the American Samoa Environmental Protection Agency

Areas Contributing Recharge to Wells in the Tafuna-Leone Plain, Tutuila, American Samoa



Scientific Investigations Report 2007–5167

U.S. Department of the Interior
U.S. Geological Survey

COVER

Block diagram showing the geology of the eastern Tafuna-Leone Plain and and the mountians to the north, Tutuila, American Samoa.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to mean sea level. Elevation, as used in this report, refers to distance above the vertical datum.

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS84).

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Areas Contributing Recharge to Wells in the Tafuna-Leone Plain, Tutuila, American Samoa

By Scot K. Izuka, Jeff A. Perreault, and Todd K. Presley

Abstract

To address the concerns about the potential for contamination of drinking-water wells in the Tafuna-Leone Plain, Tutuila, American Samoa, a numerical ground-water flow model was developed and used to delineate areas contributing recharge to the wells (ACRWs). Surveys and analyses were conducted to obtain or compile certain essential hydrogeologic information needed for the model, such as ground-water production statistics, ground-water levels under current production, and an assessment of the distribution of ground-water recharge. The ground-water surveys indicate that total production from all wells in the Tafuna-Leone Plain between 1985 and 2005 averaged 6.1 Mgal/d and showed a gradual increase. A synoptic survey indicates that current water levels in the Tafuna-Leone Plain are highest near its inland boundary, decrease toward the coast, and are slightly depressed in high-production well fields. Ground-water levels showed little effect from the increased production because hydraulic conductivites are high and withdrawal is small relative to recharge. Analysis of ground-water recharge using a soil water-budget analysis indicates that the Tafuna-Leone Plain and adjacent areas receive about 280 Mgal/d of water from rainfall, of which 24 percent runs off to the ocean, 26 percent is removed by evapotranspiration, and 50 percent goes to ground-water recharge. Ground-water recharge per unit area is generally higher at the mountain crests than at the coast, but the highest recharge per unit area is in the mountain-front recharge zone at the juncture between the Tafuna-Leone Plain and the adjacent mountains. Surface water from the mountains also contributes to ground-water recharge in the eastern Tafuna-Leone Plain, in a process analogous to mountain-front recharge described in arid areas. Analysis of stream-gage data indicates that in the mountains of Tutuila, ground water discharges and contributes substantially to the total flow of the streams. In contrast, multiple lines of evidence indicate that in the eastern Tafuna-Leone Plain, surface water recharges the highly permeable underlying aquifer.

Steady-state model simulations representing current ground-water production conditions in the Tafuna-Leone Plain indicate that most ACRWs extend less than a mile from the production wells; thus, travel distance between any point within an ACRW and its well is short. A simulation representing a condition in which all wells are operating at maximum capacity resulted in larger ACRWs, which demonstrates that increasing ground-water withdrawal from existing wells, or building and developing new wells, increases the surface area that could potentially contribute contaminants. In some places, such as in Malaeimi Valley, water can travel quickly via surface-water routes to an area where the water can infiltrate within the ACRWs of a well field.

Introduction

Nearly all of the public drinking water supply on the island of Tutuila, American Samoa, comes from ground-water resources. Most of this water comes from wells in the Tafuna-Leone Plain, an area of relatively low relief in the southwest of Tutuila (fig. 1).

Water withdrawn from wells ultimately comes from an area of recharge at the surface (fig. 2). Sources of contamination on the land surface that lie within the areas contributing recharge to wells can pose a threat to the quality of the water produced at the wells. The Tafuna-Leone Plain is the site of urbanization, industrialization, and small-scale farming that are near wells that produce drinking water. Evidence from previous studies, including the presence of fecal coliform bacteria in water sampled from wells following heavy rain (Eyre, 1994), the rapid response of chloride concentrations to rainfall peaks (Izuka, 1999), and a lack of well-developed runoff channels, indicate that in some areas of the plain, water can quickly infiltrate the surface and carry contaminants to ground-water bodies and drinking-water wells. To address concerns about the potential for contamination of water produced from wells in the Tafuna-Leone Plain, the U.S. Geological Survey (USGS), in cooperation with the American Samoa Environmental Protection Agency (ASEPA), undertook a study to identify areas contributing recharge to existing wells that produce drinking water.

Because the interaction of various factors affecting ground-water flow is complex, numerical ground-water models are the best approach to estimating the area contributing recharge to wells in geohydrologically complex areas (Franke and others, 1998). In order to develop a model that accurately represents the ground-water system in the Tafuna-Leone

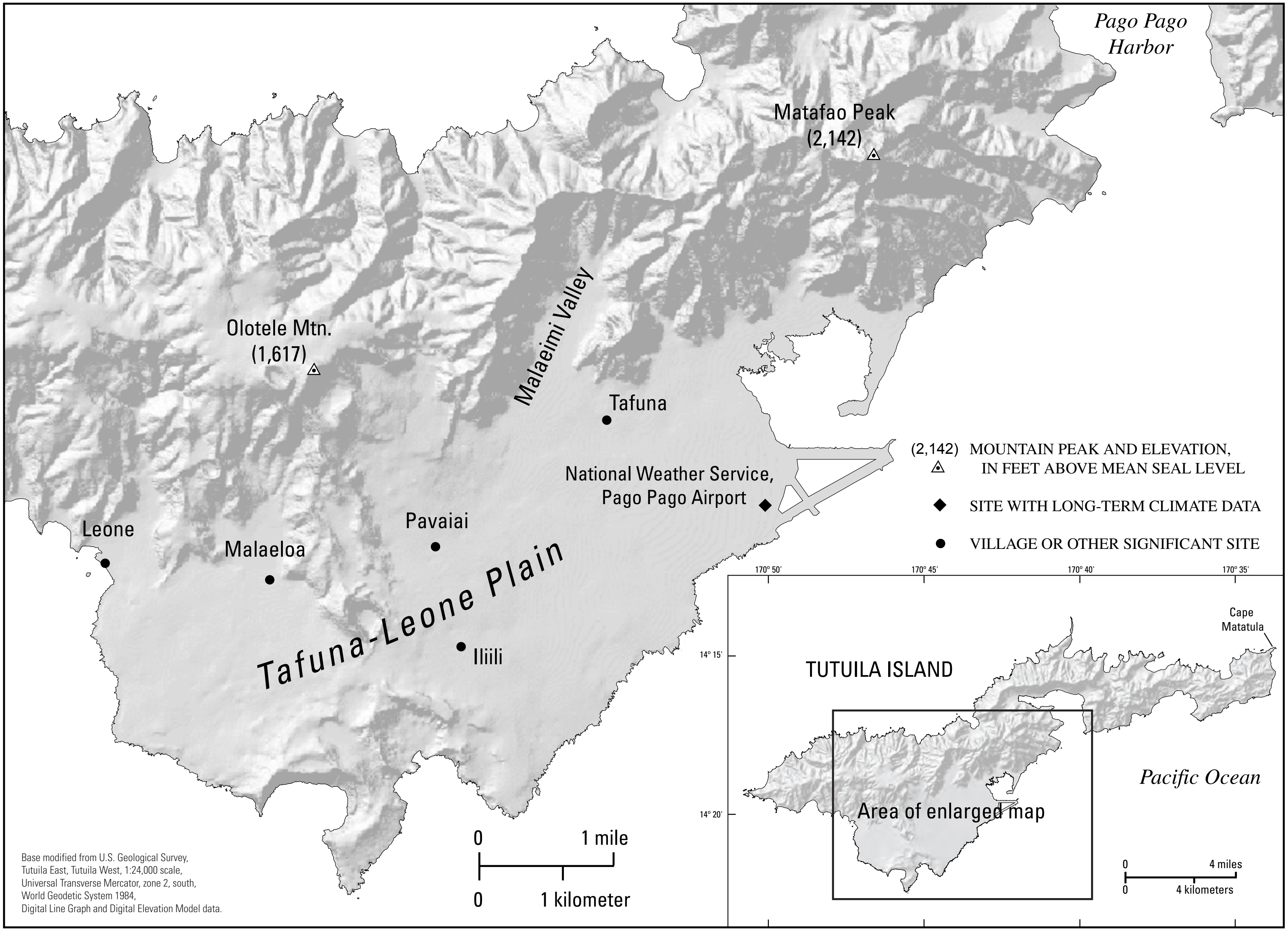


Figure 1. The Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

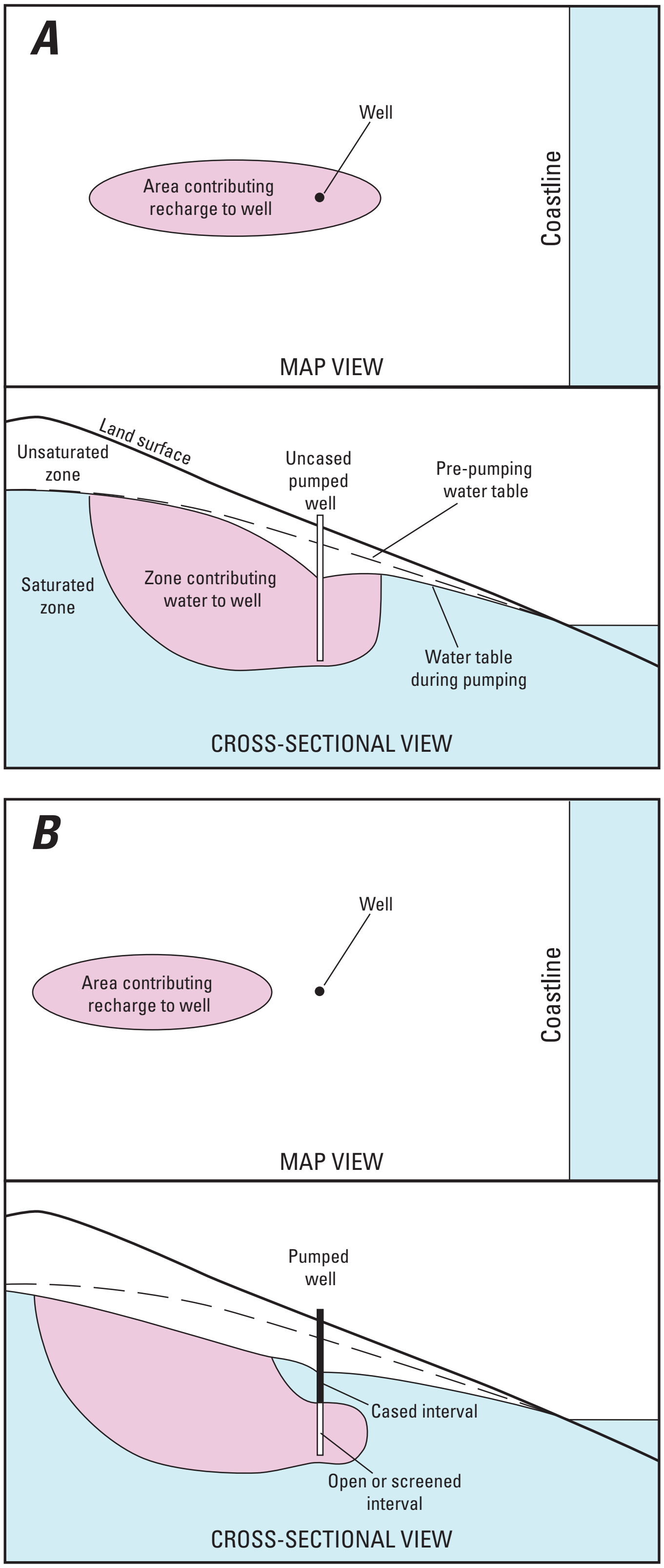


Figure 2. Conceptualization of area contributing recharge to (*A*) an uncased well and (*B*) a well cased through upper part of saturated zone.

Plain, certain hydrogeologic data and analyses were needed. A general understanding of the geology and ground-water occurrence for Tutuila was developed from early studies such as those of Stearns (1944) and Davis (1963). Later studies, such as those of Bentley (1975), Matsuoka (1978), Wong (1996), and Izuka (1999), contributed quantitative information on aquifer hydraulic properties, streamflow, and conceptual models of ground-water occurrence. Recent studies have provided some quantitative information essential to the comprehensive understanding of ground-water flow in the island, including analyses of the distribution of rainfall (Daly and others, 2006) and of potential evapotranspiration (Izuka and others, 2005a). Some information, such as well construction and accounts of current spatial and temporal ground-water production from wells, are available from records at the American Samoa Power Authority (ASPA, the agency of the American Samoa Government responsible for providing water to the public). Other critical data, however, were lacking, including a survey of water levels tied to a common elevation datum and an assessment of the distribution of ground-water recharge. Because these data sets are prerequisite to the development of a numerical ground-water flow model for the Tafuna-Leone Plain, their acquisition was incorporated into the scope of this study.

Purpose and Scope

This report describes a hydrogeologic investigation to determine areas contributing recharge to existing wells on the Tafuna-Leone Plain. The study included three principal components: (1) compilation and analysis of ground-water data, (2) computation of ground-water recharge, and (3) development of a numerical ground-water flow model to assess the areas contributing recharge to existing wells. The compilation and analysis of ground-water data included research of available historical information as well as field surveys to collect current water-level data and ground-water withdrawal data. The computation of ground-water recharge involved the incorporation of available data into a soil water-budget analysis from which ground-water recharge was derived. The numerical ground-water flow model was developed by incorporating the results of the ground-water and recharge analyses, and the model was used to determine the areas contributing recharge to wells in the Tafuna-Leone Plain.

Acknowledgments

This study was funded by a cooperative agreement between the USGS and the ASEPA. The authors are grateful to Dr. Toafa Vaiagae, Director, and Mr. Peter Peshut, Deputy Director of the ASEPA, for their cooperation and assistance. Data on well withdrawals and construction were provided by ASPA. Representatives from ASPA also assisted during water-level field surveys. Delwyn Oki, Jesse Dickenson, and Don Arnold of the USGS assisted in the completion of this study and report.

Conceptualization of the Area Contributing Recharge to a Well

The area contributing recharge to a well is the area on the land surface within which water recharging the aquifer will eventually be withdrawn from the well. This area has been referred to by various loosely defined terms, but in this report, the phrase “area contributing recharge to wells” (abbreviated ACRW, or the plural form, ACRWs) is used, which is consistent with the terminology used by Franke and others (1998). In the conceptualization shown in figure 2, water recharging at the land surface percolates downward vertically through the unsaturated zone until it reaches the water table. At and below the water table, ground-water flow is governed by the distribution of hydraulic head in the saturated aquifer—water flows from higher head to lower head, or in the downgradient direction. Inasmuch as the water table is an expression of the hydraulic head in the highest part of the saturated aquifer, an approximate idea of ground-water flow can be obtained by studying a water-table map.

The size, shape, and location of the ACRW depends on the pumping rate of the well relative to the rate of recharge in the surrounding area, the regional flow system of the aquifer, and the details of the well’s construction. In general, the ACRW is larger for larger pumping rates, but the size is also a function of the amount of recharge the area receives. The ACRW will only be large enough to encompass recharge equivalent to the water the well is withdrawing. In most areas of an island aquifer, the water table slopes from the interior of the island to the coastline, forming a regional seaward flow system. When a well withdraws water from such a system, the shape of the ACRW will be an ellipsoid that is elongate in the direction opposite regional flow (fig. 2). The greater the influence of the regional flow system (in other words, the steeper the hydraulic or water-table gradient) the more elongate the ACRW becomes. Because hydraulic properties of the rocks, aquifer recharge and discharge boundaries, and variation of ground-water recharge in space and time affect the regional flow system, they will also affect the shape and size of the ACRW.

If the open interval of the well extends upward to the water table, the ACRW will include the well, but most of the area will be on the upgradient side of the well (fig. 2). If the well is constructed such that the well’s production comes from an interval below the water table, the ACRW may be separated horizontally from the well, with all of the area on the upgradient side of the well.

Setting

Tutuila is a part of the Samoa Islands, an archipelago in the tropical South Pacific. The island has an area of 53 mi^2 and a population of about 55,000 people (U.S. Census Bureau, 2004) and is the seat of government and site of most industry in American Samoa. The island’s topography is dominated by a ridge of deeply eroded mountains that generally trend east-northeast (fig. 1). The mountains rise abruptly from sea level to elevations as high as 2,142 ft. The juxtaposition of the deeply eroded mountains with the sea creates a sinuous coastline, much of which has little or no coastal plain. The Tafuna-Leone Plain on the southwest of Tutuila is an area of gentler topography, but has hills and more than 600 ft of relief. Most of the island’s industry and much of the population is located on the relatively extensive flat areas of the Tafuna-Leone Plain; maritime industries and a large tuna-packing complex are located in the Pago Pago Harbor Area. Elsewhere, the rugged topography limits most of the population to narrow coastal areas or the floors of small valleys.

Tutuila can be divided into two broad physiographic regions: (1) the rugged mountainous region that forms most of the island, and (2) the Tafuna-Leone Plain (fig. 1). The two regions differ topographically and hydrologically. The mountains are drained by numerous streams, many of which are perennial (Matsuoka, 1978; Wong, 1996), indicating that they are fed by ground-water discharge. In contrast, the Tafuna-Leone Plain has few well-developed stream channels, and some streams with perennial flow in the mountains disappear or become intermittent when they reach the Tafuna-Leone Plain. Davis (1963) inferred, primarily on the basis of surface geology and evidence from springs and coastal freshwater seeps, that large yields may be possible from wells in the Tafuna-Leone Plain, whereas high yields are unlikely from wells in the mountainous region of Tutuila. By the mid 1970s, numerous wells had been drilled, confirming the high ground-water production potential of the Tafuna-Leone Plain and the relatively low productivity of wells for most other locations in Tutuila (Bentley, 1975).

Climate

Tutuila lies in the area influenced by the South Pacific Convergence Zone (SPCZ) (Giambelluca and others, 1988). Data from the National Weather Service Office at the Pago Pago Airport for the period 1971–2000 indicate normal daily low and high temperatures are 24 and 30°C (76 and 86°F), respectively, with a few degrees of seasonal variation, and relative humidity averages 86 percent in the morning and 75 percent in the afternoon, with a seasonal variation of a few percent (National Climatic Data Center, 2004). Wind speed averages 11 mi/h at both the airport and at Cape Matatula on the eastern tip of the island; prevailing winds are southeasterly for most of the year, but more variable and weaker from about late December to early April (Mefford, 2002, 2004; Climate Monitoring and Diagnostics Laboratory, 2004; National Climatic Data Center 2004).

Rainfall on Tutuila is relatively high because of the presence of the SPCZ and its associated storms and is seasonally variable as a result of the movement of the SPCZ (Giambelluca and others, 1988). On average, rainfall is highest from about October through May and lowest from about June through September (fig. 3). Rainfall on Tutuila also varies with location and topography relative to the prevailing winds as a result of the orographic effect (fig. 4) (Daly and others, 2006). In coastal areas, average annual rainfall ranges from 71 in. at Cape Matatula to 118 in. at the Pago Pago Airport (Mefford, 2004; National Climatic Data Center, 2002). In contrast, rainfall at the former USGS rain gage in Aasufou Village (near Olotele Mountain), at an elevation of 1,340 ft above sea level, averaged about 200 in/yr (Izuka, 1999). Although these averages are not from concurrent periods, they are computed from long-term records and show that rainfall is generally higher in the mountains and lower at the coasts. Rainfall on Tutuila also varies annually—during the period from 1970 through 2004, annual rainfall at the Pago Pago Airport ranged from a high of 45 in. above average in 1981 (163 in.) to a low of 62 in. below average during the El Niño event of 1998 (56 in.) (Izuka and others, 2005a).

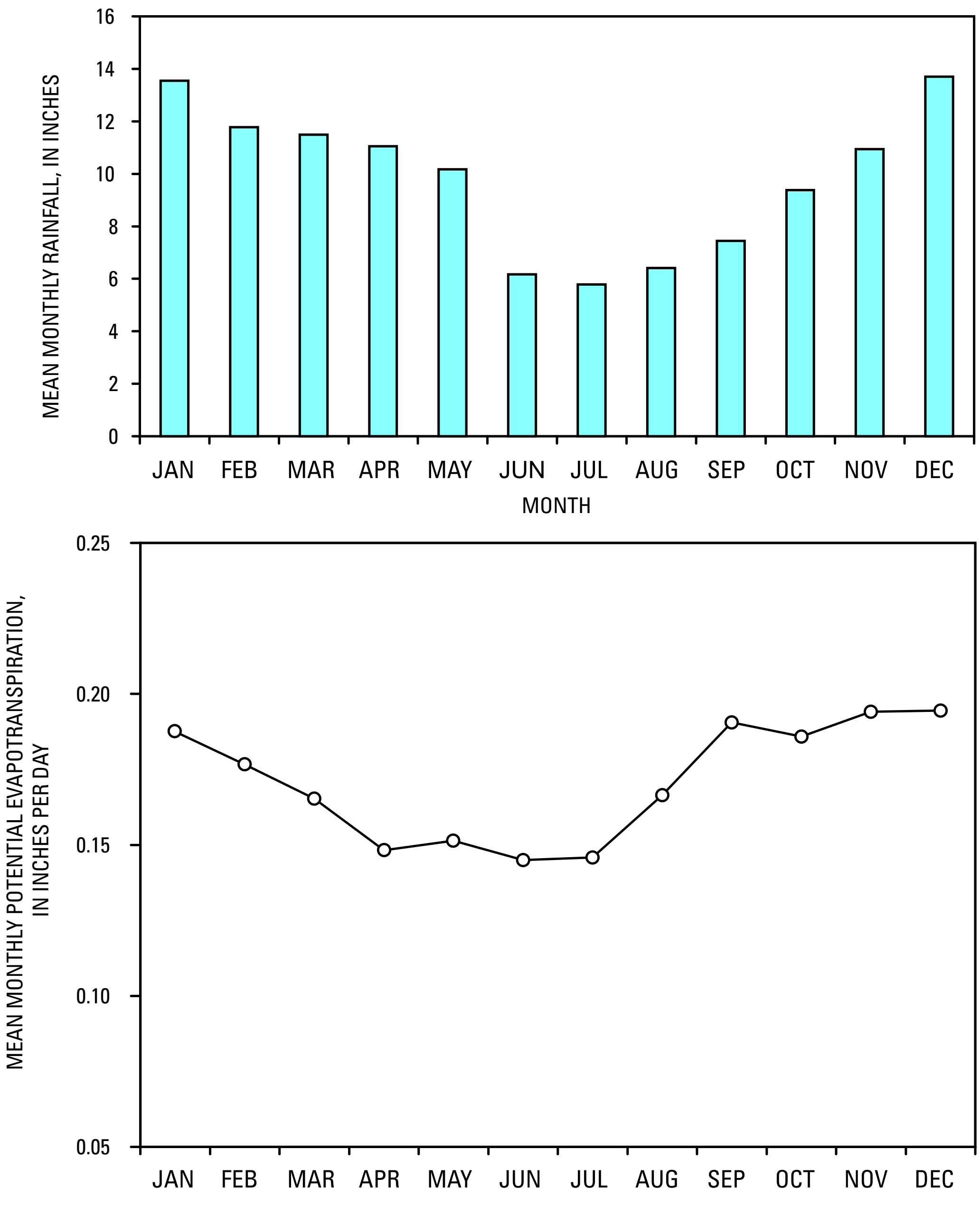


Figure 3. Monthly mean rainfall and potential evapotranspiration (PE) at the Pago Pago Airport, Tutuila, American Samoa. Rainfall data from National Climatic Data Center (2002); graph of PE modified from Izuka and others (2005a).

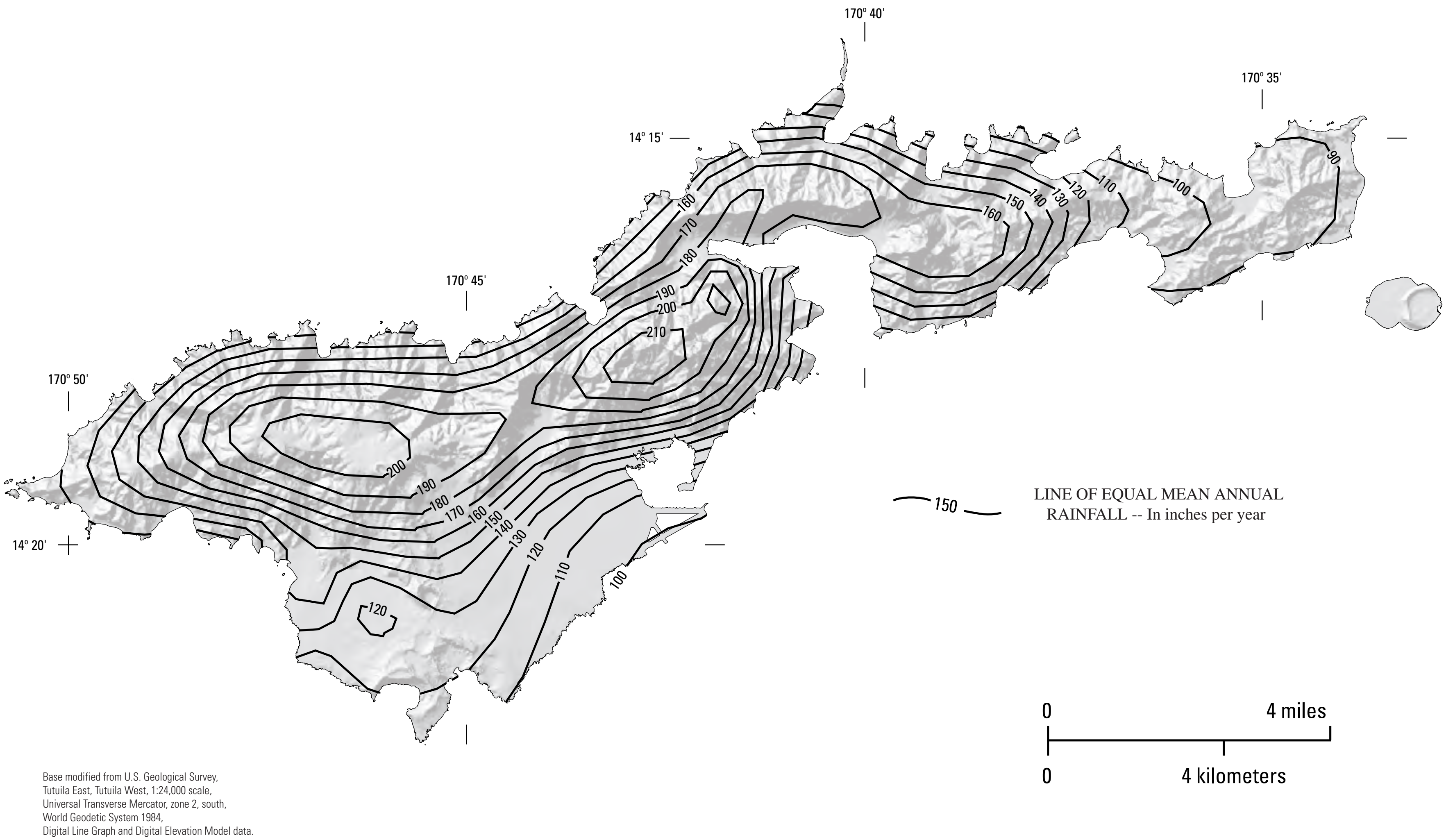


Figure 4. Mean annual rainfall on Tutuila, American Samoa, based on analysis of Daly and others (2006).

Evapotranspiration rates on Tutuila also vary spatially and temporally. Spatial variation of potential evapotranspiration (PE, the amount of water that would be evaporated or transpired from a well-vegetated soil if sufficient water were available) is linked primarily to orographic cloud cover. Mean annual PE is lowest in the interior of the island, where cloud cover is more frequent, and highest along the southern and eastern coasts of the island, where rainfall is lower and cloud cover less frequent (fig. 5). Seasonal variation of PE is linked to seasonal variation of daylight duration, with highest PE in November and December (summer in the southern hemisphere) and lowest PE in June and July (fig. 3). Evapotranspiration processes on Tutuila have the potential to remove 23 to 61 percent of the water brought by rainfall. In lower-rainfall coastal locations, PE can be 50 percent or more of rainfall, whereas in higher-rainfall interior locations PE is less than 30 percent of rainfall (Izuka and others, 2005a).

Geology

Tutuila was formed during the Pliocene and Pleistocene by midocean hot-spot shield volcanoes. The mountainous region of the island is the eroded remnants of these shield volcanoes (Stearns, 1944). What remains of the volcanoes above sea level is an accumulation of alkalic igneous rocks, including thick lava flows and pyroclastic deposits that are crosscut by dense intrusive igneous rocks (Stearns, 1944; Macdonald, 1944). Although Stearns mapped seven formations in the mountainous region, for purposes of this report, these formations will be referred to collectively as the Older Volcanics (fig. 6). This terminology is consistent with previous investigations, including those of Bentley (1975) and Izuka (1999).

The Tafuna-Leone Plain is formed by the products of younger (Holocene age) volcanism, including thin pahoehoe lava flows and pyroclastic deposits that overlie an ancient barrier reef (Stearns, 1944). These sediments and young volcanic rocks form a wedge that abuts the eroded surface of the mountains to the north (fig. 6). Most of the sedimentary part of the wedge consists of reef deposits. The reef deposits were later intruded by and buried under younger volcanic rocks. Stearns (1944) did not describe or name the buried reef deposits, but indicated that they are continuous with and similar to the existing carbonate reef that fringes other parts of the southern coast of Tutuila. Bentley (1975) referred to the buried marine sediments as Older Beach and Lagoon Deposits, to distinguish them from modern nearshore marine sediments. Well-drilling logs described in Bentley (1975) and in unpublished records at ASPA and the USGS indicate the presence of carbonate sediments at the bottom of some wells. The elevation of the contact between the carbonate sediments and overlying volcanic rock ranges from 5 to 25 feet below mean sea level in these wells.

The volcanic rocks that cover the surface of the Tafuna-Leone Plain (fig. 6) and overlie parts of the southern flank of the mountains to the north belong to the Leone Volcanics (Stearns, 1944). These rocks include lava flows and pyroclastic deposits (ash, cinder, and breccia). Most of the pyroclastic deposits form a line of cones that extend from the coast to the crest of the mountains in the north. Beneath the ridge of pyroclastic cones, volcanic dikes (massive, near-vertical sheetlike bodies of intrusive igneous rock) probably intrude the buried reef rock. Thus, not only do the pyroclastic cones divide the Tafuna-Leone Plain topographically into eastern and western regions, but the associated dikes also divide the subsurface. West of the pyroclastic cones, the Leone Volcanics includes interbedded lava flows and pyroclastic deposits, whereas to the east of the pyroclastic cones, the Leone Volcanics consists primarily of thin-bedded lava flows (Stearns, 1944). The presence of thicker pyroclastic layers in the western compared to the eastern Tafuna-Leone Plain is consistent with wind patterns in Samoa—prevailing easterly winds would have tended to blow ash and cinder toward the west during volcanic eruptions.

Recent terrigenous sediments (alluvium) fill valleys in the Older Volcanics and form a narrow coastal plain in some areas. It is likely that a narrow coastal plain of alluvium also is buried beneath the Leone Volcanics at the inland part of the Tafuna-Leone Plain.

Ground Water

Fresh ground water on Tutuila, as on other oceanic islands, forms a lens-shaped body that is underlain by saltwater (fig. 7). The freshwater lens is buoyed by the density difference between saltwater and freshwater. Between the freshwater lens and the underlying saltwater is a transition zone of brackish water. On Tutuila, the freshwater lens is recharged primarily by infiltration of rainfall. Ground water in the freshwater lens flows generally from inland areas, where rainfall and recharge are highest, toward the coast, where it discharges to springs, streams, and the ocean. On average over the long term, inflow to the freshwater lens (from ground-water recharge) is balanced by ground-water discharge (at springs and pumped wells and to the ocean). Although short-term variations such as seasonal rainfall patterns and droughts can lead to short-term imbalances, the freshwater lens is in a state of long-term average dynamic equilibrium, commonly referred to as steady state. Increasing ground-water withdrawals from wells upsets this balance and causes the shape and size of the freshwater lens to change. If the increased pumping stabilizes and persists for a long time, the freshwater lens will achieve a new steady state in which the total output (natural discharge plus the increased ground-water withdrawal rate) again equals the total input (recharge).

The saltwater underlying the freshwater lens limits ground-water development on Tutuila. Brackish water or saltwater can be drawn into a well if the well is pumped excessively or drilled too deeply into a thin part of the lens. Many wells on Tutuila have yielded water with high chloride concentrations, especially where the freshwater lens is thin (Bentley,

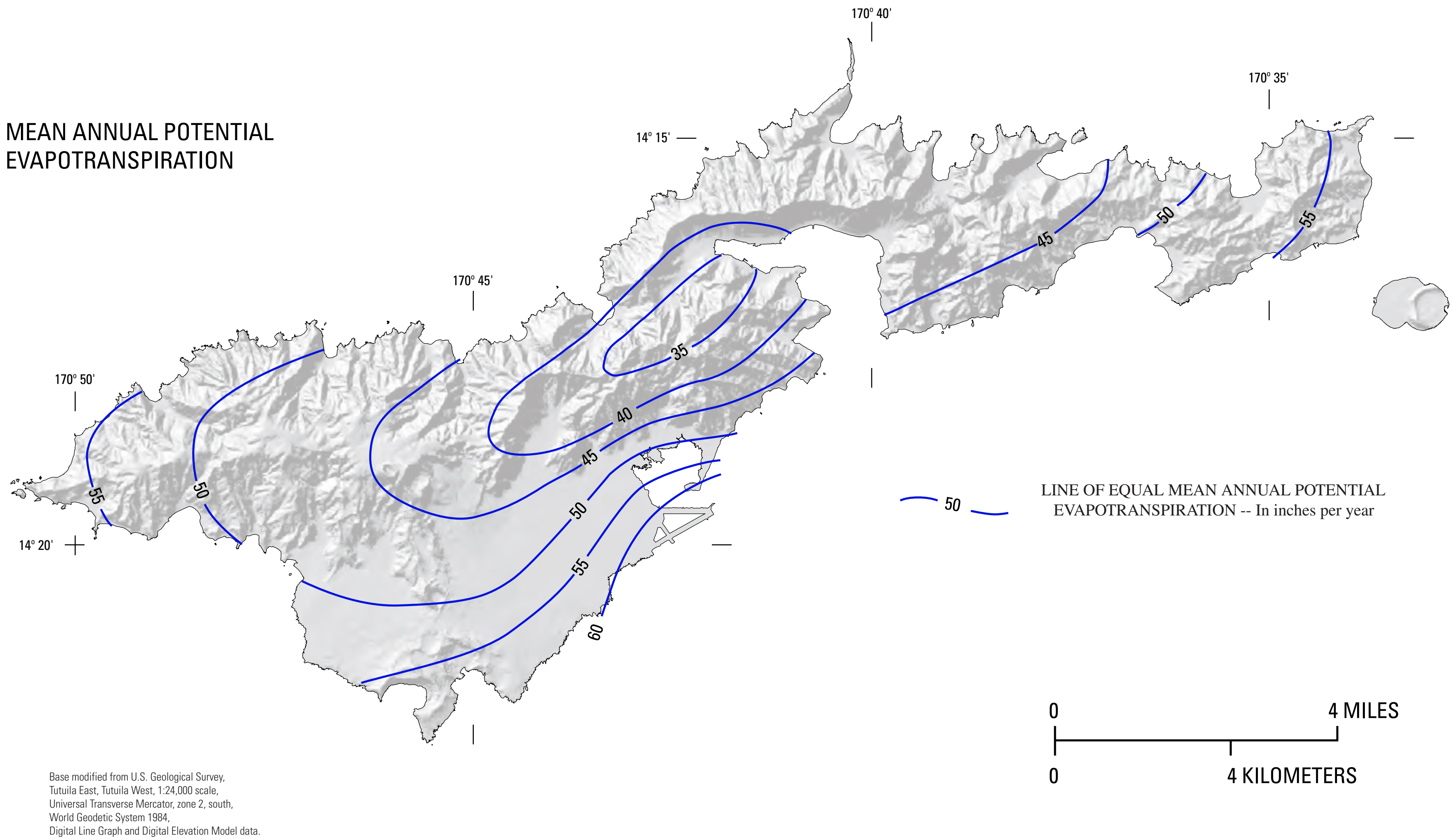


Figure 5. Mean annual potential evapotranspiration on Tutuila, American Samoa (from Izuka and others, 2005a).

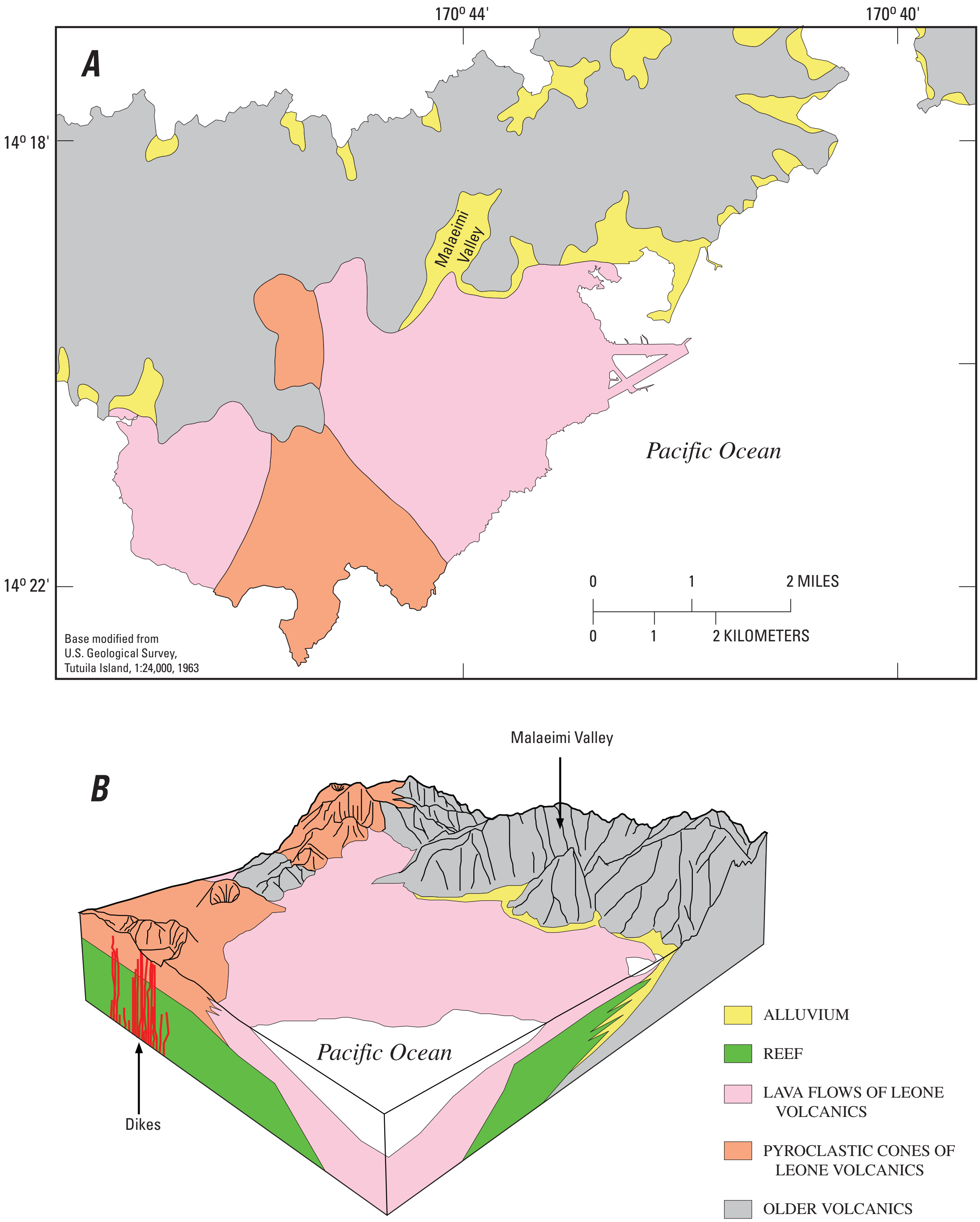


Figure 6. Simplified geologic map (*A*) and block diagram (*B*) of the Tafuna-Leone Plain, Tutuila, American Samoa (geologic map modified from Stearns, 1944, and Izuka, 1999).

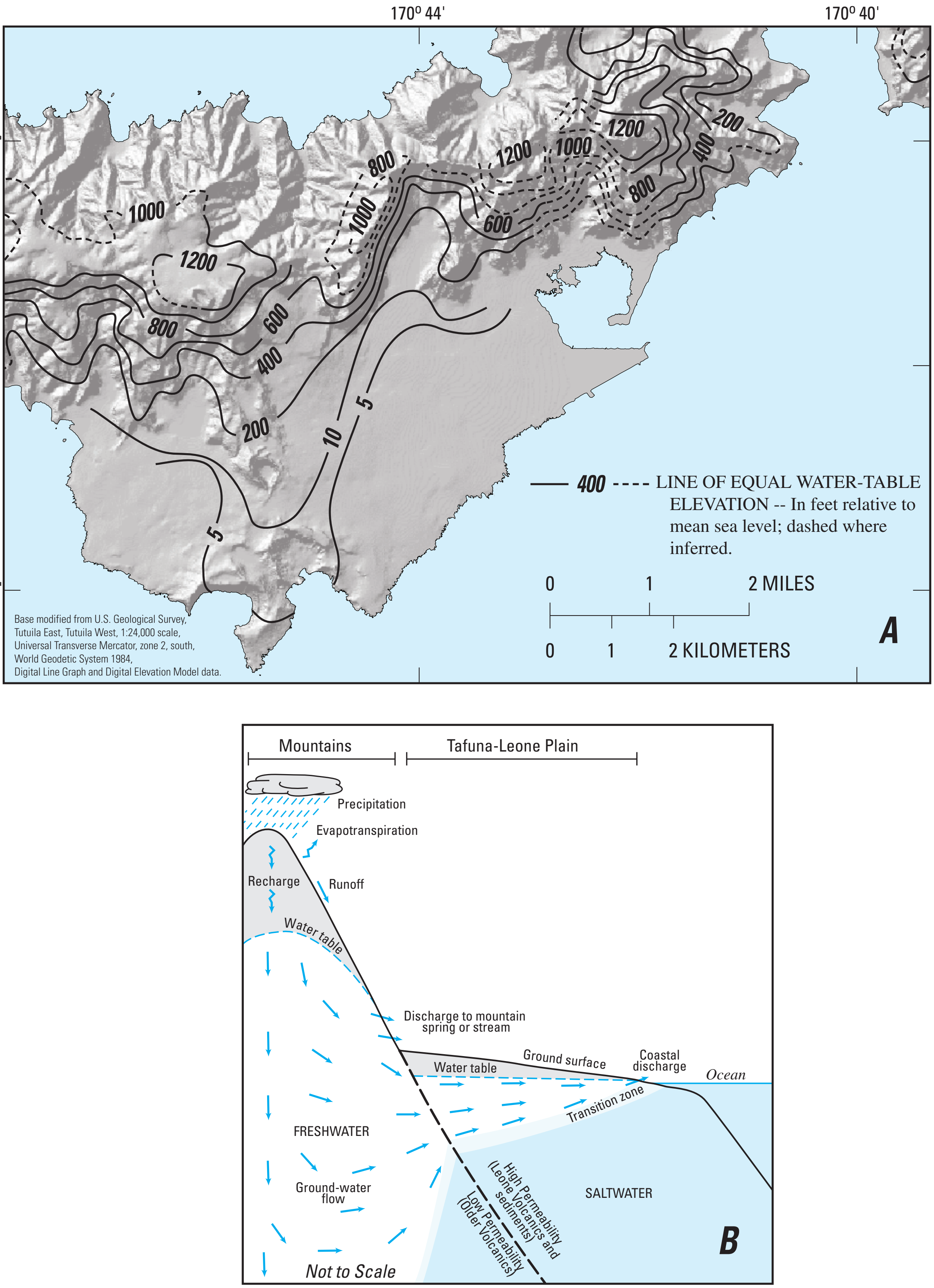


Figure 7. Conceptual model of ground-water occurrence in the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa. *A*, Water-table map. *B*, Diagrammatic section through mountains and Tafuna-Leone Plain. (Modified from Izuka, 1999.)

1975; Izuka, 1999). A few wells on Tutuila are capable of producing relatively large quantities (about 0.3 to 0.5 Mgal/d) of water with low chloride concentrations; most of these are in the Tafuna-Leone Plain. Even these wells, however, are subject to periodic increases in chloride concentrations during extended periods of low rainfall.

Izuka (1999) developed a conceptual model for ground-water occurrence in which the water-bearing rocks of the island were divided into two principal hydrogeologic regions: (1) the Older Volcanics, which include all of the Pliocene and Pleistocene volcanic rocks that form the mountainous region of Tutuila, and (2) the Leone Volcanics, which include all of the rocks beneath the Tafuna-Leone Plain (fig. 7). The Leone Volcanics were further subdivided into lava flows that form most of the flat areas of the plain, and pyroclastic cones that form a north-south ridge that bisects the plain. Because of its lower permeability, the Older Volcanics is characterized by steep water-table gradients and inland water levels that are hundreds of feet above sea level. In contrast, the predominantly high-permeability porous lava flows of the Leone Volcanics beneath the Tafuna-Leone Plain have gently inclined water-table gradients and water levels that are 10 ft or less above sea level. Most of the natural ground-water discharge occurs at the coast rather than at streams. Water levels are higher in the ridge of pyroclastic cones owing to the lower permeability of the cemented fine-grained pyroclastic deposits.

The north-south trending series of pyroclastic cones and associated dikes (fig. 6) also marks a subsurface division of the rocks of the Tafuna-Leone Plain. Dikes associated with volcanoes typically have very low permeabilities owing to their low porosity, and they greatly reduce the bulk permeability of the rocks into which they intrude (Takasaki and Mink, 1985). Although the dikes that are associated with the pyroclastic cones in the Tafuna-Leone Plain are not impermeable, they probably impede the flow of ground water between the eastern and western Tafuna-Leone Plain. Geologic differences between the eastern and western Tafuna-Leone Plain also are likely to result in differences in hydraulic properties. The combination of pyroclastic layers intercalated with lava flows probably causes rocks in the western Tafuna-Leone Plain to have lower bulk permeability than the rocks in the eastern Tafuna-Leone Plain. The line of pyroclastic cones thus marks not only a topographic divide between the eastern and western Tafuna-Leone Plain, but also the location of a barrier that impedes ground-water flow between regions having different hydrogeologic characteristics.

Ground-Water Production from Wells

In the Tafuna-Leone Plain, ground water is produced from vertical wells with either submersible or vertical shaft pumps. Information on well construction is not available for all wells, but the available data indicate that in most cases the wells produce water from the aquifer in the interval between the water table and the bottom of the well (table 1). Although most wells have solid casing that extends from the surface to a few feet below the water table, the annular space between the solid casing and the well bore is commonly sealed only above the water table. Below the solid casing, the well may have a short screen or perforated casing, or may be completely uncased. No gravel packing was used around the casing or screens.

Except for a few dug wells having low yield, ground-water production in the Tafuna-Leone Plain began in the 1960s with the drilling of wells in Leone Village and Malaeimi Valley (Bentley 1975), but those wells are no longer in use. Ground-water production data from 1985 to 2005 were obtained from ASPA. The data consist of dates and corresponding readings from a totalizing meter on each production well. Under most circumstances, the pumping rate of a well could be computed by subtracting the previous meter reading from the current meter reading and dividing by the amount of time between the readings. In some cases assumptions were made to correct apparent errors. Overall, however, the errors constituted a small fraction of the total data, and averages computed from the data can be used to assess general trends in ground-water production.

Ground-water production from the Tafuna-Leone Plain is currently distributed among four main well fields: (1) Malaeloa, (2) Iliili, (4) Tafuna, and (3) Malaeimi (fig. 8). Most wells in the Malaeloa well field were constructed in the 1970s and 1980s, although two wells were constructed in recent years (2000 and 2004; table 1). In the period 1985 to 2005, annual mean production from the Malaeloa well field varied between 1.3 and 3.0 Mgal/d (fig. 9). Production rose gradually from 1.3 Mgal/d in 1985 to about 2 Mgal/d in 1992 and remained at about 2 Mgal/d until 2003. Production in 2004-05 increased as a result of the recent construction and production of new wells. Production from the Malaeloa well field was about 3.0 Mgal/d in 2005, with each active well contributing 0.31 to 0.45 Mgal/d (table 2).

Wells in the Iliili well field were constructed in the 1970s to 1990s (table 1). Between 1985 and 1989, mean production from the well field was about 0.5 Mgal/d (fig. 9). Between 1990 and 1993, production rose gradually to about 1 Mgal/d. Production fluctuated between 0.8 and 1.2 Mgal/d during the period from 1993 to 2005 and gradually declined in the last few years of this period. Production averaged about 0.8 Mgal/d in 2005, with each active well contributing 0.13 to 0.30 Mgal/d (table 2).

Wells in the Tafuna well field were constructed in the 1970s (table 1). Annual mean production from these wells rose from about 1.5 to about 2.3 Mgal/d between 1985 and 1989, then declined to about 1.4 Mgal/d by 1995 (fig. 9). Between 1996 and 2005, production gradually increased again. In 2005, production was about 2.5 Mgal/d, with each active well contributing 0.22 to 0.50 Mgal/d (table 2).

Wells in the Malaeimi well field also were constructed in the 1970s (table 1). Between 1985 and 1992, annual mean production from the well field rose gradually from about 0.3 to 0.8 Mgal/d. Production rose sharply to 1.2 Mgal/d in 1993,

Table 1. Construction data for production wells in the Tafuna-Leone Plain, Tutuila, American Samoa.

[--, data not available]

Number	Location	Year built	Elevations (feet relative to mean sea level)		
			Measuring point [a]	Bottom	Open interval
70	Malaeloa	1976	131.3[b]	-14	6 to bottom
80	Malaeloa	1978	138.57	-24	water table to bottom
83	Malaeloa	1979	137.29	-22	water table to bottom
91	Malaeloa	1980	162b	-15	water table to bottom
92	Malaeloa	1980	163.96	--	water table to bottom
93	Malaeloa	1980	162[b,c]	-43	water table to bottom
119	Malaeloa	1978	176.40	-34	--
168	Malaeloa	2004[c]	145.24	--	--
169	Malaeloa	2000	160.98	-89	--
62	Iliili	1975	204.35	-22	water table to bottom
76	Iliili	1977	196.65[b]	-7	water table to bottom
79	Iliili	1978	214.42[b]	-10	water table to bottom
84	Iliili	1979	141.99	-23	water table to bottom
167	Iliili	1998	223.11	--	--
33	Tafuna	1973[d]	--	--	--
46	Tafuna	1973	--	--	--
53	Tafuna	1973	--	--	--
60	Tafuna	1975	102.04[b]	-23	water table to bottom
61	Tafuna	1975	110.49	-15	-3 to bottom
66	Tafuna	1975	77.35[b]	-28	4 to bottom
72	Tafuna	1976	119.16	-41	water table to bottom
77	Tafuna	1978	90.37	-59	water table to bottom
81	Tafuna	1979	109.57	-48	-12 to bottom
67	Malaeimi	1975	129.18	-26	water table to bottom
69	Malaeimi	1975	128.89	-48	water table to bottom
88	Malaeimi	1979	150.09	-45	--
89	Malaeimi	1979	142.83	-62	--
85	Mesepa	1987	251[b]	-26	water table to bottom
171	Pavaiai	2002[c]	168.72	--	--
172	Pavaiai	2003[c]	154.12	--	--
177	Pavaiai	1979	245.45	-19	water table to bottom

[a] Measuring-point elevations determined by level survey in October 2005, except where noted.

[b] Elevations from well files at the U.S. Geological Survey and American Samoa Power Authority.

[c] Value approximate.

[d] Date not certain.

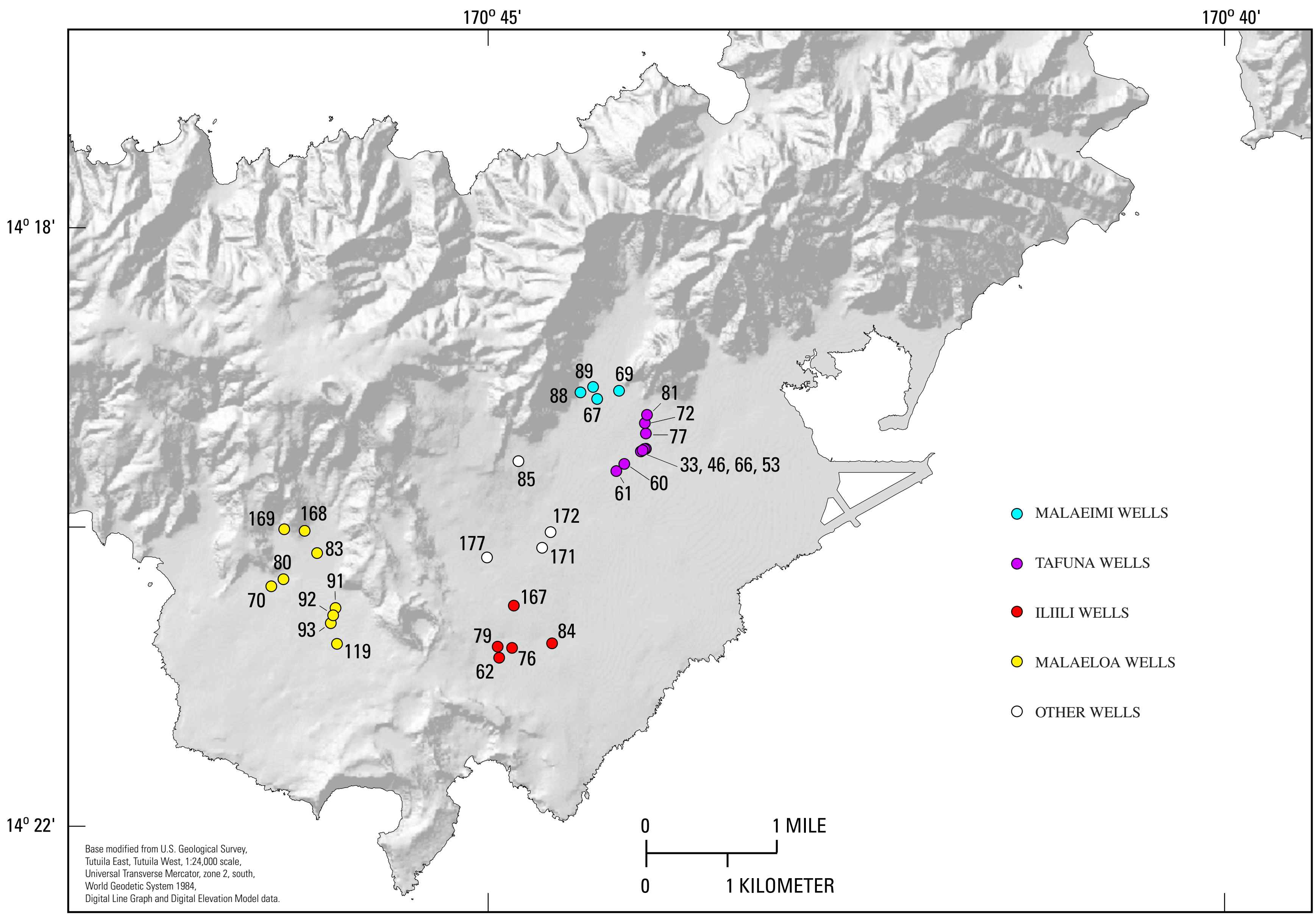


Figure 8. Production wells in the Tafuna-Leone Plain, Tutuila, American Samoa.

Table 2. Production for wells in the Tafuna-Leone Plain, Tutuila, American Samoa.

[“Highest annual mean” is the highest annual mean production for a calendar year in the period 1985 to 2005]

Well Name	Average production (million gallons per day)		
	2001 to 2005	2005	Highest annual mean
Malaeloa			
Malaeloa 70	0.408	0.400	0.426
Malaeloa 80	0.338	0.346	0.400
Malaeloa 83	0.389	0.383	0.427
Malaeloa 91	0.254	0.454	0.454
Malaeloa 92	0.000	0.000	0.336
Malaeloa 93	0.358	0.384	0.410
Malaeloa 119	0.144	0.369	0.433
Malaeloa 168	0.091	0.375	0.375
Malaeloa 169	0.385	0.312	0.414
Totals	2.367	3.023	3.675
Iliili			
Iliili 62	0.191	0.195	0.376
Iliili 76	0.300	0.302	0.330
Iliili 79	0.103	0.000	0.353
Iliili 84	0.166	0.170	0.406
Iliili 167	0.147	0.128	0.174
Totals	0.907	0.795	1.639
Tafuna			
Tafuna 33	0.242	0.217	0.287
Tafuna 46	0.015	0.000	0.210
Tafuna 53	0.000	0.000	0.145
Tafuna 60	0.427	0.430	0.467
Tafuna 61	0.212	0.400	0.400
Tafuna 66	0.247	0.291	0.441
Tafuna 72	0.489	0.496	0.548
Tafuna 77	0.261	0.245	0.293
Tafuna 81	0.377	0.434	0.434
Totals	2.270	2.513	3.225
Malaeimi			
Malaeimi 67	0.319	0.307	0.397
Malaeimi 69	0.000	0.000	0.007
Malaeimi 88	0.351	0.370	0.370
Malaeimi 89	0.379	0.374	0.563
Totals	1.049	1.051	1.337
Other areas			
Mesepa 85	0.440	0.454	0.474
Pavaiai 171	0.140	0.234	0.286
Pavaiai 172	0.122	0.213	0.216
Pavaiai 177	0.013	0.066	0.066
Totals	0.715	0.967	1.042

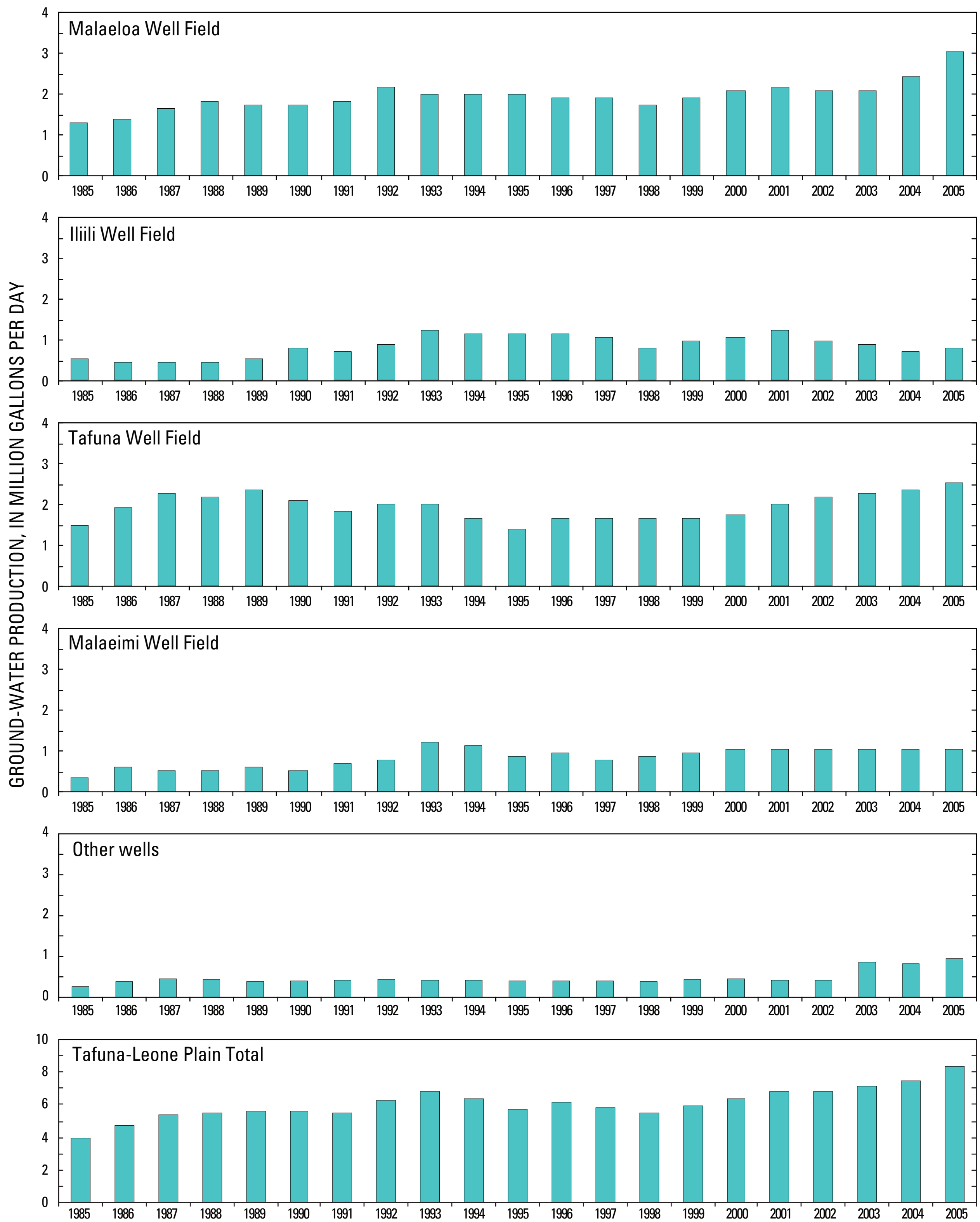


Figure 9. Mean annual ground-water production from well fields in the Tafuna-Leone Plain, Tutuila, American Samoa (data from the American Samoa Power Authority).

then declined gradually to 0.8 Mgal/d by 1998. Between 1998 and 2005, production remained nearly constant at about 1.0 Mgal/d.

Other wells scattered in various locations between these four main well fields were constructed between 1979 and 2003 (table 1). The sum of the annual mean production from these wells remained at or below 0.5 Mgal/d before 2003, then rose to 0.8 to 1.0 Mgal/d with the addition of two wells in 2003.

During the period 1985 to 2005, total production from all wells in the Tafuna-Leone Plain averaged 6.1 Mgal/d, but shows a gradually increasing trend over this period (fig. 9). Production gradually increased from 4.0 Mgal/d in 1985 to 6.8 Mgal/d by 1993. Production decreased gradually to about 5.5 Mgal/d by1998, and then increased to 8.3 Mgal/d by 2005. A graph of mean monthly production from all wells in the Tafuna-Leone Plain computed for the period 1985 to 2005 indicates that ground-water withdrawal varies by a few percent seasonally (fig. 10).

Ground-Water Levels

Records of ground-water levels in the Tafuna-Leone Plain were analyzed for trends in temporal water-level variations. The records consisted of depth-to-water measurements made between 1976 and 2005. A survey of well measuring-point elevations was conducted in October 2005 as part of this study to reference the water-level measurements to a common datum. The possibility exists that the measuring points may have changed over the years as a result of well maintenance, but because of constraints of the well design, the changes could not have been more than about 1 ft. Also, time-series plots of the historic data (fig. 11) do not show shifts in water levels that would indicate a significant change in the measuring point. Because most of the wells for which historical water-level data were available were in active well fields, the time-series plots show short-term fluctuations that probably reflect pumping effects. Wells 92 (Malaeloa well field) and 88 (Malaeimi well field) are production wells; wells 2 (Tafuna well field) and 115 (Iliili well field) are not pumped, but are near production wells (fig. 11). Short-term water-level fluctuations may also result from rapid ground-water recharge during high-intensity rainfall events (Izuka, 1999).

Despite the ambiguity in the measuring-point elevations and the short-term water-level fluctuations, ground-water levels in the Tafuna-Leone Plain show no long-term increasing or decreasing trends. Also, water levels in the monitor wells are apparently unaffected by recent (between 2000 and 2005) increases in ground-water production (fig. 9). This is consistent with the high permeability of the Tafuna-Leone Plain, which would result in small drawdowns in the new production wells and even smaller drawdowns in monitor wells at a distance from the production well.

Synoptic Water-Level Survey

For the purposes of delineating ACRWs in the Tafuna-Leone Plain, it is necessary to study the aquifer under conditions of current ground-water production. A synoptic water-level

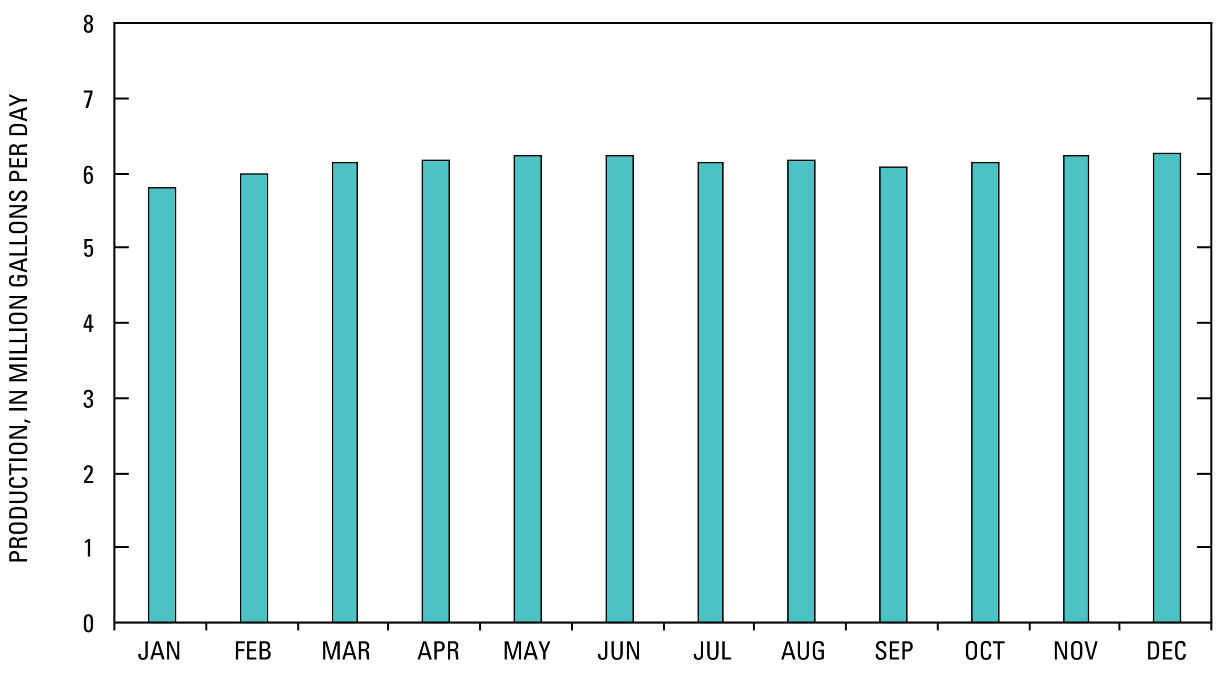


Figure 10. Mean monthly ground-water production from the Tafuna-Leone Plain, Tutuila, American Samoa. Means computed on the basis of data from 1985 to 2005 (data from the American Samoa Power Authority).

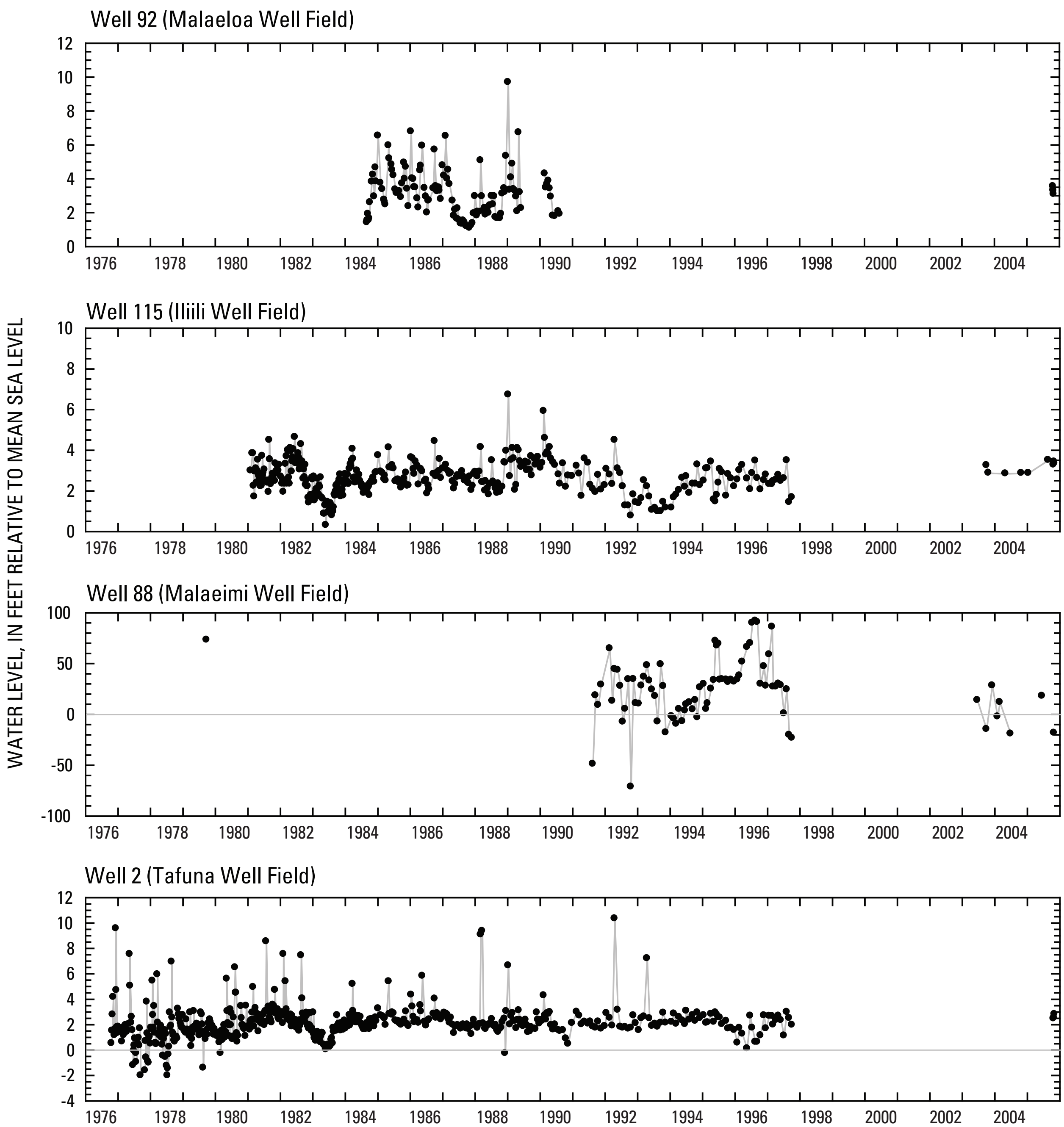


Figure 11. Water levels from selected wells in the Tafuna-Leone Plain, Tutuila, American Samoa (data from the American Samoa Power Authority).

survey was conducted to determine the current distribution of ground-water levels in the Tafuna-Leone Plain. The strategy of the synoptic survey is to measure many wells, widely distributed over the study area, as simultaneously as is practical, so that the water levels are representative of an instant in time and a single set of conditions. The synoptic survey for this study consisted of a network of 18 wells measured over a 12-hour period on October 29, 2005, and 3 wells measured on November 3, 2005 (fig. 12).

Obtaining a set of synoptic measurements from widely spaced locations on an island aquifer can be problematic because ocean tides cause short-term water-level fluctuations that propagate from the coast toward the center of the aquifer. The tidal signal in a well is similar to that of the ocean tides but the peaks and troughs lag behind, and the amplitude is attenuated relative to, the ocean tide. The lag and attenuation are a function of the distance of the well from shore—tidal signals in inland wells have greater lag and more attenuation than wells at the coast. Water levels measured at a well near the coast cannot, therefore, be compared directly to the water levels measured at the same time at a well farther inland without adjusting for the tidal effect.

Tidal data from Pago Pago Harbor (fig. 1) indicate that semidiurnal tides are dominant in Tutuila (National Oceanic and Atmospheric Administration, 2007). Assuming a semidiurnal tidal period of 12.42 hours, an estimate of the mean ground-water level over the tidal cycle was determined from water-level measurements made at each well in the synoptic survey over a period of at least 12 hours. The peak or trough was identified from plots of the water-level measurements, and the value of the plot at a point one-quarter of the tidal cycle (3.1 hours) from the trough or peak was used as the measured water level in the synoptic survey. In some cases, where no clear trend was apparent, all the water-level measurements taken during the test were averaged.

To ensure that the synoptic survey results are representative of current conditions, the survey would ideally include the effect of current ground-water production. Measuring water levels in a production well, however, can artificially bias the measurements because of well losses (which reflect the construction of the well). Well-loss effects can be avoided by measuring only nonpumped wells, but not enough nonpumped wells were available to adequately assess water-level variations in the study area. For this reason, some production wells were included in the synoptic survey.

Of the 18 wells measured on October 29, 2005, six were nonpumped wells normally used for observation. The water levels measured in these wells constitute the most reliable indicators of aquifer water levels in the synoptic survey. Another six wells were production wells whose pumps were stopped during the survey to eliminate well-loss effects, but because the withdrawals were stopped, current production conditions are incompletely represented. Stopping the pumps in these wells reduced total pumping rate in the Tafuna area by about 18 percent on the day of the test, or about 17 percent relative to the average pumping rate for October 2005.

Six of the wells measured on October 29, 2005, were production wells in which pumps were operating. To assess well-loss effects, the pumps in these wells were stopped on November 3, 2005, and the water-level recovery monitored for at least 20 minutes. The water-level change after 20 minutes was added to the water-level measurements made on October 29. Despite potential inaccuracies, the water levels determined by this method can be used to supplement the more accurate water-level measurements made in other wells.

Additional water-level measurements were collected from three production wells on November 3, 2005. These water-level measurements were taken after the pump was stopped and the well had been recovering for at least 20 minutes. The water levels were not corrected for tidal effects, but they are useful for assessing the general distribution of water levels in the study area.

Results of the synoptic survey.—The distribution of water levels in the wells measured during the synoptic survey (fig. 12) is in general agreement with the water-table map of Izuka (1999) (fig. 7), although some differences may result because the synoptic survey reflects current well-pumping conditions, whereas the water-table map represents nonpumping conditions. In the Malaeloa well field, measured water levels are highest near the inland boundary of the Tafuna-Leone Plain (wells 169 and 168) and decrease southeastward toward the coast. In the eastern Tafuna-Leone Plain, measured water levels are highest on the inland boundary (well 69) and near the base of the ridge of pyroclastic cones (well 178) and decrease to the southeast toward the coast.

In areas of high ground-water withdrawal, the water levels measured in the synoptic survey differ in detail from the water-table map of Izuka (1999). The lowest water level measured during the synoptic survey was 0.59 ft above sea level at well 81 in the Tafuna well field (fig. 12). Even though this well is near the inland boundary of the Tafuna-Leone Plain, it is in an area of high ground-water production and the well was pumping during the synoptic survey. The synoptic water-level survey thus shows a slightly depressed water table in current high-production well fields. Whereas the water-table map of Izuka (1999) indicates water levels under prepumping conditions, results of the synoptic survey more closely represent water levels under current conditions of ground-water production.

Aquifer Hydraulic Conductivity

One of the principal aquifer properties required for construction of a numerical ground-water flow model is aquifer hydraulic conductivity (*K*), which is a measure of the permeability of the aquifer. In the field, estimates of *K* are commonly determined from aquifer transmissivity (*K* multiplied by aquifer thickness) which is estimated from pumping-rate, drawdown, and time data monitored at a pumped well. Using the Theis (1935) equation for nonsteady flow for selected wells on Tutuila, Bentley (1975) estimated aquifer trans-

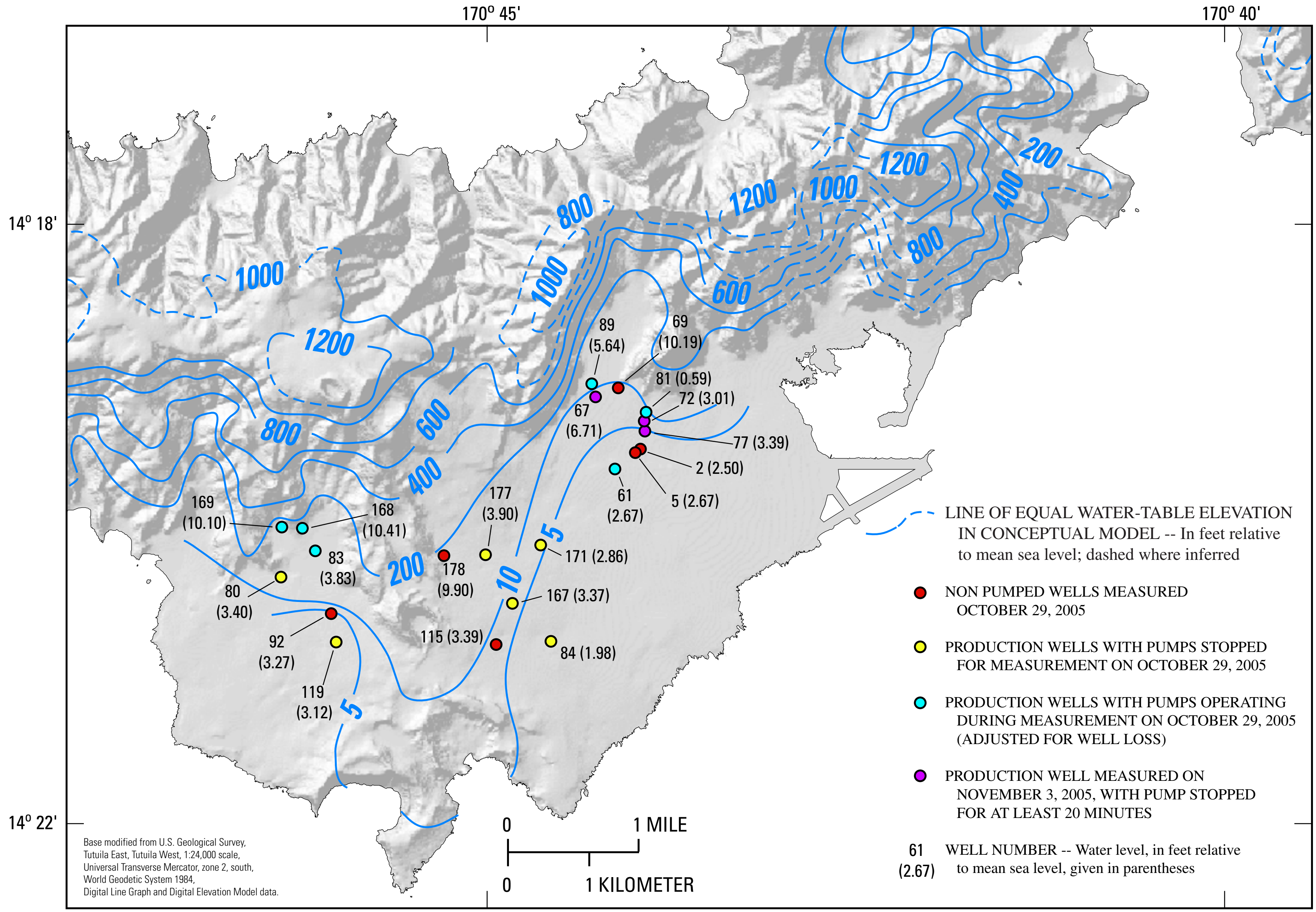


Figure 12. Water levels measured in wells in the Tafuna-Leone Plain, Tutuila, American Samoa, during the synoptic survey.

missivity to be 2,500 to 43,800 ft^2/d for wells in the Leone Volcanics and 250 to 14,000 ft^2/d for wells in recent alluvium. Bentley conceded that these estimates have limited accuracy because not all assumptions of the Theis equation could be met for the data available, but the results indicate that aquifer permeability is much higher in the Tafuna-Leone Plain than in recent alluvium. Bentley did not have sufficient data to estimate transmissivity for the Older Volcanics.

A general sense of the distribution of aquifer permeability can be obtained from measurements of well specific capacity (pumping rate divided by drawdown measured in a well). Although specific capacity is partly a function of well construction and boundary conditions, higher specific capacities generally correspond to higher aquifer permeability. Bentley (1975) compiled a list of ground-water statistics for the islands of American Samoa that included specific capacity. For wells in the Older Volcanics, Bentley reported specific capacities ranging from 0.12 to 5.5 gal/min per foot of drawdown. In contrast, wells in the Leone Volcanics of the Tafuna-Leone Plain had specific capacities ranging from 3.1 to 187 gal/min per foot of drawdown. These data indicate that the rocks penetrated by the wells in the Tafuna-Leone Plain have a substantially higher permeability than rocks elsewhere in Tutuila, which is consistent with the conceptual model by Izuka (1999).

Exchange Between Ground Water and Streams

Part of the flow measured at a stream gage may come from ground water. The ground water may discharge diffusely along the banks of the stream, or it may be concentrated in a small area such as a spring. The component of streamflow that comes from ground-water discharge is known as base flow. Whether a stream reach has significant base flow depends on the elevation of the stream stage relative to the water level in the saturated part of the underlying aquifer. If the stream stage is lower than the water level in the aquifer, ground water will seep into the stream; if the stream stage is higher than the water level in the aquifer, water will tend to seep from the stream into the ground.

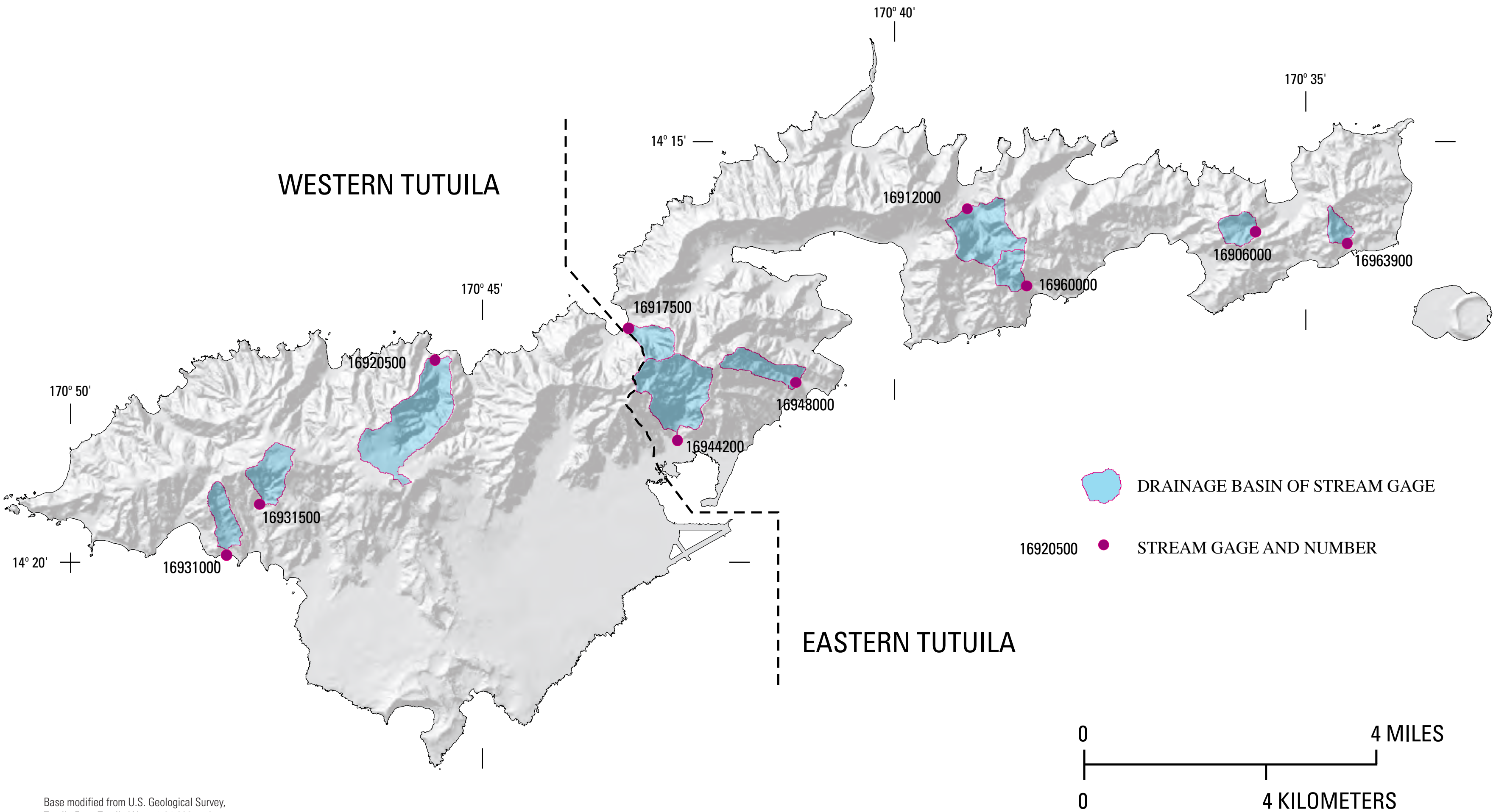
Base flow can be estimated from stream-gage data. The USGS has operated continuous-record stream gages in the mountains of Tutuila since the 1950s (fig. 13). Because the drainage areas of the stream gages are small and steep, flow is flashy and peaks recede quickly after periods of rainfall (fig. 14). In most basins, flow between the brief peaks is maintained by base flow. Of the 10 basins with continuous-record stream-gage data considered in this study, all but two (stream gages 16906000 and 16944200) have base flow that persists during periods without rain. In the mountains of Tutuila, where the water table is high (Izuka, 1999) and stream channels are deeply incised, most streams intersect the water table somewhere along their reach, resulting in high base flows measured at the stream gages.

No stream-gage data exist for the Tafuna-Leone Plain, but several lines of evidence indicate that the ground-water/streamflow relations of parts of the plain, especially the eastern plain, differ from those in the rest of Tutuila. The eastern Tafuna-Leone Plain has very low relief and has no well-developed stream channels, indicating that little water runs directly off the ground surface to the ocean. Well hydraulic performance and water-quality data indicate that water quickly infiltrates the surface and recharges the highly permeable underlying aquifer. Streams draining the mountains to the north become intermittent or disappear when they reach the plain, indicating that surface runoff from the mountains infiltrates the ground within a short distance of the juncture between the Older Volcanics and the Leone Volcanics. This surface runoff would include not only stream flow, but probably also some nonchannelized (sheet) flow, although nonchannelized flow cannot be measured with conventional stream-gage methods. Thus, ground-water recharge in the eastern Tafuna-Leone Plain is enhanced by the surface-water runoff it receives from the adjacent mountains.

Ground-Water Recharge

Ground-water recharge in this study was estimated using a modification of the soil water-budget method developed by Thornthwaite and Mather (1955). The modified method is described in detail by Oki (2002) and Izuka and others (2005b); a review of the features relevant to this study is given here. The method operates on the premise that part of the water that falls on the land surface as rain runs off to the ocean via streams while the remainder infiltrates the soil, where it is temporarily stored and subject to evapotranspiration (fig. 15). When more water infiltrates than can be held in the soil given its water-storing capacity, antecedent water content, and losses from evapotranspiration, the excess water is passed to the underlying aquifer and becomes ground-water recharge. The method thus constitutes a soil water budget in which input (from precipitation) is balanced by output (to runoff, evapotranspiration, and recharge) and water storage in the plant-soil system. The water-storage capacity of the soil is determined by the thickness of the soil within the root zone (root depth) and the available water capacity of the soil.

The water-budget method requires discretization of the study area into subareas within the basin having homogeneous precipitation, runoff, and evapotranspiration characteristics. These areas were defined by merging geographic-information-system (GIS) spatial datasets (coverages) created from maps and other data. Time is discretized into regular intervals for the water budget calculations. The smaller the interval, the more accurately the water budget will simulate short-duration events such as episodic rainfall. In this study, the water budget was computed on a daily interval. The water budget computes the recharge for each subarea by stepping through consecutive days, using the ending soil moisture for one day as the antecedent soil moisture for the next day. By computing the water budget for thousands of consecutive days (in this study,



Base modified from U.S. Geological Survey,
Tutuila East, Tutuila West, 1:24,000 scale,
Universal Transverse Mercator, zone 2, south,
World Geodetic System 1984,
Digital Line Graph and Digital Elevation Model data.

Figure 13. Stream gages and their drainage areas on Tutuila, American Samoa.

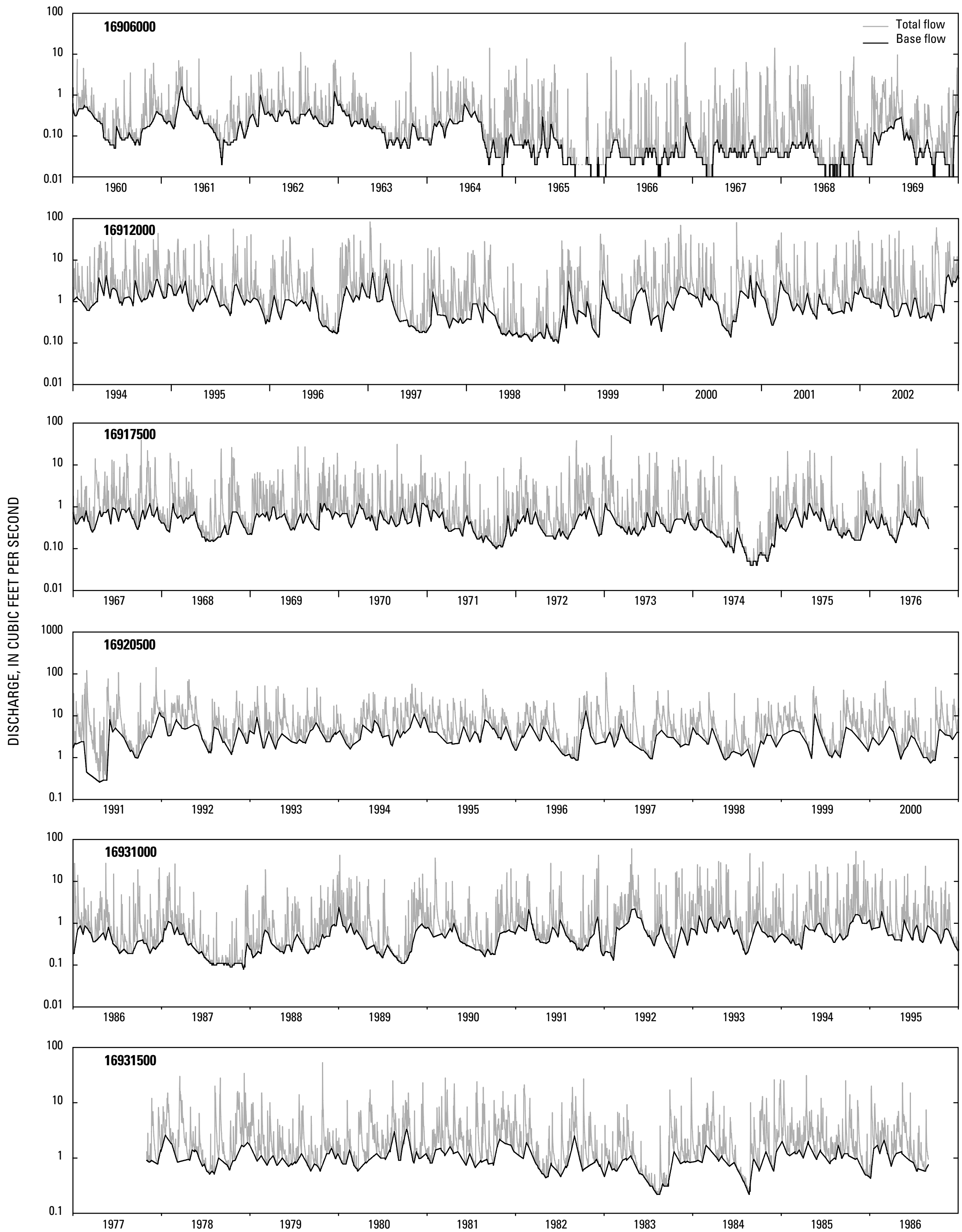


Figure 14. Hydrographs of daily mean flow for selected periods from stream gages on Tutuila, American Samoa.

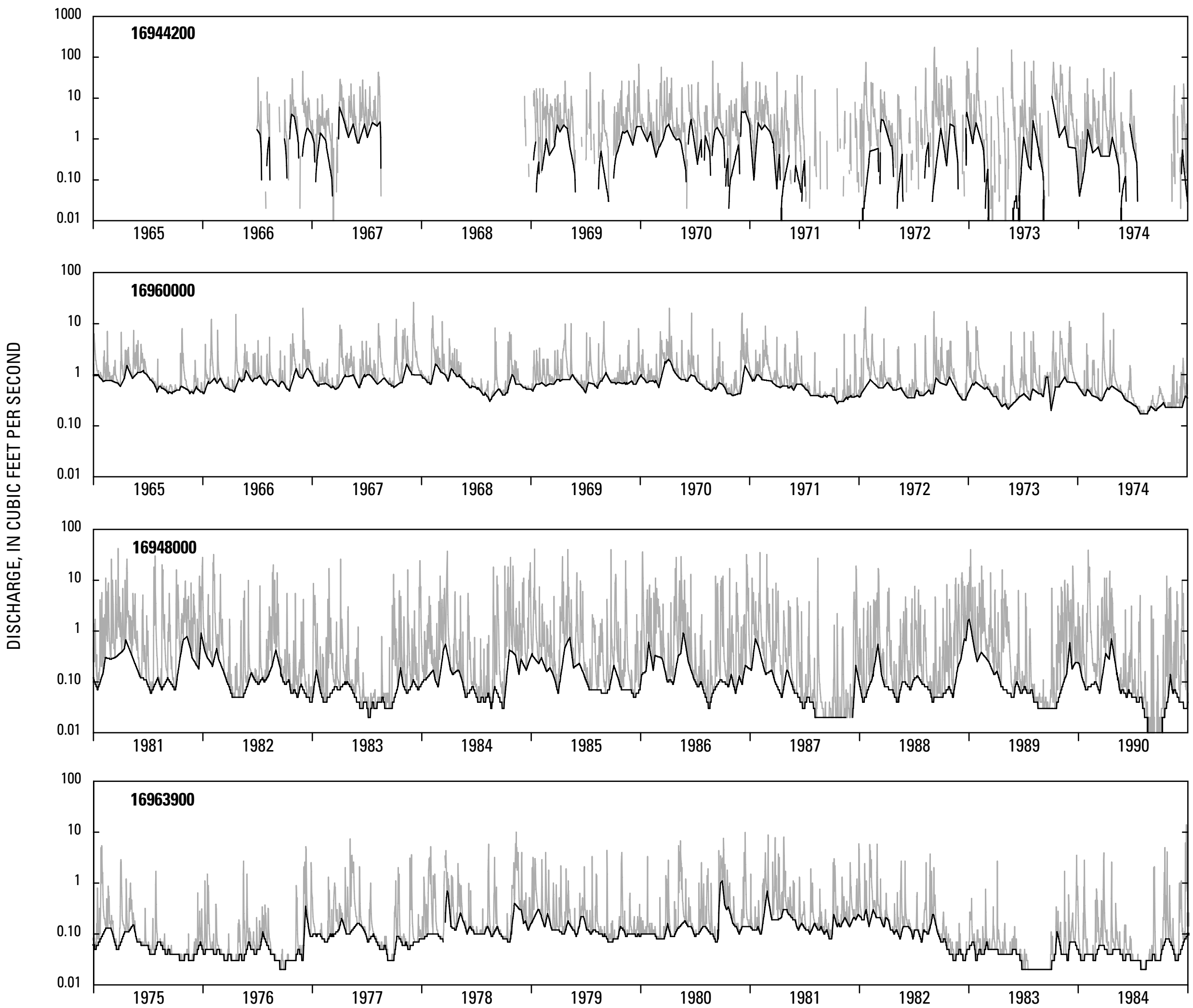


Figure 14. *Continued.*

the equivalent of 30 years), the water budget converged on a long-term average ground-water recharge value.

Factors Affecting Ground-Water Recharge

Spatial and temporal variations in precipitation (rainfall and fog drip), crop irrigation, runoff, and evapotranspiration affect ground-water recharge. Irrigation was not considered in this study because Tutuila has no large-scale agriculture. Fog drip also was not considered in this study because the highest elevation on Tutuila is lower than that at which fog drip is considered significant in Hawaii, where the contribution of fog drip to the water budget has been more extensively studied (Juvik and Ekern, 1978). Each of the remaining factors constitutes a parameter in the water-budget computation of recharge for the Tafuna-Leone Plain and surrounding area. Some parameters may have considerable uncertainty associated with them because a range of values are plausible, but one of the values in the range is usually considered most plausible. This section describes only the most plausible values selected for the water-budget computation. Parameter uncertainty (that is, plausible values other than the ones used) and its implications on recharge computations are discussed in a later section of this report.

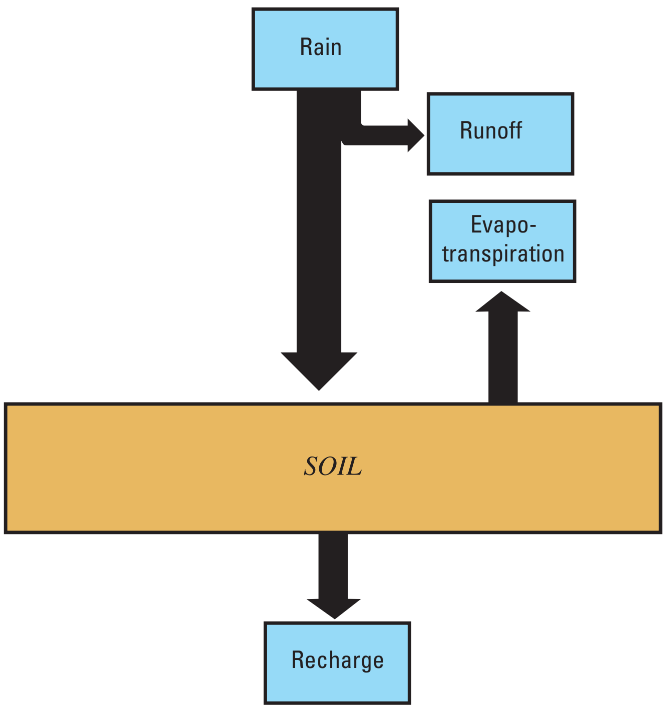


Figure 15. Concepts of the soil water budget used to estimate ground-water recharge in this study (modified from Izuka and others, 2005b).

Precipitation

The daily water-budget approach used in this study required daily rainfall data for every location in the study area. Daily rainfall data, however, are available only from individual rain gages scattered within the study area. In this study, the rainfall distribution required for the water-budget computations was synthesized from the mean monthly rainfall distribution maps of Tutuila (Daly and others, 2006). The original maps consisted of twelve (one for each month) geographically referenced raster data sets. These data sets were discretized using GIS to create coverages with bands of equal mean monthly rainfall with one-inch resolution.

Daily rainfall was synthesized from the mean monthly rainfall maps using the method of fragments similar to the method described by Izuka and others (2005b). In this method, month-by-month patterns of daily rainfall (fragments) derived from the records of selected individual rain gages were imposed on the mean monthly rainfall-distribution coverages. In this study, data for fragments were computed from the rainfall data from 16 gages on Tutuila (fig. 16). Data from these gages for the period from 1971 to 2000 were obtained from the USGS National Water Inventory System (NWIS) database and the National Climatic Data Center (2002). Fragments were linked to subareas within the study area by means of fragment zones (table 3). For each month, the island was divided into four fragment zones bounded by lines of equal mean monthly rainfall. As with the mean monthly rainfall distribution maps, lines bounding the fragment zones were derived from the monthly raster data of Daly and others (2006), but for the fragment zones, the lines were selected to optimize the distribution of fragments among the zones. To account for interannual variations, the mean monthly rainfall was multiplied by a monthly mean weighting factor, derived from the long-term (1971–2000) rainfall records at the Pago Pago Airport (National Climatic Data Center 2002).

Runoff and Infiltration

The volume of water that infiltrates the soil after a period of rainfall can be estimated by subtracting the amount of direct runoff (water that flows over the land surface into the stream) from rainfall (fig. 16). Direct runoff for the drainage basins of some streams in the study area can be determined from long-term stream-gage records of daily mean flow. In this study, the hydrograph-separation program of Wahl and Wahl (1995) was used to separate the base-flow component from the direct-runoff component for selected streams (table 4). The mean monthly direct-runoff values were then divided by the mean monthly rainfall (derived from the rainfall-distribution maps of Daly and others, 2006) within the drainage area of each stream gage to obtain monthly ratios of runoff to rainfall.

Few stream gages on Tutuila have sufficient records to compute direct runoff, base flow, and runoff-to-rainfall ratios. It was therefore necessary to extrapolate ratios computed for areas that have stream gages to areas that do not. Runoff-to-rainfall ratios were computed for 10 stream gages on Tutuila (fig. 13, table 5). For most months, the stream gages in western Tutuila had higher runoff-to-rainfall ratios than those in eastern Tutuila. To determine the runoff-to-rainfall ratios that would be used in this study, the stream gages on Tutuila were divided into eastern and western regions. The monthly runoff-to-rainfall ratios for all basins in the western region were averaged separately from those in the eastern region; these regionally averaged monthly ratios were used to compute runoff in the water budget analysis.

Evapotranspiration

The mean monthly PE distribution maps of Izuka and others (2005a) were used in the water-budget computation of ground-water recharge for this study. Whereas PE is the amount of water that could potentially be evaporated or transpired given the energy budget of an area, the amount of actual evapotranspiration (AE) may be less because water is not always available for evapotranspiration at the potential rate. The availability of water for evapotranspiration is a function of supply and storage. In the water-budget analysis, evapotranspiration occurs in the soil layer within the reach of plant roots. Water is supplied primarily by precipitation; storage is provided by soil and is a function of the soil's thickness and water-storing capacity. Evapotranspiration also varies depend-

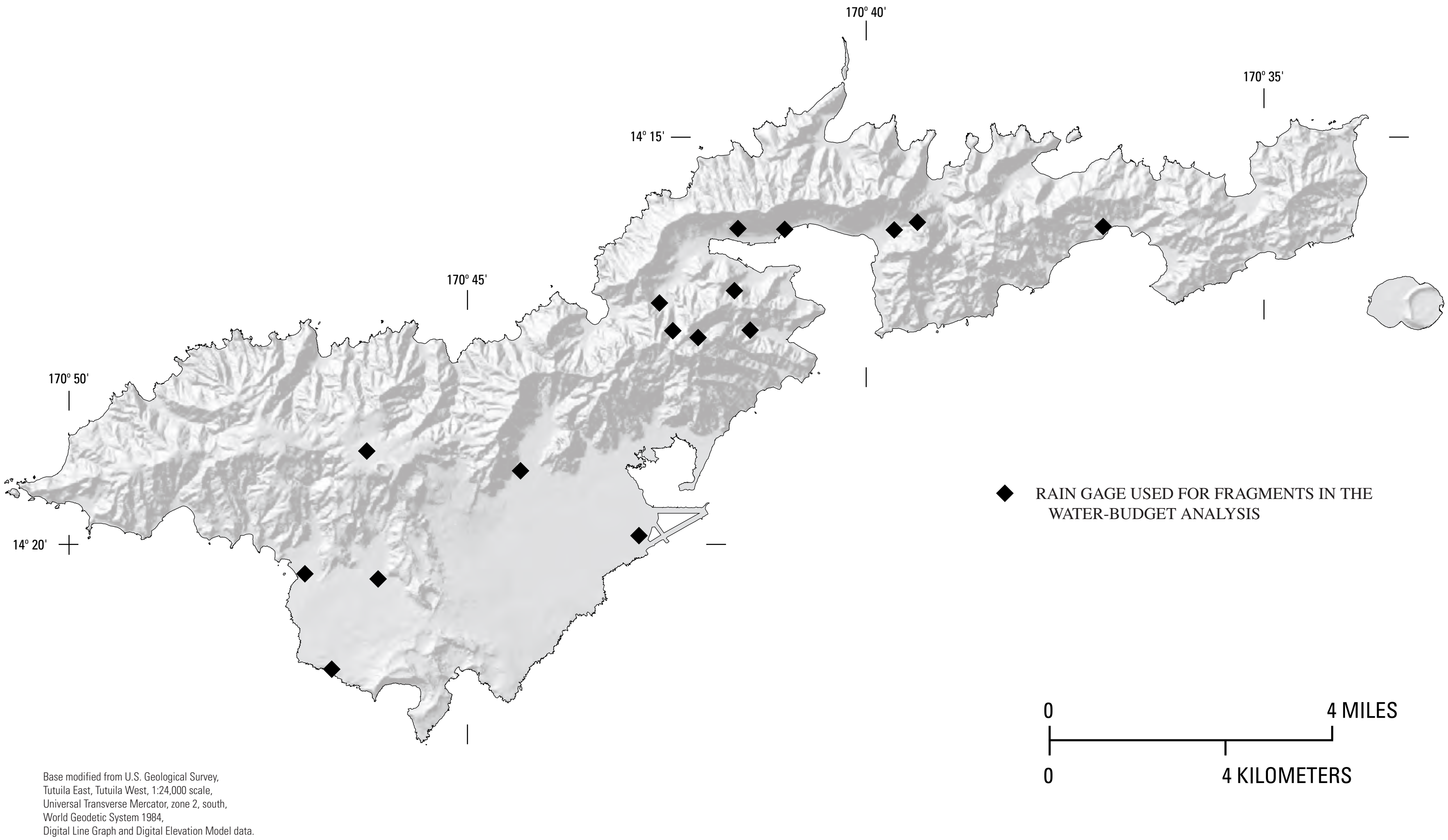


Figure 16. Rain gages used for the method of fragments in the water-budget analysis of ground-water recharge in the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

Table 3. Fragment zones in the water-budget analysis of recharge in the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

Month	Zone 1		Zone 2		Zone 3		Zone 4	
	Rainfall range (inches)	Number of fragments	Rainfall range (inches)	Number of fragments	Rainfall range (inches)	Number of fragments	Rainfall range (inches)	Number of fragments
January	9 to 13	57	13 to 17	45	17 to 21	47	21 to 25	38
February	8 to 12	53	12 to 16	27	16 to 20	83	20 to 24	34
March	8 to 12	54	12 to 16	48	16 to 20	65	20 to 24	24
April	7 to 11	58	11 to 15	14	15 to 19	88	19 to 23	31
May	7 to 11	52	11 to 15	33	15 to 19	79	19 to 23	36
June	5 to 9	54	9 to 13	38	13 to 17	64	17 to 21	27
July	4 to 8	62	8 to 12	48	12 to 16	60	16 to 20	27
August	3 to 7	53	7 to 11	27	11 to 15	83	15 to 19	39
September	5 to 9	60	9 to 13	59	13 to 17	48	17 to 21	35
October	8 to 12	55	12 to 16	23	16 to 20	50	20 to 24	70
November	7 to 11	52	11 to 15	20	15 to 19	87	19 to 23	39
December	11 to 15	61	15 to 19	53	19 to 23	34	23 to 27	36

Table 4. Streamflow components for gaged drainage basins on Tutuila, American Samoa.

[N, window size used for hydrograph separation; f, turning-point factor used in hydrograph separation]

Station	N (days)	f	Streamflow components (cubic feet per second)		
			Base flow	Direct runoff	Total
Vaitolu 16906000	3	0.9	0.15	0.27	0.42
Pago 16912000	3	0.9	1.05	2.33	3.38
Leele 16917500	3	0.9	0.45	1.06	1.51
Leafu 16963900	3	0.9	0.09	0.22	0.31
Atauloma 16931000	4	0.9	0.51	1.04	1.55
Papa 16944200	4	0.9	0.64	3.54	4.18
Afuelo 16948000	4	0.9	0.26	1.21	1.47
Alega 16960000	4	0.9	0.66	0.54	1.20
Aasu 16920500	5	0.9	2.88	3.66	6.54
Asili 16931500	5	0.9	1.01	1.53	2.54

Table 5. Runoff-to-rainfall ratios for stream-gage drainage basins on Tutuila, American Samoa.

Stream gage name and number	Month											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
					Eastern Tutuila							
Vaitolu 16906000	0.121	0.215	0.174	0.172	0.093	0.233	0.148	0.153	0.141	0.177	0.107	0.285
Pago 16912000	0.371	0.349	0.366	0.299	0.298	0.198	0.244	0.251	0.235	0.356	0.258	0.364
Leele 16917500	0.276	0.257	0.102	0.295	0.245	0.270	0.395	0.389	0.355	0.446	0.251	0.284
Papa 16944200	0.355	0.166	0.108	0.358	0.330	0.242	0.311	0.281	0.242	0.166	0.162	0.272
Afuelo 16948000	0.338	0.318	0.271	0.288	0.294	0.219	0.235	0.293	0.302	0.314	0.266	0.355
Alega 16960000	0.228	0.257	0.175	0.238	0.167	0.240	0.201	0.188	0.167	0.187	0.130	0.301
Leafu 16963900	0.300	0.179	0.286	0.254	0.527	0.103	0.172	0.198	0.248	0.251	0.377	0.382
Average	0.284	0.249	0.212	0.272	0.279	0.215	0.244	0.250	0.241	0.271	0.222	0.320
					Western Tutuila							
Aasu 16920500	0.267	0.259	0.257	0.215	0.252	0.170	0.218	0.286	0.234	0.276	0.227	0.280
Atauloma 16931000	0.418	0.390	0.335	0.375	0.394	0.266	0.295	0.395	0.308	0.424	0.319	0.465
Asili 16931500	0.314	0.221	0.577	0.257	0.225	0.124	0.194	0.475	0.233	0.445	0.410	0.273
Average	0.333	0.290	0.390	0.282	0.290	0.187	0.236	0.385	0.259	0.382	0.319	0.339

ing on whether the soil is at field capacity, nearly depleted of moisture (near the wilting point), or at some point between these conditions. In the water-budget computations used in this study, the method of Allen and others (1998) was used to model the change in evapotranspiration between field capacity and wilting point.

The availability of water in the soil is a function of the soil's available water capacity, which is a measure of the amount of water that can be stored in the soil. In this study, the distribution of available water capacity in soils is based on soil surveys described in Nakamura (1984). For many soil types, different values were reported for different depths. In these cases, the water-budget computation used the depth-weighted mean available water capacity for all soil layers within the root depth. Except for valleys, taluses, and narrow coastal areas, most of the study area was covered with soils that were less than 30 in. thick. Most of the mountains in the study area have thin soil because slopes are steep. An exception is the area near Olotele Mountain (fig. 1) where pyroclastic deposits from the Leone Volcanics mantle the eroded Older Volcanics. In the Tafuna-Leone Plain, soils are thin because the rocks are young. Soils are reported to be as much as 43 in. thick in some parts of the plain, but below 18 in. the soil consists mostly of fragmented lava flows (Nakamura, 1984).

Root depths (which limit the depth of active evapotranspiration in the water budget) were estimated for various types of vegetation. The distribution of vegetation type used in this study was based on a survey by Donnegan and others (2004). Root depths assigned to each of the vegetation classifications ranged from 6 in. for grass-covered areas to 36 in. for forests (table 6). These root depths are consistent with root depths used for soil water-budget analyses in the Hawaiian islands (Izuka and others, 2005b), which, like Tutuila, are basaltic volcanic islands in the tropical Pacific. Except for a small fraction of land area that has low-intensity urbanization, nearly all of the Tafuna-Leone Plain and surrounding areas is covered with vegetation, most of which is tropical forest.

Table 6. Root depths for vegetation categories in the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

Land cover	Root depth (inches)
Rain forest	36
Modified forest	36
Shrub and grass	12
Developed land	12
Sand beach and bare rock	6
Cleared land	6
Mangrove	6

Other Input Data

In addition to the principal data sets described above, the water-budget computation required other data that have a smaller effect on estimates of ground-water recharge because the data pertain to only a small part of the study area, affect a minor computational adjustment in the water budget, or represent starting conditions whose initial values become irrelevant as the daily water budget is computed over several decades. The values assigned to these parameters in the water-budget computation for the study area are listed in table 7.

Special Recharge Processes in the Eastern Tafuna-Leone Plain

As discussed earlier, ground-water/streamflow relations in the eastern Tafuna-Leone Plain (fig. 17) differ from the rest of Tutuila in that little water runs directly off the ground surface to the ocean. Most of the water the area receives from rainfall and from runoff from the mountains to the north quickly infiltrates the surface and recharges the highly permeable underlying aquifer of the eastern Tafuna-Leone Plain. In this study, a special conceptualization was developed to account for the unique recharge processes in the eastern Tafuna-Leone Plain. Even though the eastern Tafuna-Leone Plain lies in the western-Tutuila region for the purposes of assigning runoff-to-rainfall ratios (fig. 13), it probably has much less runoff than the rest of the region. This is one of the key premises of the special recharge conceptualization for the eastern Tafuna-Leone Plain. To account for the lower runoff, the runoff-to-rainfall ratio (table 5) for the eastern Tafuna-Leone Plain was multiplied by a factor of 0.25. Because there are no stream gages on the eastern Tafuna-Leone Plain, it is not possible to quantify precisely how much lower the runoff from the region is. The effect of the uncertainty of this parameter on the recharge computation is assessed in the sensitivity analysis.

A second key premise is that some of the water that runs off the mountains that lie to the north of the eastern Tafuna-Leone Plain infiltrates the plain near the base of the mountains. This conceptualization is analogous to mountain-front recharge, which is commonly described for arid areas (Wilson and Guan, 2004). Although the Tafuna-Leone Plain is in a wet climate, the permeability of the plain is so high that much of the water running directly off the mountains infiltrates in a narrow zone at the base of the mountain, in a manner similar to the high infiltration that occurs in the alluvial fans at the base of mountains in arid climates. In the water-budget analysis for this study, some of the direct runoff from selected sectors of the mountains upgradient from the eastern Tafuna-Leone Plain (fig. 17) was added to recharge at the mountain-front zone. The mountain-front zone was defined by the extent of the Pavaiai Stony Clay Loam with 6 to 12 percent slope as shown in the map of Nakamura (1984). This soil unit has as much as 55 percent pebble-size or larger rock clasts (Nakamura, 1984), which indicates that it is the piedmont for the northern mountains. During high-intensity rainfall, some surface runoff from the mountains may flow through poorly defined rills and discharge to the ocean, but this runoff has not been quantified precisely. To account for the possibility that not all of the runoff from the sector of the mountains upgradient from the eastern Tafuna-Leone Plain becomes mountain-front recharge, the runoff was reduced by multiplying by a factor of 0.75 before being added to recharge in the mountain-front zone (the remaining fraction of 0.25 is presumed to reach the ocean during extremely intense rainfall; the effect of the uncertainty of this parameter on ground-water recharge is assessed in the sensitivity analysis). This adjusted runoff was added directly to the recharge in the mountain-front zone without being processed through the soil water budget. This step in the computation assumes that recharge in the mountain-front zone is so rapid that the soil quickly reaches field capacity and therefore virtually all of the adjusted runoff contributes to ground-water recharge.

Ground-Water Recharge Estimates

Recharge was estimated for the area shown in figure 18 (this area is larger than, but includes, the land area in the numerical ground-water flow model described later in this report). The area of the recharge analysis received a total water

Table 7. Values of miscellaneous parameters in the computation of the water budget for the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

Parameter	Value
Starting soil moisture storage	50 percent of capacity
Root depth for non-vegetated areas	6 inches
Impervious surface interception capacity	0.5 inches
Recharge rate under surface-water bodies	12 inches per year
Percent of pervious area in urbanized areas	50 percent
Depletion fraction for evapotranspiration method of Allen and others (1998)	0.50

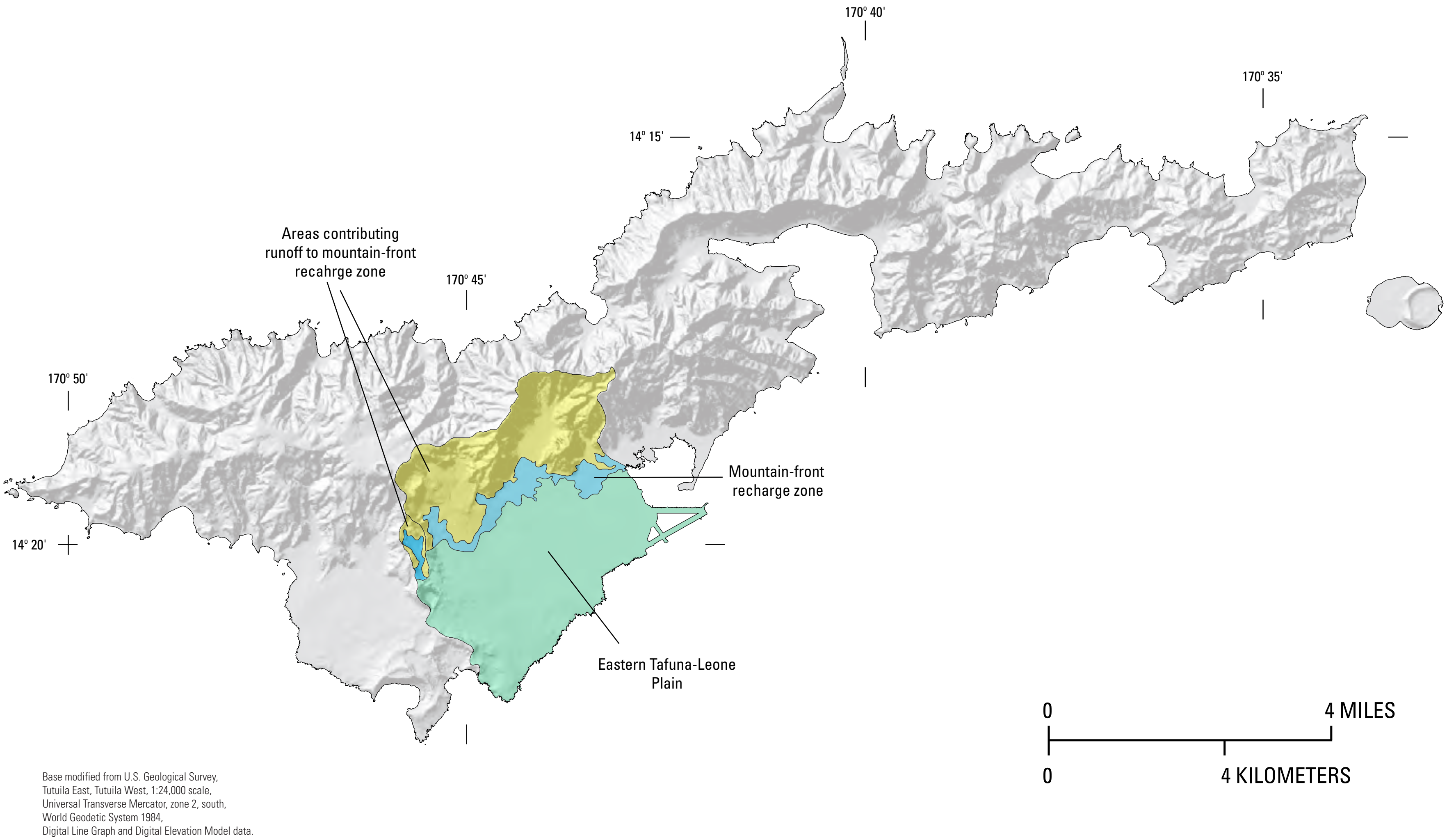


Figure 17. Areas of special recharge processes in the water-budget analysis for the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

input of 280 Mgal/d from rainfall (table 8). Of this total input, 66 Mgal/d (24 percent) was removed by direct runoff to the ocean and another 73 Mgal/d (26 percent) was removed by AE. The estimated total ground-water recharge in the study area is 141 Mgal/d (about 50 percent of input), 134 Mgal/d of which resulted from direct infiltration of rainfall and 7 Mgal/d from mountain-front recharge.

The distribution pattern of ground-water recharge (fig. 18) is similar to the distributions of rainfall (fig. 4) and evapotranspiration (fig. 5), with higher recharge at the mountain crests and lower recharge at the coast. In the Tafuna-Leone Plain, recharge is higher in the east than in the west because of the lower runoff-to-rainfall ratio in the east (consistent with the gentle slope and high permeability of the rocks). The highest recharge rate in the study area is in the mountain-front recharge zone, which receives additional water from direct runoff from the adjacent mountains to the north.

Sensitivity Analysis of Recharge Estimates

The ground-water recharge estimates described above are based on parameter values that were considered to be the most plausible for the study area. For some parameters, however, other values or ranges of values also could be considered plausible, giving rise to a degree of uncertainty. In the sensitivity tests discussed below, parameters were varied individually within ranges that encompassed their associated uncertainties to assess how the uncertainty affects the recharge estimates. Parameters tested included rainfall, root depth, available water capacity, runoff-to-rainfall ratio, the factor used to reduce runoff from the eastern Tafuna-Leone Plain, and the factor used to reduce mountain runoff before adding it to recharge in the mountain-front-recharge zone. For discussion purposes, the results using the most plausible parameter values are herein referred to as the “best estimate.” Results of the sensitivity tests are given and compared to those from the best estimate in table 9.

***Parameter uncertainties having minor effects on recharge estimates.*—**Varying available water capacity and root depth within ranges that encompassed the uncertainty associated with these parameters had relatively minor effects on estimated recharge (table 9). The effect of uncertainty in available water capacity for each soil type was tested in a range from 0.8 to 1.2 times the reported values in Nakamura (1984). Root depths were tested in a range from 0.5 to 1.5 times the root depths used in the best estimate. Testing these parameters over these ranges resulted in recharge estimates that differed from the best-estimate recharge by 1 percent or less. The lack of sensitivity to these parameters is likely due to the thin soils and high rainfall, which cause soils to remain at or near field capacity most of the time in this area.

Thin soils limit the amount of water that can be stored in the soil, the depth from which roots can withdraw water, and hence the effect that evapotranspiration can have on the water budget. As a result, a large fraction of water that infiltrates the ground surface passes through the soil and becomes recharge, regardless of the available water capacity or the depths of roots.

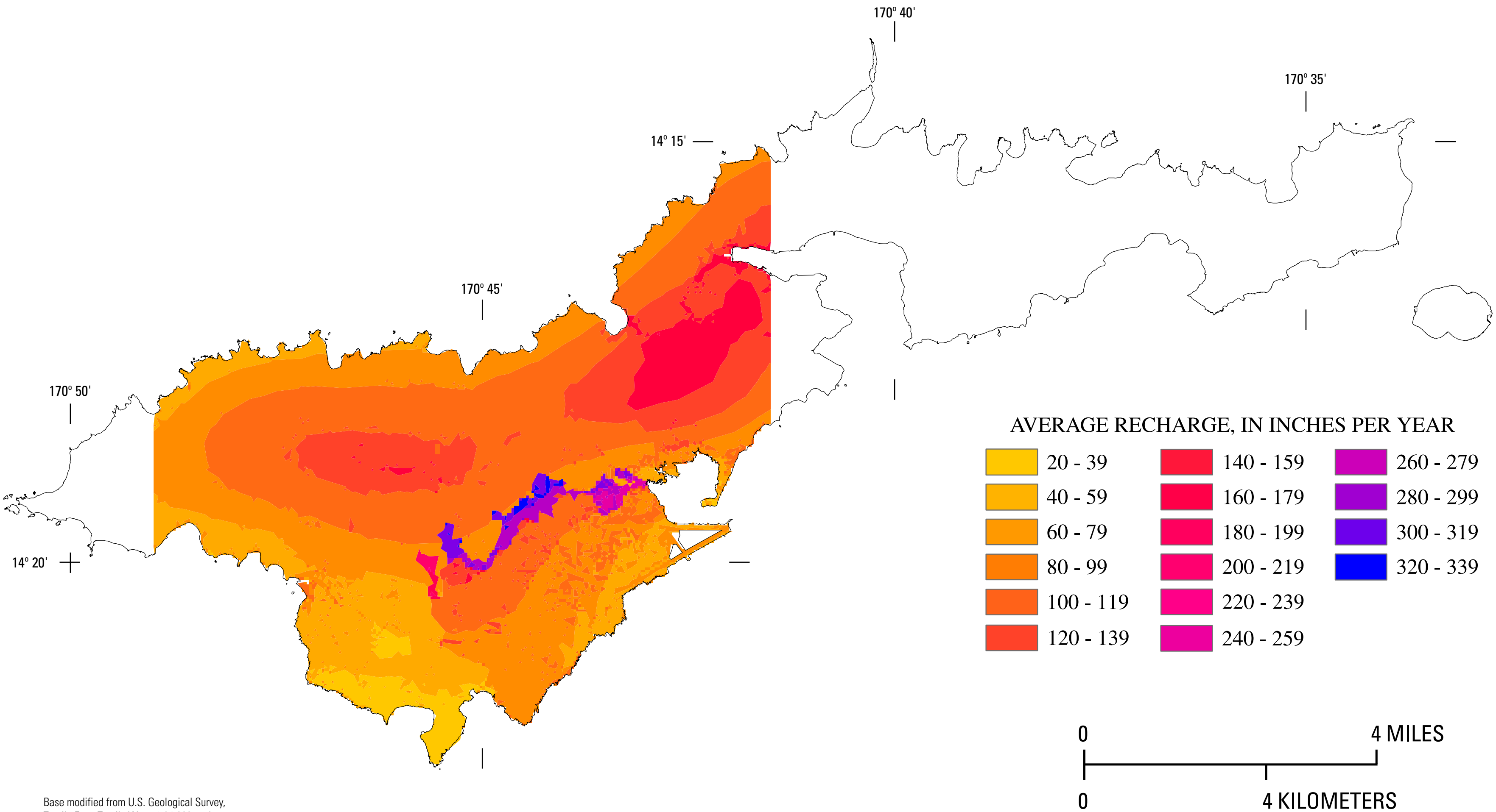
Varying the factors used to reduce runoff from the eastern Tafuna-Leone Plain and to reduce mountain runoff before adding it to recharge in the mountain-front-recharge zone also had little effect on estimated recharge (table 9). Although there are no stream gages to quantify these parameters, the parameters were tested over ranges that encompass plausible values. The factor used to reduce runoff from the eastern Tafuna-Leone Plain was varied over a range of 0.125 to 0.50 (which is 0.5 to 2 times the value of 0.25 used in the best estimate). The factor for reducing mountain runoff before it was added to the recharge at the mountain-front zone was varied over a range of 0.55 to 0.95 (a value of 0.75 was used in the best estimate). The sensitivity tests of these parameters resulted in recharge estimates that differed from the best-estimate recharge by 2 percent or less. The recharge estimate is not sensitive to these parameters because the mountain-front recharge constitutes only a small fraction (about 5 percent) of the total recharge in the study area. Mountain-front recharge has a substantial effect, however, on the distribution of ground-water recharge (fig 18).

Parameter uncertainties having significant effects on recharge estimates.—The source of water in the water-budget analysis is rainfall; uncertainties in the accuracy of the rainfall data set can therefore have a significant effect on recharge estimated from the water budget. The rainfall data used in this study consist of rainfall-distribution maps interpreted from spot rain-gage data of varying periods of record using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly and others, 2006); the process of regionalizing rainfall from spot and varying-period data involves assumptions that can lead to uncertainties. To examine how uncertainty in the rainfall data may affect recharge, rainfall for the entire study area was varied over a range from 10 percent below to 10 percent above the rainfall used in the best estimate. The resulting recharge was 15 percent lower to 15 percent higher than the best-estimate recharge (table 9).

Using runoff-to-rainfall ratios from a few basins to estimate regional runoff also leads to uncertainty. The approach

Table 8. Results of the water-budget analysis for the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

Water-budget component	Million gallons per day
Rain	280
Runoff to ocean	66
Actual evapotranspiration	73
Recharge total	141
Direct infiltration of rainfall	134
Mountain front	7



Base modified from U.S. Geological Survey,
Tutuila East, Tutuila West, 1:24,000 scale,
Universal Transverse Mercator, zone 2, south,
World Geodetic System 1984,
Digital Line Graph and Digital Elevation Model data.

Figure 18. Distribution of estimated ground-water recharge in the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

Table 9. Results of sensitivity tests for water-budget estimates of ground-water recharge in the Tafuna-Leone Plain and surrounding areas, Tutuila, American Samoa.

[RF, rainfall; MFR mountain-front recharge; RO, runoff; AET, actual evapotranspiration; RCH, total recharge including MFR]

Parameter	Test	Water-budget component (million gallons per day)					Percent difference in RCH relative to best estimate[1]
		RF	MFR	RO	AET	RCH	
Rainfall	1.1 times value in best estimate	308	8	80	74	162	15
	0.9 times value in best estimate	252	7	66	73	120	-15
Root depth	1.5 times value in best estimate	280	7	73	74	141	0
	0.5 times value in best estimate	280	7	73	71	143	1
Available water capacity	1.2 times value in best estimate	280	7	73	74	140	0
	0.8 times value in best estimate	280	7	73	72	142	1
Runoff-to-rainfall ratio	Highest values[2]	280	10	92	73	125	-11
	Lowest values[3]	280	6	58	73	154	9
Reduction factor for RO from the eastern Tafuna-Leone Plain	0.125	280	7	71	73	143	1
	0.50	280	7	76	73	138	-2
Reduction factor for mountain runoff before adding to MFR	0.95	280	9	73	73	143	1
	0.55	280	5	73	73	139	-1

[1]Negative value indicates test result is lower than best estimate.

[2]Highest monthly value in east used for all of eastern Tutuila; highest value in west used for all of western Tutuila

[3]Lowest monthly value in east used for all of eastern Tutuila; lowest value in west used for all of western Tutuila

used in this study assumes that the average of the runoff-to-rainfall ratios computed for basins having continuous-record stream gages in a region is representative of all areas in the region. To assess the uncertainty in this parameter, the runoff-to-rainfall ratios for eastern and western Tutuila were varied between the highest and lowest monthly values computed for the drainage basins within the respective regions (table 9). The lowest ratios resulted in a recharge estimate that was 9 percent higher than the best estimate, and the highest ratios resulted in a recharge estimate that was 11 percent lower than the best estimate.

Net recharge uncertainty.—The sensitivity tests show that uncertainties in the water-budget component parameters can lead to uncertainty in the recharge estimate. The net effect of all component uncertainties on the recharge estimate can be quantified by the equation,

$$U = (u_1^2 + u_2^2 + u_3^2 + \ldots)^{1/2}, \qquad \text{(equation 1)}$$

where:

U is the total uncertainty of the recharge estimate [L^3/T], and

$u_1^2 + u_2^2 + u_3^2 + \ldots$ is the sum of the squares of the component parameter uncertainties [L^3/T].

The component uncertainties are computed from the sensitivity analysis results by the equation:

$$u = (u_{upper} - u_{lower})/2$$

where:

u is the uncertainty in recharge for a given component [L^3/T],

u_{upper} is the high recharge value resulting from the test of the given component [L^3/T], and

u_{lower} is the lower recharge value resulting from the test of the given component [L^3/T].

The total recharge uncertainty determined from equation 1 and the component uncertainties listed in table 9 is 25.8 Mgal/d. Assuming that the soil water-budget approach is a reasonably accurate representation of the ground-water recharge process, the total uncertainty is 18 percent of the best-estimate recharge value of 141 Mgal/d.

Numerical Simulation of Areas Contributing Recharge to Wells

Assessing the flow of water to wells in the Tafuna-Leone Plain requires simultaneous consideration of multiple interrelated factors including recharge, natural ground-water discharge, well withdrawals, ground-water levels, and aquifer hydraulic properties. Numerical ground-water flow modeling is currently the most comprehensive method available for analyzing this complex interrelation. For this study, a steady-state model was developed to simulate ground-water flow conditions in the Tafuna-Leone Plain and adjacent mountains to the north (fig. 19). A steady-state model represents the equilibrium conditions that would develop if factors such as recharge and ground-water withdrawal are constant in time.

The ground-water flow model of the Tafuna-Leone Plain was developed using the finite-difference ground-water modeling program MODFLOW-2000 (Harbaugh and others, 2000). Models constructed using MODFLOW-2000 can simulate the ground-water system in three dimensions, simulate wells and well-production rates, and interface with the particle-tracking program MODPATH (Pollock, 1994). Input files required for MODFLOW-2000 and MODPATH were created using the numerical-modeling preprocessor Argus ONE (Argus Holdings, 2006) with the MODFLOW-2000 graphical user interface (MODFLOW GUI) developed by Winston (2000).

Model Structure

The numerical model is based on the conceptual model of ground-water occurrence on Tutuila described by Izuka (1999) and incorporates the additional hydrogeologic data and information collected for this study. To ensure that the no-flow boundaries at the margins of the numerical model did not artificially affect the outcome of the simulations, the model area included not only the Tafuna-Leone Plain, but also the adjacent mountains to the north as well as offshore areas (fig. 19), and the model extended to a depth of 6,000 ft below sea level (table 10). The model domain was divided into 10 layers, each layer having 214 rows and 138 columns of cells. Each model cell represented a square area 300 ft by 300 ft. Layer thicknesses varied from 70 to 2,030 ft.

The primary source of water to the model was ground-water recharge. Recharge entered the top layer of the model, with a distribution that was based on the distribution of ground-water recharge computed in the water-budget analysis (fig. 18). Water exited the model by one of three routes: (1) discharge at the coast, (2) discharge to streams, or (3) withdrawal from wells. Ground-water discharge at the coast is a function of the difference in head between the ocean and adjacent coastal cells. To simulate hydraulic head in the ocean, cells representing ocean areas in the model were assigned a constant head of zero, which represents mean sea level (fig. 20).

Table 10. Top and bottom elevations and thicknesses of layers in the numerical ground-water model of the Tafuna-Leone Plain, Tutuila, American Samoa.

Layer	Elevation (feet relative to mean sea level)		Layer thickness (feet)
	Top	Bottom	
1	2,000	-30	2,030
2	-30	-100	70
3	-100	-200	100
4	-200	-400	200
5	-400	-600	200
6	-600	-800	200
7	-800	-1,000	200
8	-1,000	-2,000	1,000
9	-2,000	-4,000	2,000
10	-4,000	-6,000	2,000

Two different approaches to simulating ground-water discharge to streams in the model were needed, because ground-water/streamflow relations in the eastern Tafuna-Leone Plain differ from those of the mountains to the north. In the mountains, ground-water discharge to streams in the model is a function of the difference in head between the stream cell (which represents stream stage) and the adjacent aquifer cells, and of the hydraulic conductance of the stream bed. When the head in the aquifer is higher than the stage in the stream, ground water discharges to the stream. The process is theoretically reversed when stream stage is higher than the head in the aquifer, but seepage into the ground from the small, flashy streams in the mountains of Tutuila is considered negligible for the purposes of the model. Although seepage-loss measurements during high stage do not exist for Tutuila, stream hydrographs (fig. 14) indicate that the momentary rise in stream stage during the period of a direct-runoff peak is so brief that it is unlikely to cause much water to seep from the stream into the ground. Therefore, the exchange between streams and ground water is primarily one way—from aquifer to stream, not from stream to aquifer. To simulate this one-way relation in the ground-water model, streams in the mountains of Tutuila were simulated using the DRAIN package of MODFLOW-2000. Head in a simulated stream was set equal to the elevation of the stream as estimated from the topographic map of Tutuila (U.S. Geological Survey, 2001). Ground water discharging to streams in the model becomes simulated base flow.

For most mountain streams that discharge to the ocean, simulated base flow exits the model. For streams flowing onto the eastern Tafuna-Leone Plain (fig. 17), however, base flow contributes to mountain-front recharge (in a manner similar to the contribution of direct runoff to mountain-front recharge, as discussed in the water-budget analysis). To simulate this ground-water/streamflow exchange in the model, simulated

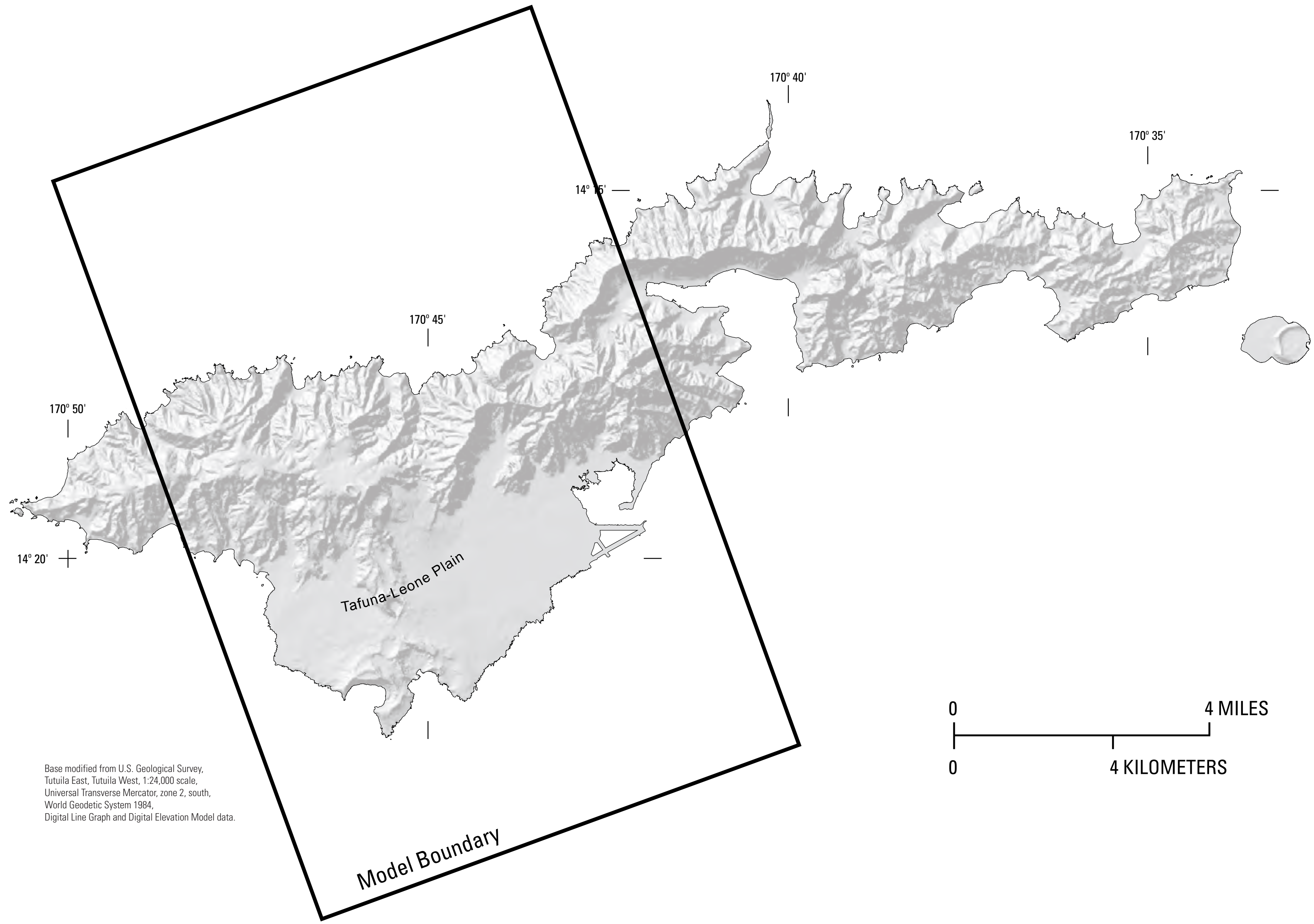


Figure 19. Extent of the numerical ground-water flow model of the Tafuna-Leone Plain, Tutuila, American Samoa.

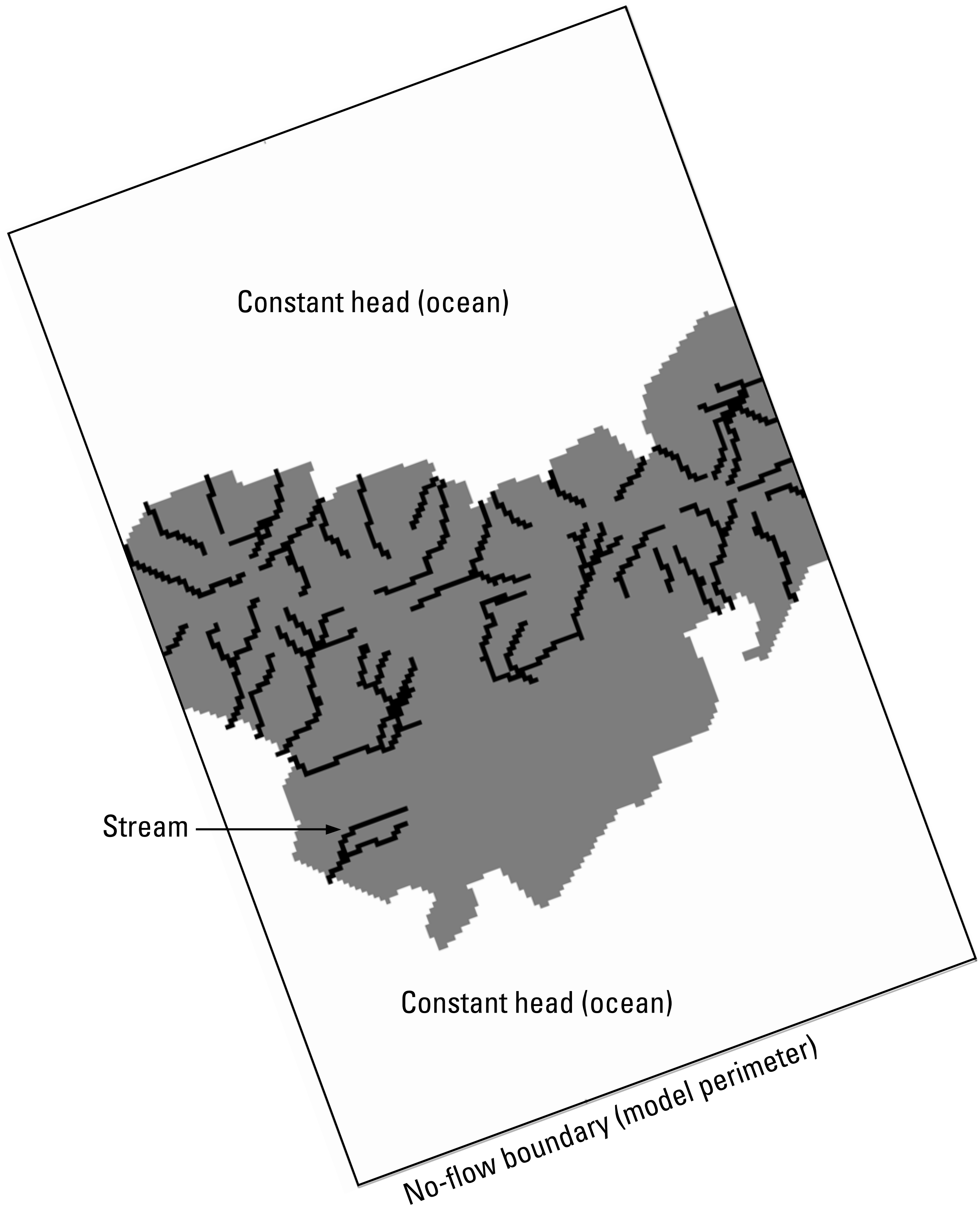


Figure 20. Boundaries and other features of the numerical ground-water flow model of the Tafuna-Leone Plain, Tutuila, American Samoa.

base flow of model streams on the south-facing flank of the mountains above the eastern Tafuna-Leone Plain was routed to ground-water in an area of the model corresponding to the mountain-front zone in the recharge analysis using area injection wells in the WELL package of MODFLOW-2000 (Harbaugh and others, 2000). If simulated base-flow rates changed during the model calibration process (discussed below), the injection rate was adjusted accordingly.

Withdrawal of ground water from the model is simulated by specifying a withdrawal rate for the model cell representing the well. If the cell encompasses more than one well, the sum of the withdrawal rates for all wells in the cell is specified for that cell. Because well-construction data are not available for all wells in the study area, and because model discretization limits the ability to simulate the open intervals of wells precisely, the simulated wells in the model were given a single interval (water table to 30 ft below mean sea level) from which to withdraw water from the aquifer. This interval is consistent with the average of the open intervals of wells for which well construction data are available (table 1).

Model Input and Calibration

The ground-water flow model of the Tafuna-Leone Plain is a steady-state model in which water levels, recharge, natural discharge, withdrawal from wells, and storage do not change with time. Average values of computed recharge and measured or estimated well-production rates were used to represent steady-state conditions. Ground-water recharge to the model was computed from the long-term-average recharge distribution estimated in the water-budget analysis (fig. 18) by using a GIS to merge the recharge distribution with the grid of the ground-water flow model and computing the area-weighted average of all recharge subareas (polygons) within the cell. Model-simulated production rates for wells were set equal to the average production rate for the 5-yr period prior to the synoptic water-level survey (table 2). These ground-water-production and recharge conditions approximate the conditions in existence in 2005.

During model calibration, horizontal and vertical hydraulic conductivities (K_h and K_v, respectively) were adjusted until simulated ground-water levels matched ground-water levels measured during the synoptic survey. The hydraulic properties of the stream beds also were adjusted until simulated ground-water discharge to streams matched base flows computed from the hydrograph-separation analysis of stream-gage data.

Results of Model Calibration

Hydraulic properties in the calibrated model.—To match water levels and stream base flow in the calibrated model, the modeled area was divided into seven hydrogeologic units, each having unique values of K_h and K_v (table 11, fig. 21). The geometry and hydraulic properties of the hydrogeologic units in the model is consistent with current understanding of the regional geology (fig. 6).

Stearns (1944) noted significant variations in the igneous rocks of the Tafuna-Leone Plain. These variations can have a bearing on the hydraulic properties of the rocks. The eastern half of the Plain consists mostly of pahoehoe lava flows, the western half has ash layers intercalated with pahoehoe, and the two halves of the Plain are separated by a ridge of volcanic cones. In the calibrated ground-water model, volcanic rocks of the Tafuna-Leone Plain are divided into four hydrogeologic units that are consistent with the observations of Stearns and subsequent hydrologic studies (Davis, 1963; Bentley, 1975; Izuka, 1999). The Tafuna Lava hydrogeologic unit of the model (table 11; fig 21) represents the pahoehoe lava flows in the eastern part of the Plain, and the Leone Lava unit represents the intercalated pahoehoe and ash in the western part of the Plain. The Pyroclastics unit represents the ash, cinder, and tuff that form the volcanic cones, and the Dikes unit represents

Table 11. Hydraulic conductivites of the hydrogeologic units in the numerical ground-water model of the Tafuna-Leone Plain, Tutuila, American Samoa.

Hydrogeologic unit in model	Description	Hydraulic conductivity in model (feet per day)	
		Horizontal	Vertical
Alluvium	Alluvium in valleys, along coastline, and buried beneath the Tafuna-Leone Plain	850	8.5
Tafuna Lava	Pahoehoe lava flows in eastern part of the Tafuna-Leone Plain	3,100	310
Leone lava	Ash and lava flows in western part of Tafuna-Leone Plain	1,300	13
Pyroclastics	Unconsolidated or loosely consolidated ash and cinder	34	0.34
Dikes	Near-vertical sheetlike intrusive igneous bodies formed during eruption of the Leone Volcanics	1.0	0.1
Reef	Ancient reef buried beneath the Tafuna-Leone Plain	900	9.0
Older Volcanics	Pliocene-Pleistocene thick alkalic lava flows and dikes forming the mountains north of the Tafuna-Leone Plain	0.45	0.0045

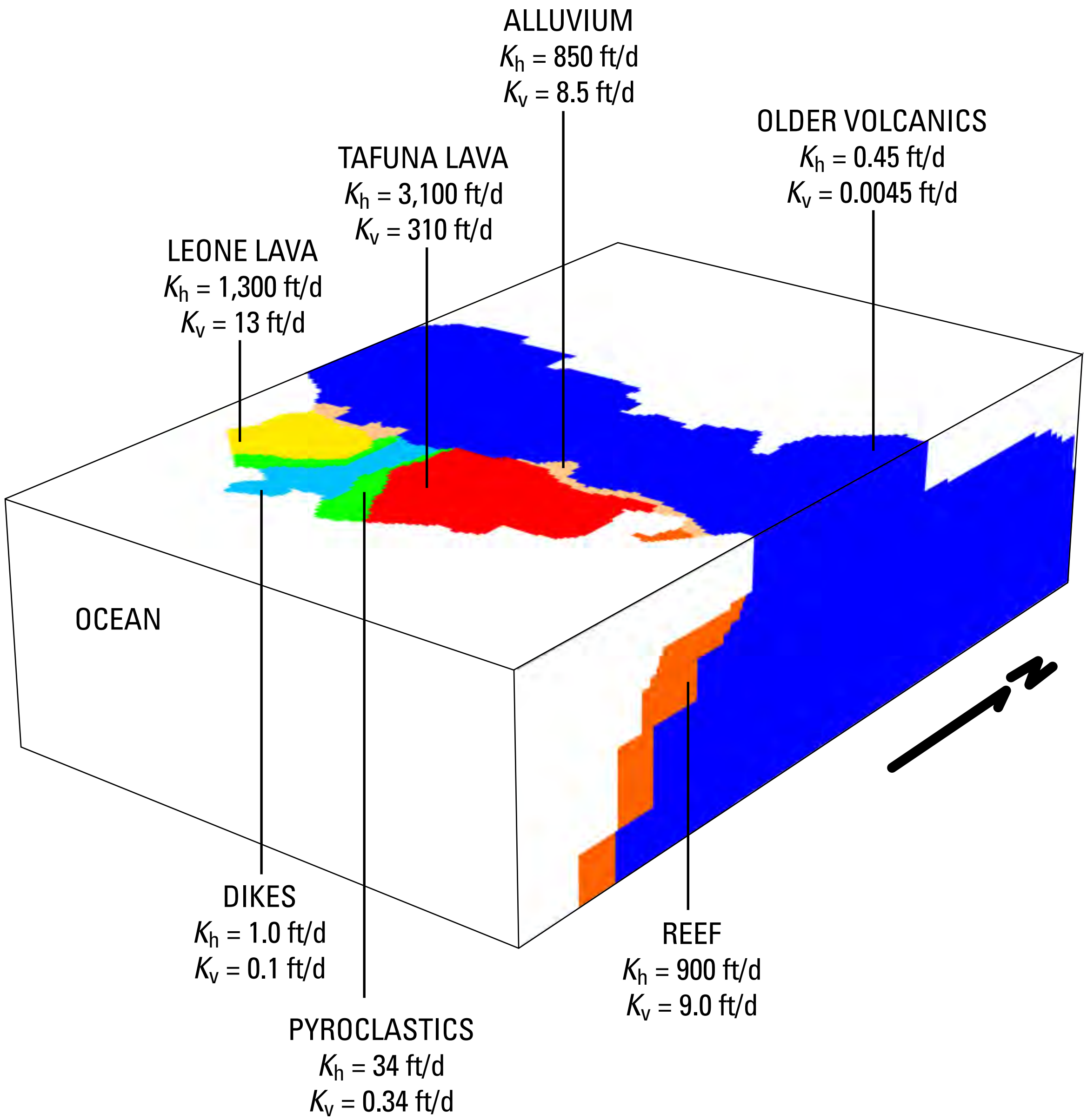


Figure 21. Hydrogeologic units and horizontal (K_h) and vertical (K_v) hydraulic conductivities, in feet per day (ft/d), in the calibrated numerical ground-water model of the Tafuna-Leone Plain, Tutuila, American Samoa.

the magma that solidified in the fissures feeding the volcanoes and now presumably forms a swarm of vertical sheets of dense rock beneath the ridge of volcanic cones.

In the calibrated model, the Tafuna Lava unit has a K_h of 3,100 ft/d (table 11; fig. 21). This high value of K_h is consistent with the high T and specific capacities reported by Bentley (1975) for wells in this area. The high value of K_h in the modeled Tafuna lava is also comparable to that of young basaltic aquifers in Hawaii (Takasaki and Mink, 1982; Hunt, 1996). Because lava flows are layered structures, it is expected that hydraulic conductivity in the vertical direction will be smaller than in the horizontal direction. The ratio of K_v to K_h is not well known for basaltic aquifers, but has been commonly considered to range between 1:10 and 1:100 in numerical ground-water models of Hawaiian aquifers (Hunt, 1996). A value of 310 ft/d was used for K_v (corresponding to a K_v to K_h ratio of 1:10) in the Tafuna Lava hydrogeologic unit of the calibrated model. The Leone Lava unit in the calibrated model has a K_h of 1,300 ft/d and a K_v of 13 ft/d. These values are within the range of hydraulic conductivities reported from basaltic aquifers in Hawaii, but lower than those of the Tafuna Lava unit because of the intercalated low-permeability ash layers. The base of the Tafuna Lava and Leone Lava units in the model was set between -30 ft and -100 ft elevation, which is consistent with data from subsurface drilling.

The Pyroclastics unit in the calibrated model represents a group of rocks that range from unconsolidated cinder to indurated tuff (Stearns, 1944) and therefore probably has a wide range of hydraulic properties (table 11; fig. 21). The permeability of well-indurated tuff can be extremely low, whereas the permeability of cinder can be much higher. It is not possible, within the scope of the numerical model, to differentiate between the various types of pyroclastic deposits, but the bulk permeability of pyroclastic rocks is likely to be less than that of the lava flows. The Pyroclastic unit in the calibrated model has a K_h of 34 ft/d and a K_v of 0.34 ft/d. The base of the Pyroclastics unit in the model was set at an elevation of -30 ft.

The Dikes unit in the calibrated model simulates a complex of volcanic dikes that have intruded into the layered sedimentary and igneous units of the Tafuna-Leone Plain and adjacent mountains (table 11; fig. 21). Although the host rock into which the dikes intrude may have moderate to high permeability, the presence of dense dike rock reduces the overall permeability of the Dike unit. In other well-studied volcanic island aquifers such as those in Hawaii, K_h in dike complexes ranges from about 1 to 500 ft/d (Takasaki and Mink, 1982), depending on how closely spaced the dikes are in the host rock. The Dike unit in the calibrated model of the Tafuna-Leone Plain ground-water model has a K_h of 1 ft/d and a K_v of 0.1 ft/d.

Beneath the Tafuna Lava and Leone Lava units is the Reef unit of the calibrated model (table 11; fig. 21). This unit represents the wedge of sediments that forms both the ancient fringing reef buried beneath the igneous components beneath the Tafuna-Leone Plain as well as the modern reef adjacent to the plain (table 11). Drilling logs indicate that the Reef unit contains marine carbonate (reef) rock, but it is also likely to contain clastic sediments derived from Tutuila by erosion. Similar hydrogeologic units (known as caprock) in Hawaii have horizontal hydraulic conductivites that range from a few to hundreds of feet per day (Takasaki and Mink, 1982; Hunt 1996). In the calibrated model of the Tafuna-Leone Plain, the Reef unit has a K_h of 900 ft/d and a K_v of 9 ft/d.

To the north and partly underlying the igneous and sedimentary units of the Tafuna-Leone Plain is the hydrogeologic unit referred to as the Older Volcanics in this report (table 11; fig. 21). This unit represents the Pliocene-Pleistocene alkalic lava flows and dikes forming the mountains north of the Tafuna-Leone Plain. Evidence discussed earlier in this report indicates that the Older Volcanics has substantially lower permeability than the rocks of the Tafuna-Leone Plain. The Older Volcanics unit in the calibrated model has a K_h of 0.45 ft/d and a K_v of 0.0045 ft/d. These values are similar to those used by Izuka and Gingerich (1998) and Izuka (2006) for thick alkalic lava flows in the Lihue Basin on Kauai, Hawaii.

The Alluvium unit (table 11; fig 21) represents the terrigenous clastic sediments that were deposited along the coast penecontemporaneously with the sediments of the Reef unit, as well as the sediments that partially fill valleys. The unit has a much smaller volume than any of the other hydrogeologic units in the model, but one of the monitor wells used for matching the calibrated model and measured water levels (well 69 in the Malaeimi well field) is within the unit. In the calibrated model of the Tafuna-Leone Plain, the Alluvium unit has a K_h of 850 ft/d and a K_v of 8.5 ft/d. These values are consistent with the moderate to high transmissivities reported by Bentley (1975) for alluvium on Tutuila.

In the MODFLOW GUI, the model-simulated stream-bed conductance is controlled by a lumped parameter known as the conductance multiplier, which is equivalent to the product of stream-bed width and stream-bed vertical hydraulic conductivity divided by stream-bed thickness. The MODFLOW GUI multiplies the stream-bed conductance by the length of the stream in a given cell to obtain stream-bed hydraulic conductance for that cell. In the calibrated model, all streams were assigned a conductance multiplier of 0.027 ft/day, which is analogous to a stream bed having a width of 12 ft, thickness of 2 ft, and a stream-bed K_v of 0.0045 ft/d. This value of K_v is equal to that of the Older Volcanics (table 11, fig. 21).

Model-simulated versus measured ground-water levels and base flow.—Simulated ground-water levels in the calibrated model closely match ground-water levels measured in the six monitor wells during the synoptic survey (red dots in fig. 22). The agreement between water levels in the model and the monitor wells is within a root-mean-square (RMS) of residuals (differences between the measured and simulated water levels) of 0.05 ft (table 12). Because the measured water levels are from monitor wells, they are not subject to the inaccuracies associated with measuring water levels in production wells. The water levels were measured in 2005 and therefore are representative of the steady-state water table under the conditions (2005) simulated in the model. For these reasons, water levels from the six monitor wells are considered the best available data for the purposes of model calibration.

Water levels in production wells that were measured in the synoptic survey also are shown in figure 22. Most of the production wells from which pumping was stopped during the synoptic survey (blue dots in fig. 22) plot on or near the line representing agreement between simulated and measured water levels. Although the model does not replicate these water levels as accurately as those of the monitor wells, the match is reasonably close considering the difficulty in measuring water levels in production wells whose pumps were recently stopped. In contrast, the model-simulated water levels do not closely match the water levels measured in production wells that were pumped during the synoptic survey (white dots in fig. 22), but this result is expected because of the large uncertainty associated with measuring water levels in a pumped well.

Except for the production wells that were pumped during the survey, the model-simulated water levels generally matched those of the synoptic survey (fig. 22 and 23). The simulated water levels also are consistent with the water-table map and conceptual model of Tutuila developed by Izuka (1999) (fig. 7).

Table 12. Measured and model-simulated water levels for monitor wells in the Tafuna-Leone Plain, Tutuila, American Samoa.

Monitoring point (well location and number)	Hydrogeologic unit in model	Water level (feet relative to mean sea level)	
		Measured	Simulated
Pavaiai 178	Pyroclastics	9.90	9.89
Malaeloa 92	Leone Lava	3.27	3.25
Iliili 115	Tafuna lava	3.39	3.33
Tafuna 2	Tafuna Lava	2.50	2.56
Malaeimi 69	Alluvium	10.20	10.30
Tafuna 5	Tafuna Lava	2.67	2.65
		Root mean square of residuals	0.05

Four stream gages (16920500 at Aasu, 16931500 at Asili, 16917500 at Leele, and 16944200 at Papa) lie within the area simulated by the ground-water flow model of the Tafuna-Leone Plain. The total base flow of these streams, computed from the hydrograph-separation analysis of the stream-gage data, is 4.98 ft^3/s (table 4). In the calibrated model, the simulated base flow to these streams was 5.14 ft^3/s, which is within 4 percent of the base flow indicated by the stream-gage data.

The total simulated water input to the calibrated model is 136 Mgal/d, of which 99 percent comes from recharge and 1 percent from mountain-stream base flow that infiltrates the mountain-front zone (table 13). In the steady-state model, the simulated ground-water discharge equals the simulated input. Of the total simulated discharge, discharge to the ocean accounts for 78 percent (106 Mgal/d), discharge to streams accounts for 17 percent (23 Mgal/d), and well production accounts for 5 percent (7 Mgal/d).

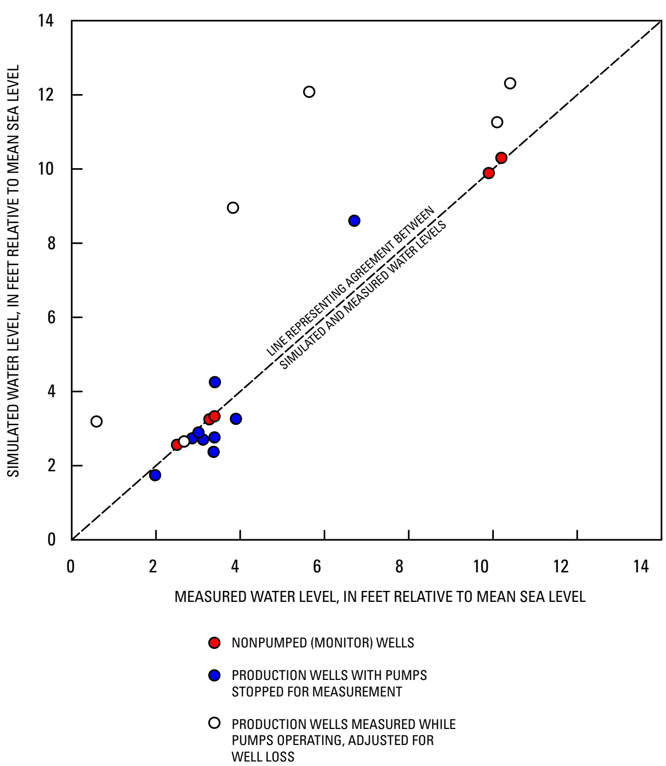


Figure 22. Comparison of ground-water levels measured during the synoptic survey with simulated water levels in the numerical ground-water model of the Tafuna-Leone Plain, Tutuila, American Samoa.

Table 13. Water balance of the calibrated numerical ground-water flow model of the Tafuna-Leone Plain, Tutuila, American Samoa.

Water-balance component in model	Rate (million gallons per day)
Input	
Redirected base flow to mountain-front zone	2
Recharge	134
Total	136
Discharge	
Discharge to ocean	106
Well production	7
Discharge to streams	23
Total	136

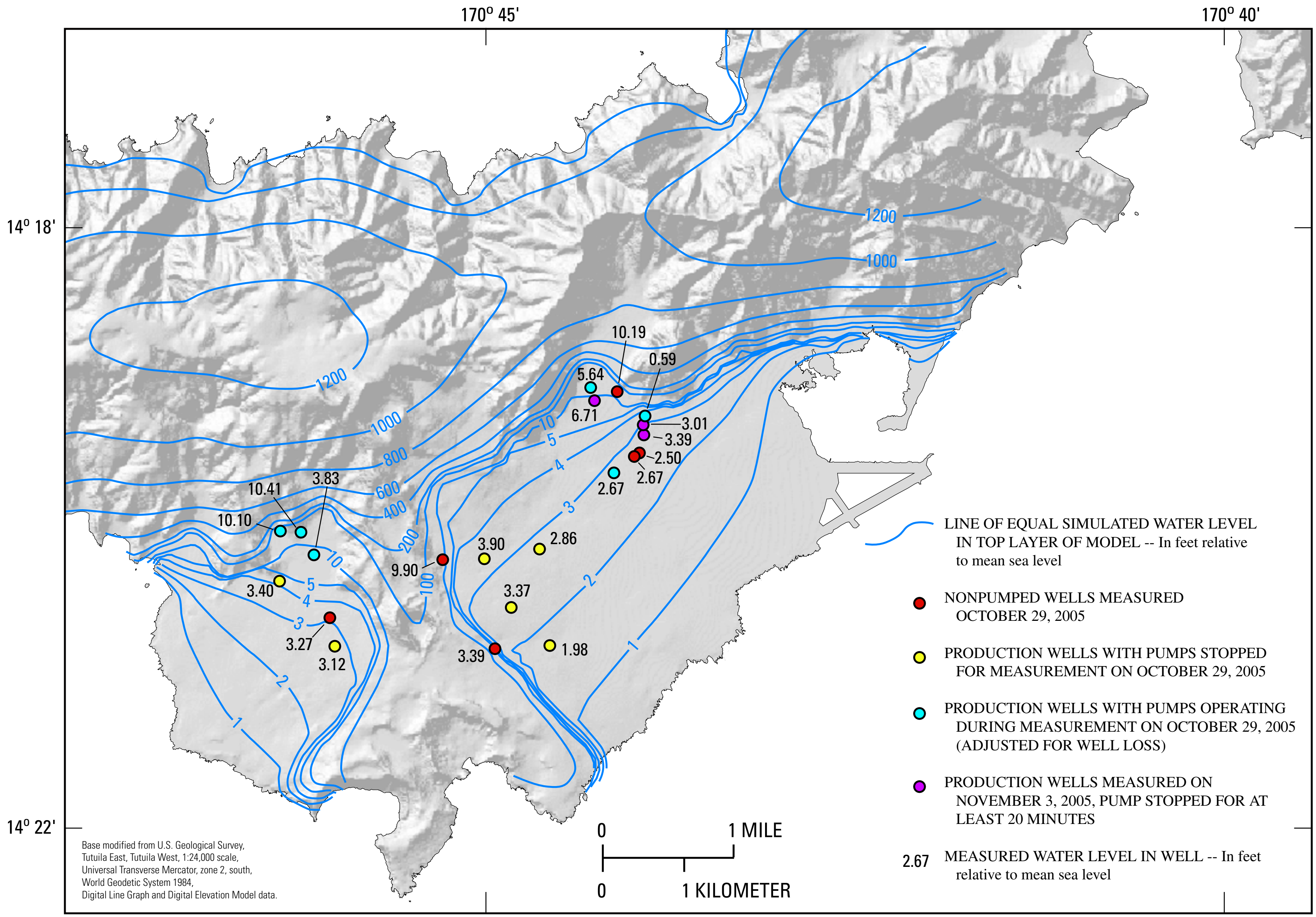


Figure 23. Distribution of simulated head in the numerical ground-water model of the Tafuna-Leone Plain, Tutuila, American Samoa.

Areas Contributing Recharge to Wells

The ACRWs in the study area were determined using the particle-tracking program MODPATH (Pollock, 1994). MODPATH simulates the motion of particles as though they were entrained in the ground-water flow system represented by the ground-water flow model. Particle motion can be tracked in both the forward and backward directions. The backward-tracking capability is the key to assessing the ACRWs. The ACRWs in the model can be determined by tracking a large number of simulated particles from the well back to their points of origin on the water table. In the analysis for this study, 1,000 particles were tracked from each well back to the points on the water table from which they originated. Assuming that ground-water movement between the land surface and the water table is vertical, the distribution of simulated originating points represents the ACRWs.

As with the ground-water-flow aspects of the model of the Tafuna-Leone Plain, the particle tracking done by MODPATH represents steady-state conditions; therefore, the time it takes a particle to travel from its point of origin to the well is not considered in this study. Steady-state conditions were simulated with the model and used to assess ACRWs under two different conditions of ground-water production shown in table 2. In one simulation, production rates of wells in the model were set at the average production rate for the 5-year period preceding the synoptic survey (2001 to 2005). In the other simulation, production rates for each well in the model were set at the highest annual mean on record in the 20-year period 1985 to 2005. The resulting ACRWs for both simulations are shown in figure 24.

Simulation Using 2001-05 Average Ground-Water Production

Simulation of a ground-water production rate that is equal to the 2001-05 average ground-water production rate approximates conditions that existed in 2005. The ACRWs in this simulation form elongate ovals extending landward from the wells, indicating influence from the regional flow system (fig. 24). Because ground-water flows from inland areas to the coast, most of the water reaching the wells originates from recharge in areas that are inland from the wells.

The size of a given ACRW depends on the production rate of the well and recharge rates in the area surrounding the well (fig. 2). Most of the ACRWs in this simulation extend less than a mile from their production wells (fig. 24). The small size of the ACRWs is consistent with the high recharge in the study area. The ACRWs do not have to expand far to accommodate the production at the well. The small ACRWs also indicate, however, that the travel distance from source to wells is short. The ACRWs in the eastern Tafuna-Leone Plain are smaller than in the western Plain, despite both having high ground-water production rates, because recharge rates are high in the high-permeability rocks in the east (fig. 18). The particularly high recharge in the mountain-front zone also limits the expansion of the ACRWs in the Tafuna and Malaeimi well fields. Even so, the ACRWs in the Tafuna and Malaeimi well fields extend into Malaeimi Valley and the surrounding mountains.

Because this model simulation represents current conditions in the Tafuna-Leone Plain, it can aid in assessing the potential for contamination of existing wells from existing or proposed land uses. Water recharging within the ACRWs will eventually reach one of the existing wells in this simulation, thus providing a route for water-borne contaminants to be carried from the ground surface to the wells. Whether the contaminants will actually reach the wells depends on a number of factors including the chemical or biological reactions taking place between the recharge locations and the wells, but delineation of the ACRWs provides an estimate of the area from which potential contamination may come.

Simulation Using Highest Annual Mean Ground-Water Production

The simulation of the highest annual mean ground-water production represents a theoretical condition in which all wells in the Tafuna-Leone Plain are operating at their practical maximum capacity. The simulation does not necessarily represent the actual potential production from the Tafuna-Leone Plain because it does not consider the likelihood for saltwater intrusion or other possible limitations to ground-water availability. The purpose of this simulation is to examine how the ACRWs in the Tafuna-Leone Plain will be affected by increasing the production rate of existing wells.

The ACRWs resulting from this simulation are larger than those resulting from the simulation using the 2001-05 average production rates (fig. 24). This result is expected because the ground-water production rates from each well field are 27 to 81 percent higher in this simulation than in the previous simulation (table 2). Part of the increase is the result of higher production at each well, and part of the increase is the result of pumping from wells that were not included in the previous simulation. The simulation demonstrates that increasing production from any of the wells, or building and developing new wells, increases the surface area that could potentially contribute contaminants to wells in the Tafuna-Leone Plain.

Intersection of ACRWs and the Mountain-Front Recharge Zone

Some ACRWs in the eastern Tafuna-Leone Plain intersect with the mountain-front recharge zone (fig. 25). Mountain-front recharge therefore provides a potential path for surface water from the mountains to enter the ground in close proximity to production wells. In some places, streams, the mountain-front recharge zone, and the ACRWs come together, providing a means for direct transport of surface water from within the watershed to wells. In Malaeimi Valley, for example, surface

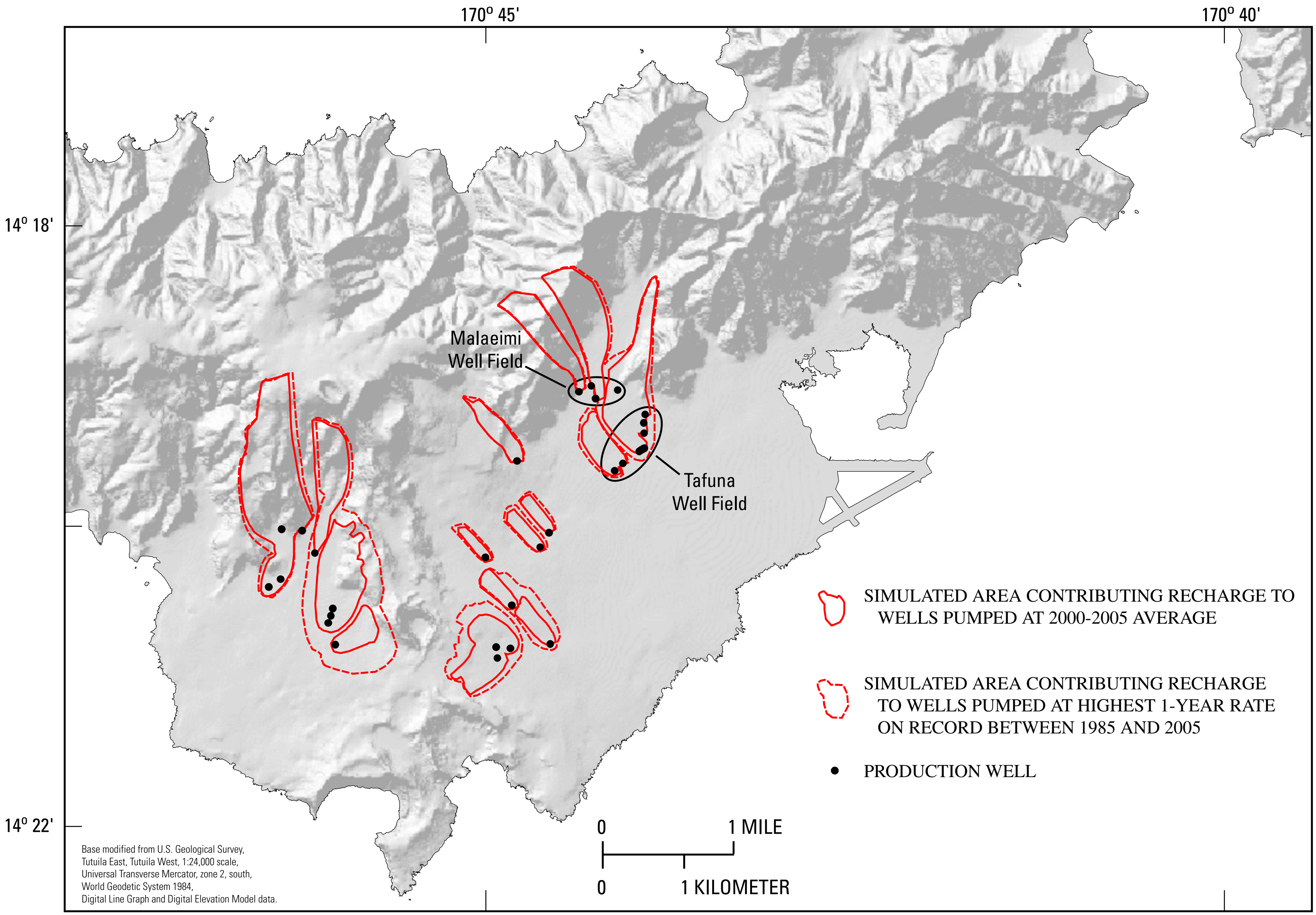


Figure 24. Model-simulated areas contributing recharge to wells in the Tafuna-Leone Plain, Tutuila, American Samoa.

water reaching the stream from anywhere in the basin can flow in the stream channel to an area that is both part of the mountain-front recharge zone and ACRWs in the Tafuna well field. The potential thus exists for water-borne contaminants to move from anywhere in the valley to some of the most productive wells on Tutuila.

A model-simulated ACRW does not assess the surface-water routes that may bring water into the ACRW. Analysis of surface-water routes is not within the scope of this study, but can improve assessment of the area on the land surface that can be a source of contaminants to wells.

Testing Model Sensitivity to Parameter Uncertainty

The accuracy of the model simulations is linked to how accurately model input parameters, such as recharge, well depths, and aquifer hydraulic conductivity, represent actual conditions and how sensitive the model results are to the uncertainties associated with each parameter. To test the sensitivity of model results to uncertainties, selected input parameters were varied in separate model simulations (table 14). In each test, two aspects of model sensitivity were examined: (1) the effect on simulated ground-water levels and how closely they matched the observed ground-water levels that were used for model calibration and (2) the effect on the size and shape of the ACRWs. To measure the effect of varying parameter values on model-simulated ground-water levels, the RMS of the residuals was computed for the six monitoring points used for matching water levels in the model (higher RMS values correspond to greater mismatches between measured and model-simulated values). To assess the effect of parameter uncertainty on the size and shape of the ACRWs, the results of the sensitivity tests are plotted on maps together with the ACRWs from the calibrated model (figs. 26, 27, and 28).

Sensitivity to uncertainties in hydraulic conductivities.—Sensitivity to uncertainties in hydraulic conductivites was tested by multiplying the values of K_h and K_v used in the calibrated model by factors of 2.0 and 0.5 (table 14). To reduce the number of test simulations, the Dikes, Pyroclastics, and Alluvium (DPA) hydrogeologic units were tested together. Similarly, the Tafuna Lava and Leone Lava units were tested together. The Older Volcanics and Reef units were tested separately.

The RMS values resulting from varying K_h and K_v of the Older Volcanics was relatively small (0.20 to 0.26 ft; table 14). This lack of sensitivity is expected because none of the six observation points is in the Older Volcanics (table 12). Varying hydraulic conductivities of the Tafuna and Leone Lava

Table 14. Measured water levels and simulated water levels in the calibrated and sensitivity-test models for monitor wells in the Tafuna-Leone Plain, Tutuila, American Samoa.

[RMS, root-mean-square error; K_h, horizontal hydraulic conductivity; K_v, vertical hydraulic conductivity; DPA, Dikes, Pyroclastics, and Alluvium units combined]

Source of water levels	Water levels at monitoring wells (feet relative to mean sea level)						RMS
	Well 178	Well 92	Well 115	Well 2	Well 69	Well 5	
Measured water levels	9.90	3.27	3.39	2.50	10.20	2.67	NA
Calibrated model	9.89	3.25	3.33	2.56	10.30	2.65	0.05
Sensitivity tests							
Multiply recharge by 1.25	11.30	4.01	3.94	3.03	11.90	3.13	1.02
Multiply recharge by 0.75	7.46	2.20	2.30	1.77	7.62	1.86	1.64
Well depth set at 100 feet below mean sea level	9.89	4.04	3.68	2.71	11.00	2.75	0.48
Multiply K_h and K_v of Leone and Tafuna Lavas by 2.0	8.96	2.39	2.77	1.84	8.97	1.90	0.87
Multiply K_h and K_v of Leone and Tafuna Lavas by 0.5	10.80	4.56	3.81	3.17	11.90	3.31	1.03
Multiply K_h and K_v of Older Volcanics by 2.0	9.73	3.44	3.38	2.64	10.60	2.73	0.20
Multiply K_h and K_v of Older Volcanics by 0.5	9.86	2.94	3.26	2.42	9.71	2.51	0.26
Multiply K_h and K_v of DPA by 2.0	6.91	2.92	2.75	2.55	7.59	2.63	1.65
Multiply K_h and K_v of DPA by 0.5	15.00	3.51	4.44	2.56	15.10	2.66	2.92
Multiply K_h and K_v of Reef by 2.0	8.66	2.49	2.48	1.58	9.15	1.66	1.00
Multiply K_h and K_v of Reef by 0.5	11.40	4.54	4.39	3.67	11.70	3.77	1.27

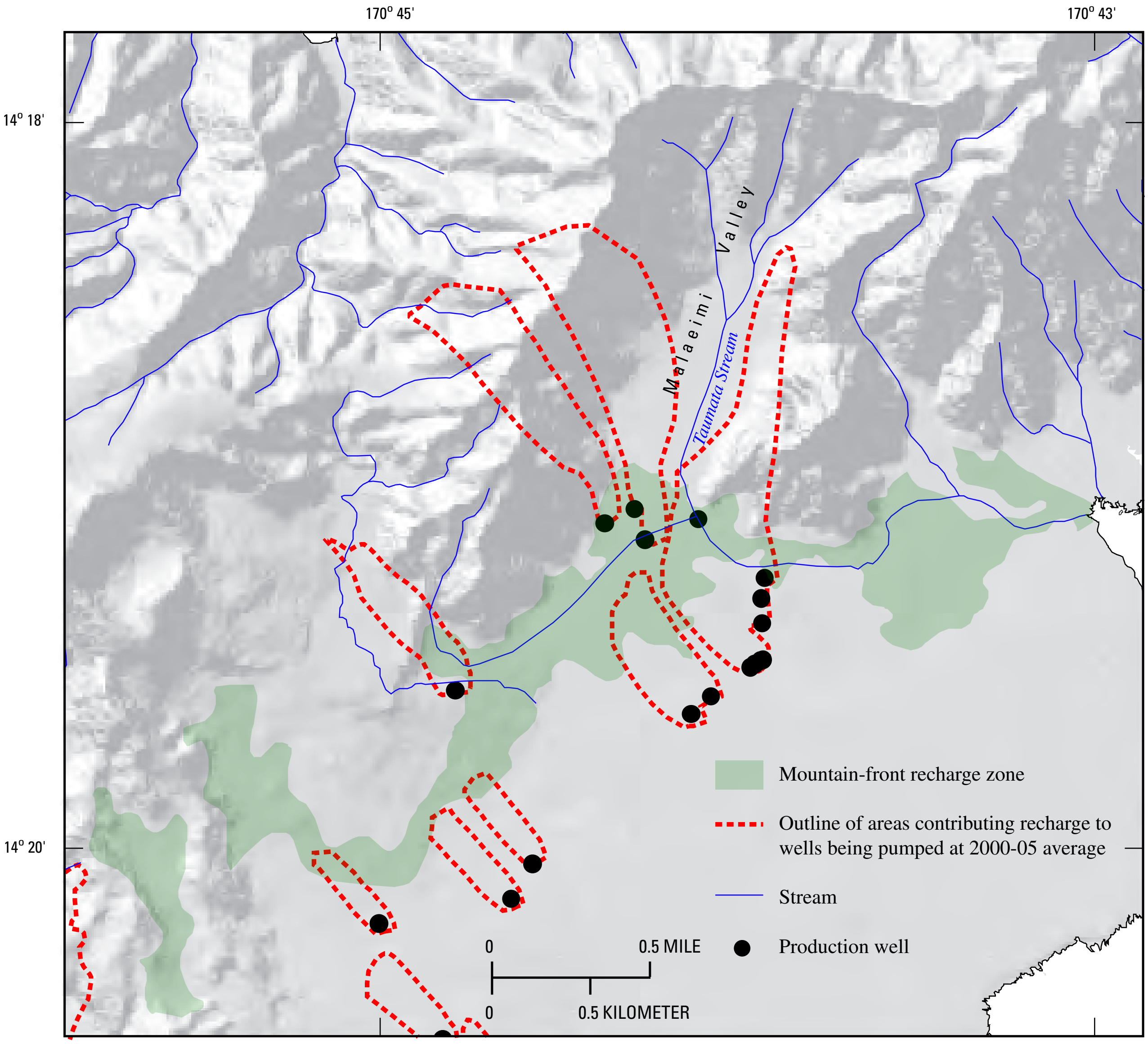


Figure 25. Intersection of model-simulated areas contributing recharge to wells with mountain-front-recharge zones in the Tafuna-Leone Plain, Tutuila, American Samoa.

hydrogeologic units resulted in higher RMS values, ranging from 0.87 to 1.03 ft. Varying the hydraulic conductivities of the Reef unit also resulted in higher RMS values (1.01 to 1.27 ft). These higher model sensitivities to the hydraulic conductivities of the Tafuna Lava, Leone Lava, and Reef units are expected because most of the monitoring points are in either the Tafuna or Leone Lavas and are underlain by the Reef.

Varying K_h and K_v of the DPA units resulted in the highest RMS values (1.65 to 2.92 ft) of all the sensitivity tests (table 14). Differences between the simulated water levels in the sensitivity test and measured water levels from the synoptic survey ranged from 0.01 ft to 5.10 ft. The largest differences between measured an simulated water levels were in well 178, which is in the Pyroclastics unit, and well 69, which is in the Alluvium unit. These differences accounted for most of the large RMS values from the DPA sensitivity tests. Differences were small in wells that are not in the Dikes, Pyroclastics, or Alluvium units. Thus, although the overall RMS values indicate that the model results are sensitive to the hydraulic conductivity of the DPA units, the sensitivity is in a limited area.

The size and shape of the ACRWs are affected little by varying hydraulic conductivities over the ranges tested in the sensitivity analyses (figs. 26, 27). Varying the hydraulic

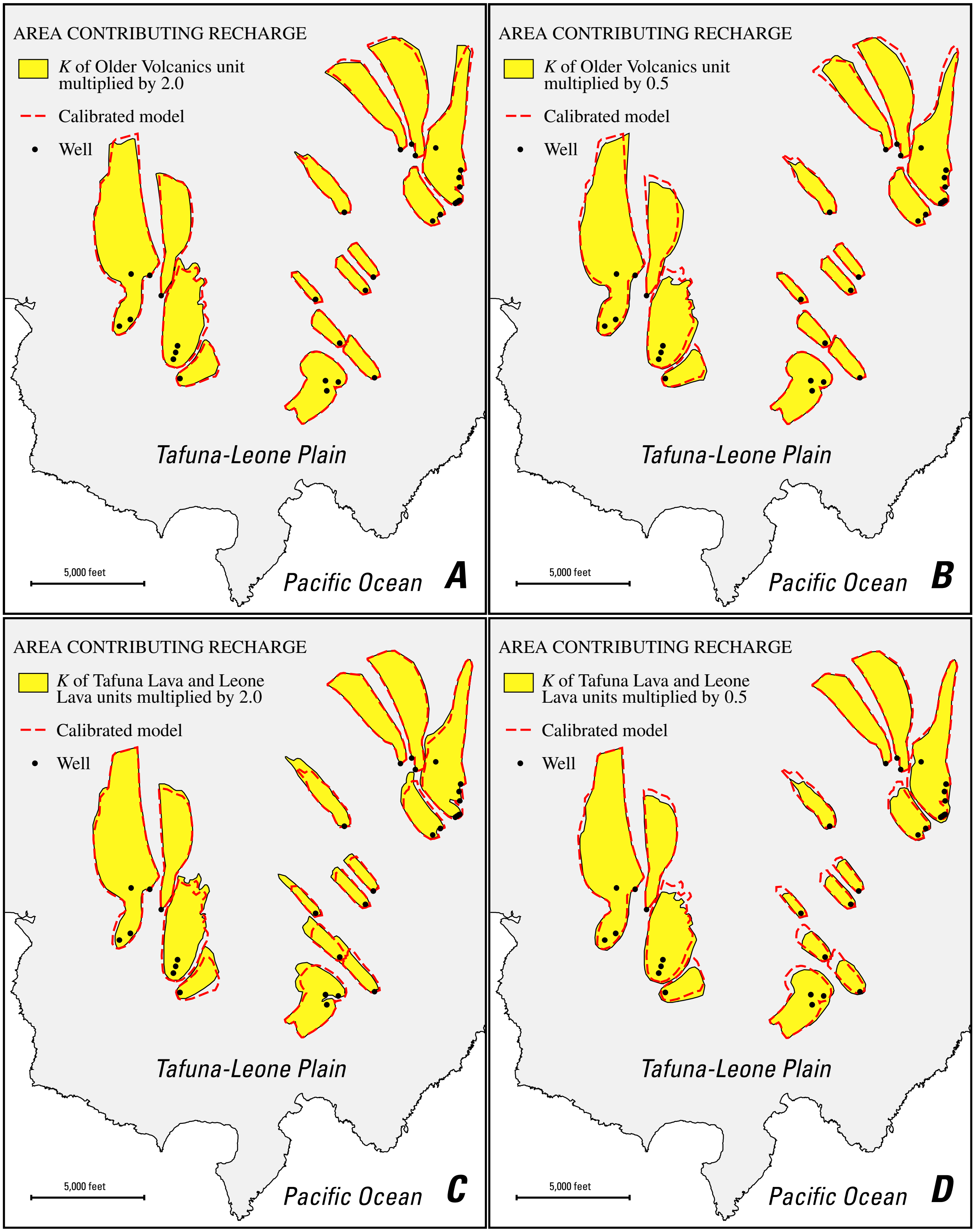


Figure 26. Tests of sensitivity of simulated areas contributing recharge to wells to hydraulic conductivity (*K*). Results from calibrated model are shown for comparison. *A*, *K* of Older Volcanics unit multiplied by 2.0. *B*, *K* of Older Volcanics unit multiplied by 0.5. *C*, *K* of Tafuna Lava and Leone Lava units multiplied by 2.0. *D*, *K* of Tafuna Lava and Leone Lavas units multiplied by 0.5.

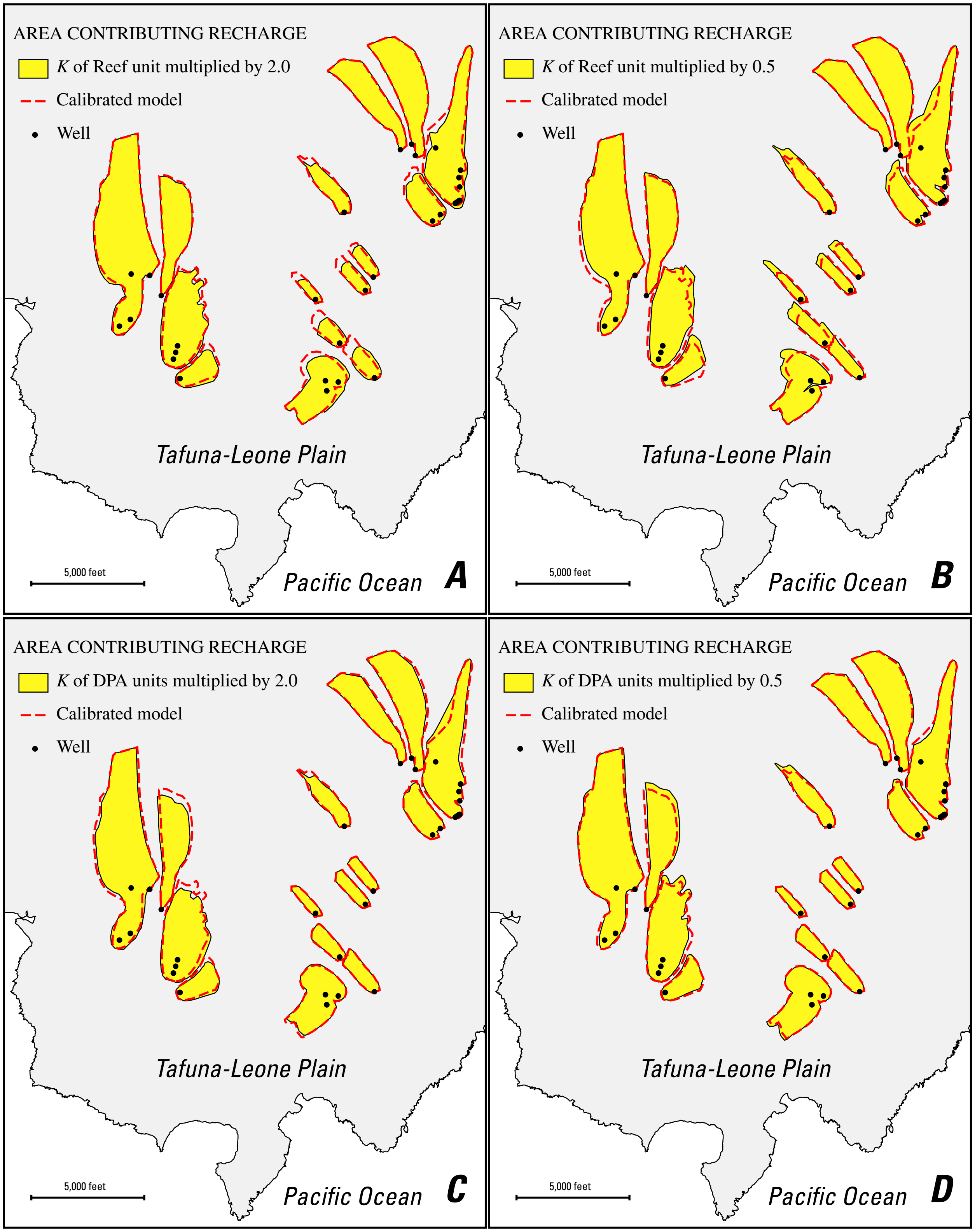


Figure 27. Tests of sensitivity of simulated areas contributing recharge to wells to hydraulic conductivity (*K*). Results from calibrated model are shown for comparison. *A*, *K* of Reef unit multiplied by 2.0. *B*, *K* of Reef unit multiplied by 0.5. *C*, *K* of Dikes, Pyroclastics, and Alluvium (DPA) units multiplied by 2.0. *D*, *K* of DPA units multiplied by 0.5.

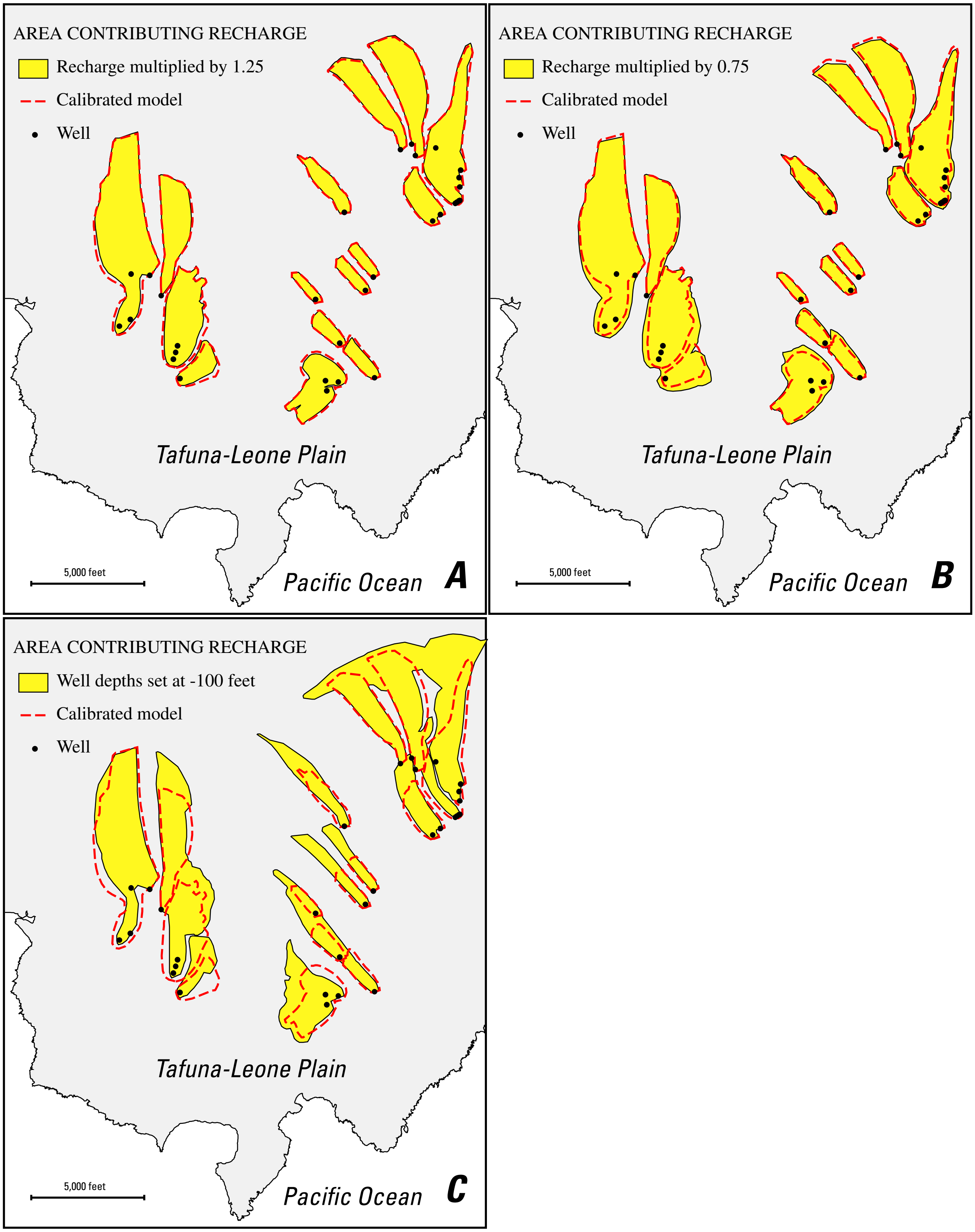


Figure 28. Tests of sensitivity of simulated areas contributing recharge to simulated recharge and well depth. Results from calibrated model are shown for comparison. *A*, simulated recharge multiplied by 1.25. *B*, Simulated recharge multiplied by 0.75. *C*, Well depths set at 100 feet below sea level.

conductivities of the different units affected the ACRWs of the wells that are in or near the units, but the ACRWs of the calibrated and test simulations are largely the same.

Sensitivity to uncertainties in recharge.—The effect of uncertainties in recharge was tested by multiplying the values used in the calibrated model by factors of 1.25 and 0.75. This range encompasses the estimated uncertainty of the water-budget recharge computation (18 percent). Varying recharge over this range resulted in RMS values of 1.02 to 1.64 ft (table 14). Differences between the simulated water levels in the sensitivity test and measured water levels from the synoptic survey ranged from 0.46 ft to 2.58 ft. The effect was greater on wells outside the Tafuna Lava hydrogeologic unit. Because the Tafuna Lava has the highest hydraulic conductivity in the model, its response to varying recharge rates will be less than in units having lower hydraulic conductivity. This test indicates that the model-simulated water levels at some of the monitoring sites are sensitive to uncertainties in recharge.

The size and shape of the ACRWs are less sensitive to uncertainties in recharge. The ACRWs in the simulation in which recharge was increased by a factor of 1.25 are slightly smaller than those in the calibrated model (fig. 28*A*). This result is expected because a smaller area of contribution is needed if recharge is higher. Conversely, the ACRWs in the simulation in which recharge was decreased by factor of 0.75 are slightly larger than those in the calibrated model (fig. 28*B*). Inasmuch as the primary objective of the study is the delineation of ACRWs, the effect of uncertainties in recharge on study conclusions are minor. The actual effect of these uncertainties on the ACRWs is likely to be even smaller, given the recharge-computation estimated uncertainty of 18 percent, which is much smaller than the range tested in the sensitivity analysis (plus or minus 25 percent).

Sensitivity to uncertainties in well depth.— Because construction records are not available for all wells, the depths of all production wells in the model were set at 30 ft below sea level. The available records indicate that some wells may be deeper, but few are deeper than 100 ft below sea level. To test the sensitivity of the model results to uncertainties in well depth, a simulation was run in which all model wells had a depth of 100 feet below sea level. The test resulted in a higher but still relatively small RMS value (0.48 ft; table 14), which indicates that the simulated water levels at the monitoring sites are not sensitive to uncertainties in well construction. The simulation indicates, however, that the shape and position of the ACRWs can be substantially affected by the depth of the simulated wells (fig. 28*C*). Most of the ACRWs resulting from the 100-ft well depths are more elongate and shifted toward the up-gradient direction relative to the ACRWs resulting from the 30-ft well depths used in the calibrated model. Inasmuch as existing records indicate that most well depths are between 30 and 50 ft below sea level, the calibrated model probably represents the actual well depths more closely than does the sensitivity test.

Model Capabilities and Limitations

The numerical ground-water flow model developed for this study has flexibility that allows it to be used for assessing ACRWs not only for existing wells, but also for future proposed wells. A proposed new well with a hypothetical pumping rate can be added to the model, and the ACRW can be determined, provided the well is not so close to the model boundary that it violates the assumptions used in defining the boundary conditions. Alternatively, the simulated production rate of existing wells can be increased to examine the effect on ACRWs. This capability gives water-resource managers the ability to assess potential source areas of contamination that may affect future ground-water development.

The calibrated model is a plausible representation of the ground-water system in the Tafuna-Leone Plain, but it was constructed with the primary objective of delineating areas contributing recharge to existing wells. This objective dictated the selection of the kind of model that was constructed. To some degree, the type of model and the data used in its development constrain the interpretations that can be made and limit the use of the model for purposes beyond the scope of this study.

The model does not indicate how long it will take water to travel from the ACRW to the well. This travel time is an important consideration for assessing whether a contaminant that infiltrates the ground surface within an ACRW has the potential to reach the well. Some contaminants are active for only a limited time once they are incorporated into ground water. Whether a given contaminant infiltrating within an ACRW is a threat to the water quality at the well depends on how long the contaminant remains viable and how long it takes the contaminant to move from its infiltration point to the well. Although travel times cannot be quantified with the steady-state model developed in this study, the model does indicate that ACRWs for many wells in the Tafuna-Leone Plain are small. It is reasonable to conclude that the travel time is probably short. This conclusion is consistent with the elevated bacteria counts in wells in the Tafuna-Leone Plain following heavy rain (Eyre, 1994).

The model does not simulate the effects of diffusion and dispersion, which cause contaminants to spread in directions other than the advective transport simulated in the model. Dispersion and diffusion can cause the ACRWs to be slightly larger than determined in this study. In many cases, however, dispersion and diffusion play a smaller role than advection in contaminant transport. Technology for modeling diffusion and dispersion does exist, but it requires specific data on contaminant concentrations and hydrologic properties of the aquifer, the collection of which is beyond the scope of this study.

The model does not consider the potential for surface-water transport of contaminants from elsewhere to the ACRW. As discussed earlier, this transport can expand considerably the area that can potentially deliver contaminants to a well. Analysis of surface-water routes is needed to fully delineate the area on the land surface that can be a source of contaminants to wells.

The model does not distinguish between saltwater and freshwater beneath the Tafuna-Leone Plain. The delineation of ACRWs for shallow wells such as those in the Tafuna-Leone Plain, however, primarily involves processes near the ground-water table, whereas the transition from freshwater to saltwater is deep in the aquifer. Thus, the omission of the saltwater-freshwater system from the model is likely to have little bearing on the objectives and conclusions of this study. The applicability of the model for other purposes, however, may be limited. Because ground-water availability in coastal and island aquifers is constrained by the possible intrusion of saltwater into wells, the model in this study is of limited use in the estimation of safe yields. Many of the data sets developed for the model in this study, however, such as the conceptual model, distribution of recharge, and distribution of hydraulic conductivity, can be transferred in future studies to a model that simulates the saltwater-freshwater system.

Summary and Conclusions

Water produced from wells ultimately comes from an area of recharge at the surface, therefore sources of contamination on the land surface can pose a threat to the quality of the water produced at the wells. To address concerns about the potential for contamination of existing wells in the Tafuna-Leone Plain on the island of Tutuila, American Samoa, a steady-state numerical ground-water flow model was developed for the purpose of delineating the areas contributing recharge to wells (ACRWs). The process of developing the model also resulted in auxiliary information that advances understanding of ground-water resources in the Tafuna-Leone Plain.

Ground-water production from the Tafuna-Leone Plain is currently distributed among four main well fields (Malaeloa, Iliili, Tafuna, and Malaeimi). The ground-water surveys indicate that total production from all wells in the Tafuna-Leone Plain between 1985 and 2005 averaged 6.1 Mgal/d and showed a gradual increase in this period. Increases in ground-water production had little effect on ground-water levels measured in monitor wells because hydraulic conductivites in most of the Tafuna-Leone Plain are high. Ground-water levels also show frequent short-term fluctuations, but no long-term increasing or decreasing trends. A synoptic survey of ground-water levels conducted in October 2005 indicates that water levels in the Tafuna-Leone Plain are highest near the inland boundary and decrease toward the coast. The trend is in general agreement with earlier studies, except that the synoptic survey indicated that water levels are slightly depressed in high-production well fields.

Ground-water discharge contributes substantially to the total flow of streams in the mountains of Tutuila. In contrast, surface water in the eastern Tafuna-Leone Plain quickly infiltrates the surface and recharges the highly permeable underlying aquifer. Surface water from the mountains also contributes to ground-water recharge in the plain, in a process analogous to mountain-front recharge described in arid areas. Although the Tafuna-Leone Plain has a wet climate, the permeability is so high that most of the water running directly off the mountains infiltrates in a narrow zone at the base of the mountain, in a manner similar to the high infiltration that occurs in the alluvial fans at the base of mountains in arid climates.

Estimates of ground-water recharge using a daily soil water-budget analysis indicate that the Tafuna-Leone Plain and adjacent areas receive about 280 Mgal/d of water from rainfall, of which 66 Mgal/d (24 percent) runs off to the ocean, 73 Mgal/d (26 percent) is removed by evapotranspiration, and 141 Mgal/d (about 50 percent) goes to ground-water recharge. In general, ground-water recharge is higher at the mountain crests and lower at the coast, but the highest recharge rate in the study area is in the mountain-front recharge zone. The total uncertainty in the ground-water recharge estimate is 18 percent; the recharge estimate is most sensitive to uncertainties in rainfall and runoff-to-rainfall ratios.

A steady-state ground-water flow model was developed to delineate ACRWs in the Tafuna-Leone Plain. Most of the ACRWs resulting from a simulation representing current ground-water production conditions are within a mile of the production wells; thus, travel distance between any point within an ACRW and its well is short. Water recharging within the ACRWs will eventually reach one of the existing wells, thus providing a route for water-borne contaminants to be carried from the ground surface to the wells. Because this model simulation represents current conditions in the Tafuna-Leone Plain, it can aid in assessing the potential for contamination of existing wells from existing or proposed land uses.

Larger ACRWs result from a simulation which represents a condition in which all wells are operating at maximum capacity, which demonstrates that increasing ground-water withdrawal from existing wells, or building and developing new wells, increases the surface area that could potentially contribute contaminants.

In some places, streams, the mountain-front recharge zone, and the ACRWs intersect, providing a means for direct transport of surface water from all areas within a watershed to wells. In Malaeimi Valley, for example, surface water reaching the stream from anywhere in the basin can flow in the stream channel to an area where the water can infiltrate within the ACRWs of the Tafuna well field. Although the model does not assess the surface-water routes that may bring water into the area contributing recharge to a well, such an analysis is needed to fully delineate the area on the land surface that can be a source of contaminants to wells.

The size and shape of ACRWs in the model are not sensitive to variations in hydraulic conductivities and recharge within the ranges tested in sensitivity analyses. In most cases, the ACRWs of the calibrated and test simulations differed by only a small amount. Varying model well depths during the sensitivity analysis had a substantial effect on the shape and position of the ACRWs, but the well depths used in the calibrated model are a plausible representation of existing well depths, given the well-construction data available for the study area.

The ground-water flow model developed for this study can be used for assessing ACRWs not only for existing wells and production rates but also for future proposed wells or changes in production. The model cannot, however, simulate time-related aspects of the ground-water system, such as how long it will take water to travel from the ACRW to the well. The model also does not distinguish between saltwater and freshwater beneath the Tafuna-Leone Plain, which limits use of the model for purposes outside those of this study.

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