GROUND-WATER RESOURCES RECONNAISSANCE OF THE YAP MAIN ISLANDS, FEDERATED STATES OF MICRONESIA

By Patricia J. Shade, Stephen S. Anthony, and Kiyoshi J. Takasaki

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CONVERSION TABLE

The following table may be used to convert the inch-pound units used in this report to metric units.

Multiply inch-pound units	By	To obtain metric units
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
acre-foot (acre-ft)	1,233	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
Volume Per Unit Time (includes Flow)		
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	cubic decimeter per second (dm^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Temperature		
degree Fahrenheit (°F)	°C = 5/9 x(°F-32)	degree Celsius (°C)

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ABSTRACT

At present, water shortages occur on the four main islands of Yap every year during the dry season, and especially during extended drought periods such as in 1983. Shortages occur primarily because of inadequate storage and substantial transmission loss. The Yap government intends to eliminate these shortages by establishing centralized water systems that will supply 24-hour per day service to the populated areas, and by improving village-scale water systems in the remote areas.

The projected water demand by the population of the four main islands of Yap in the year 2000 is 507,000 gallons per day. This demand can be met by increasing the storage and surface area of established rainwater-catchment and spring-fed village-scale systems, and by increasing ground-water development in the volcanic formations found in the old airport area on Yap, on the southern Yap plateau, and on Gagil-Tamil island. Existing wells in the volcanic formations have yields of 25 to 50 gallons per minute. Proposed exploratory wells in these areas will better define sustainable yield, extent, and water-bearing characteristics of the principal aquifers.

Wells completed in the aquifer at the old airport had a combined yield of 77 gallons per minute in 1986. The proposed exploratory wells in the old airport area could lead to increased development from this aquifer and reduce natural losses due to drainage to surrounding gulches and evaporation from pond surfaces.

Exploratory wells sited along the southern Yap plateau, in the volcanic formation, will provide data that could facilitate better description of the geology and water-bearing characteristics of the aquifer. The proposed drill sites could tap a thicker, more productive, volcanic formation than was found during previous exploration. The new wells along the plateau could be able to supply the area population.

The Gagil-Tamil aquifer is the most promising source, with a 1986 combined well yield of 200 gallons per minute. Water balance calculations and streamflow analyses in the Eyeb and Mukong Stream basins indicate that more than 0.5 million gallons per day are recharging the ground-water reservoir in both of these basins. The proposed exploratory wells in these basins and elsewhere in the area will develop some part of this water, and will better define the water-bearing characteristics of the volcanic formation and the coral limestone that lie beneath the volcanics in a small part of the Mukong Stream basin.

The largest water demand is in the Colonia area, the state capital. This area is underlain by schist that is impermeable, as compared with the volcanic formation, and is not productive aquifer material. Wells drilled previously into this material had small yields, about 10 gallons per minute. The schist formation underlies most of the island of Yap and large parts of the other islands. Therefore, although it is not expected that exploratory wells drilled in this formation will produce more than about 10 gallons per minute, the hydrologic information gained from the exploration is transferable and valuable. The Colonia water demand can be met by increasing development from the old airport and/or Gagil-Tamil aquifers. Indications are that although the ground-water supply is limited, there is enough to meet the present water demand and that projected for the year 2000.

INTRODUCTION

The demand for potable water in the Yap main islands in the Federated States of Micronesia is increasing as a result of a growing population and new commercial development. During extended dry periods, water demand commonly exceeds supply.

The water-supply problem on the Yap main islands was accentuated during a drought in 1983 (Van der Brug, 1985), when rainfall was only 27 percent of normal for the period January through May. The subnormal rainfall created a severe problem because nearly all of the water for the central water-supply system on Yap island comes from a surface-water impoundment. The total storage of the system is 27 million gallons (Mgal). The average daily demand in the area served by the system is about 188,000 gallons per day (gal/d). The system cannot provide water continuously during extended dry periods.

During the 1983 drought, the reservoirs were inadequate because of an extended system, heavier demand, and losses in the distribution lines. On February 17, 1983, the reservoirs ran dry. Beginning in February 1983, water from the old airport swamp, and later a nearby swampy area, was transported in makeshift tank trucks to five sites where water was distributed to the general public. An attempt to ration the water to 3 gallons per person in the morning and again in the evening was abandoned when people panicked. In a more or less continuous operation, water was hauled from these two sites until the end of the drought. The return of rainfall to normal alleviated the water-supply problem until the next dry period.

One way to alleviate the chronic water-supply shortages is to supplement the existing system with a ground-water supply. In a study of the 1983 drought, Van der Brug (1985) showed that populations on islands dependent on rainfall or surface runoff suffer more during droughts than those on islands that utilize ground water. Therefore, in 1986 the Yap State government entered into a cooperative agreement with the U.S. Geological Survey to conduct an island-wide reconnaissance ground-water resources investigation.

Purpose and Scope

This report describes the geohydrologic framework of the Yap main islands, and discusses the drilling of exploratory wells to evaluate the potential for increasing ground-water development. Field investigations were made of the geology and the water-supply systems on the islands of Yap, Gagil-Tamil, Maap, and Rumung. Included in this effort were water balance calculations to estimate ground-water recharge, hydrologic monitoring at wells and streams, and compiling of rainfall, pan evaporation, and water-quality data that have been recorded since the publication of a water-resource summary of the Yap main islands by the U.S. Geological Survey (Van der Brug, 1983).

Previous Investigations

Geologic and vegetation maps of the four main Yap islands were included in the report, "Military geology of Yap main islands, Caroline Islands" (Johnson and others, 1960). A soil map of the four Yap main islands and tables of soil characteristics were in a soil survey by Smith (1983). Van der Brug (1983 and 1985) presented a thorough compilation of water-resources data collected on the Yap main islands, and analyses of surface-water data.

The previous ground-water exploration work by Tom Nance (1979, 1982, and Lyon Associates, Inc., 1980) provided the first aquifer information in the form of geologic drill-hole logs, and ground-water pumping test analyses. Nance (Lyon Associates, Inc., 1980) also supplied comprehensive data regarding village and the larger scale water-supply systems.

Acknowledgments

Interest in and support for the project by the Governor of Yap, the Honorable Petrus Tun, and the ex-Governor, John Mangefel, are gratefully acknowledged. We wish to thank Mr. Constantine Yinug, Director, Office of Planning and Budget for assistance to the project, and Mr. Edward Brettin, Director of the Yap Community Action Program, for providing village-scale water-supply system data, and knowledge of the island's population and culture. We are especially grateful for the field assistance provided by Adrian Gimed of Public Utilities and Contracts.

PHYSICAL SETTING

Geographic Location

The four main islands of Yap State, Rumung, Maap, Gagil-Tamil, and Yap lie between 9°27′ and 9°38′ N. latitude and 138°03′ to 138°12′ E. longitude, in the western Pacific Ocean. The islands are approximately 450 miles southwest of Guam and 3,800 miles west of Honolulu, Hawaii (fig. 1). The four

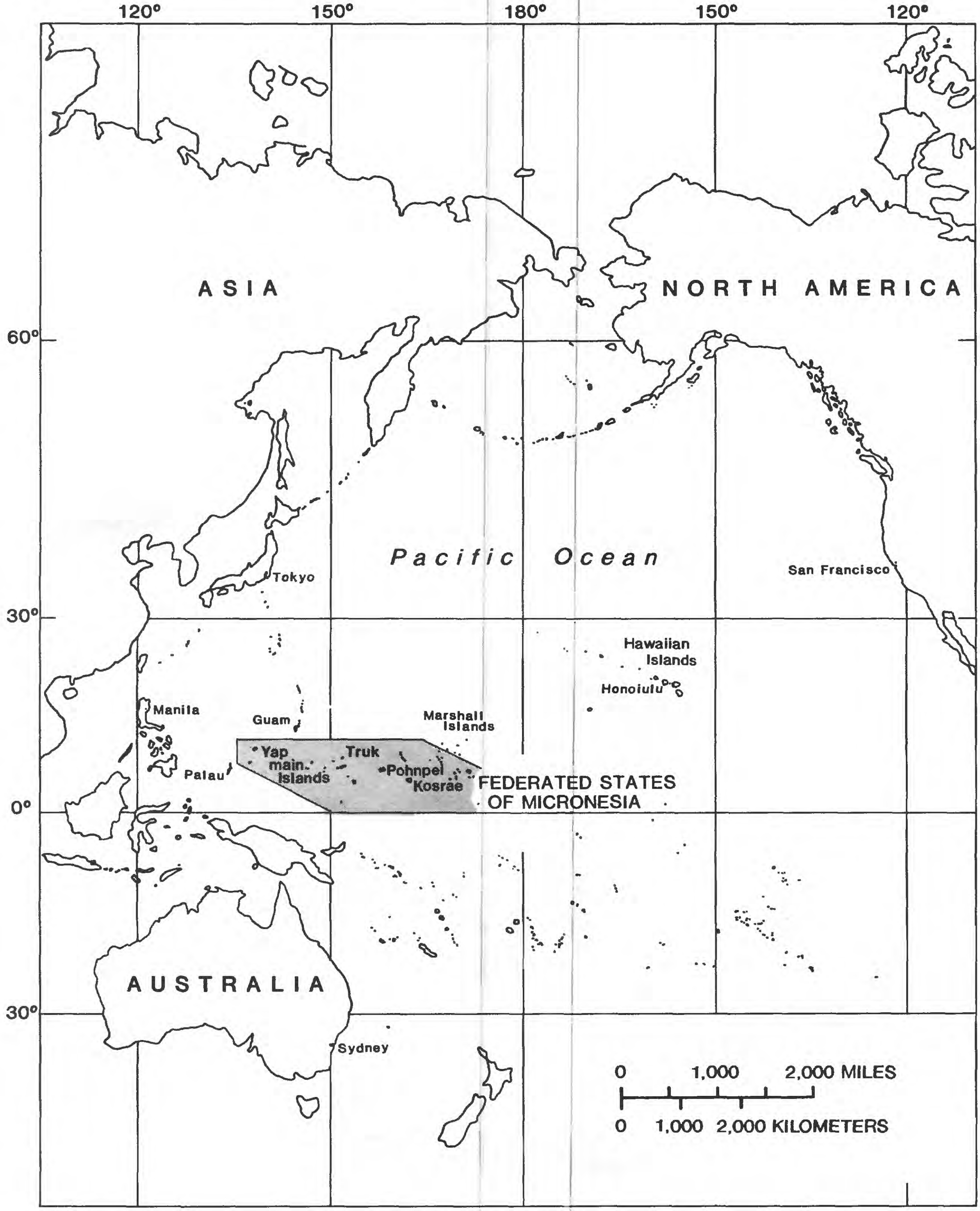

Figure 1. Location of the Yap main islands.

islands are separated by narrow channels and are surrounded by a fringing reef (fig. 2). The total land area is 38 square miles (mi^2), with Rumung being the smallest (1.6 mi^2) island and Yap the largest (21.7 mi^2). The town of Colonia on Yap island is the center of business and government in the State of Yap.

Mangrove swamps occupy much of the shoreline of all the islands. The interior sections are hilly, and in some places are covered with dense forests. Other interior areas are covered with savannah-type vegetation. On Yap island a range of hills trends northeast-southwest and averages about 500 feet (ft) above sea level.

Population

The population of the Yap main islands was 5,196 in 1980 (U.S. Dept. of Commerce, 1983). On the basis of an annual growth rate (rate of natural increase plus net migration) of 3.3 percent (Nance, 1979), the Yap main island's estimated population was 6,520 in 1987. As of 1985, the growth rate, excluding migration, was 1.7 percent for the entire state of Yap (Office of Planning and Budget, 1985) and was estimated to be about 2 percent for the four Yap main islands. Of the 6,500 people living on the four main islands, almost 4,300 people live on the island of Yap. Fewer than 200 people live on the island of Rumung, about 400 live on the island of Maap, and about 1,700 live on Gagil-Tamil island. Most of the population live in villages along the coast and in Colonia.

Climate

The climate of Yap is warm and humid with a mean annual air temperature of 81°F and relative humidity of about 80 percent. Daily maximum and minimum temperatures vary by about 12°F, and monthly mean temperatures vary only slightly, by about 2°F. Relative humidity also varies throughout the day with the higher values, about 90 percent, occurring late at night and the lower values, about 75 percent, occurring in mid-afternoon (U.S. National Oceanic and Atmospheric Administration, 1986).

The 1949 through 1986 mean annual rainfall, recorded at the Weather Service station near the old airport on southern Yap, is 120 inches (U.S. Weather Bureau, 1959, and U.S. National Oceanic and Atmospheric Administration, 1956 through 1986). The dry season generally occurs from January through April, when monthly rainfall averages about 6 inches, and the wet season from June through October, when rainfall averages about 12 inches. May, November, and December are transitional months, and each has a mean monthly rainfall of about nine inches. Showers and variable winds are common during the summer because of the close proximity of the intertropical convergence zone (ITCZ) to Yap. The ITCZ is where the northeast and southeast tradewinds converge, causing strong ascending motion and rainfall (Wallace and Hobbs, 1977). Cyclonic storms occur most frequently during the summer and occasionally into December. During the wet summers the prevailing wind is

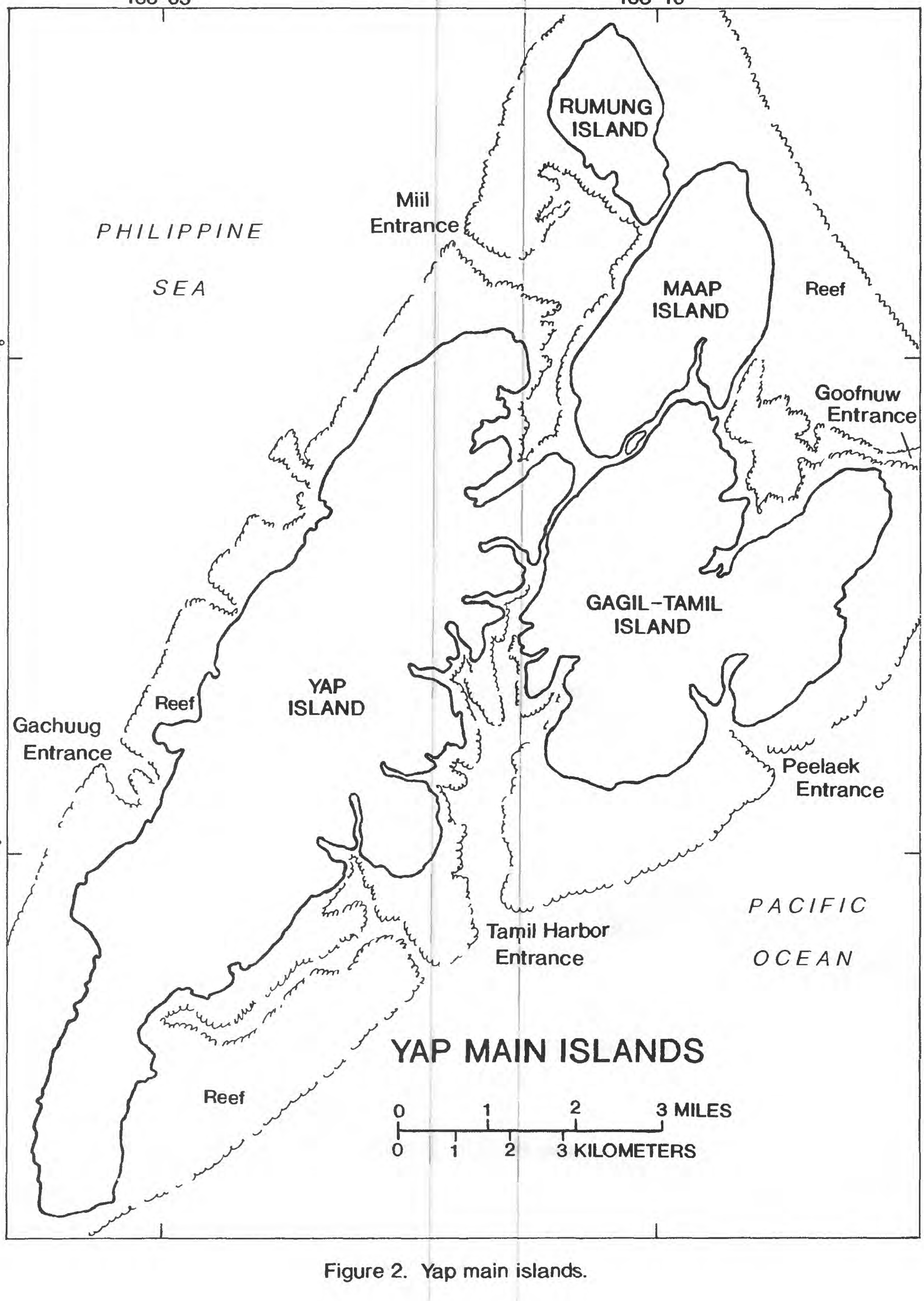

Figure 2. Yap main islands.

southwesterly. Typhoons are rare, as most of them pass to the north of the main islands. During the drier part of the year, November through May, northeast trade winds predominate.

The U.S. Geological Survey (USGS) has collected rainfall data at the old U.S. Coast Guard Loran station on Gagil-Tamil since December 1981 (table 1). Data are incomplete for 1982 and are not included in the table. These data have not previously been published. Generally, this recorded rainfall is less than rainfall recorded at the old airport (table 2). However, Van der Brug's (1983) discussion of historical rainfall data indicates there is little variability in annual rainfall throughout the Yap main islands. From 1969 to 1973 and in 1976, the U.S. Coast Guard collected rainfall data at about the same location as the U.S. Geological Survey's present station location. He found that these data compared well with the rainfall recorded by the National Weather Service at the old Yap airport during that time period. There is uncertainty regarding the quality of the historical rainfall data collected at the Loran station location as well as at other locations. It appears that the island's low relief, in general, does not induce intense orographic rainfall. Showers are often localized and with a longer period of record at the U.S. Geological Survey's station, perhaps a statistically significant analysis of the differences between these data and the old airport rainfall data can be made.

The mean annual rainfall at the old airport is 120.71 inches and has a standard deviation of 17.71 inches. The period of record is from 1949 to 1986. Assuming a normal distribution of annual rainfall values and computing the area beneath the distribution curve (Viessman and others, 1977), there is only a 3.67 percent probability the annual rainfall for any given year will be less than or equal to the 1983 drought rainfall of 88.84 inches.

Table 1.--U.S. Coast Guard Loran station, rainfall data, in inches

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Total
1983	0.70	0.19	2.24	0.45	3.05	7.93	12.98	13.53	9.97	8.41	7.29	4.15	70.89
1984	7.29	10.95	2.73	1.50	1.55	9.49	6.15	15.46	7.20	14.82	12.31	6.25	95.70
1985	12.62	3.03	4.77	8.00	8.15	16.98	11.33	14.02	13.87	9.95	4.91	11.55	119.18
1986	6.57	7.95	9.72	4.30	7.31	13.56	13.01	6.26	11.93	10.15	11.54	5.08	107.38

Table 2.--Monthly and annual rainfall data for the airport station, in inches, for the period 1948-86

Obtained by U.S. Navy during 1948-51 and by National Weather Service since 1952
(U.S. National Oceanic and Atmospheric Administration, 1981-86).
Location: 1948 to March 1968, lat 9°31'N, long 138°08'E.
March 1968 to present, lat 9°29'N, long 138°05'E, altitude 44 ft, at Yap Airfield.
A 4-inch diameter rain gage was used to Dec. 31, 1953 and an 8-inch diameter gage thereafter.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Total
1948	--	--	--	--	--	--	--	--	11.79	11.46	13.03	15.65	--
1949	8.24	3.99	4.19	5.18	6.62	11.44	4.99	7.62	19.57	15.39	6.09	7.53	100.85
1950	6.92	1.08	16.46	4.25	5.75	12.37	8.92	10.55	14.85	12.11	15.59	11.28	120.13
1951	5.86	10.84	3.46	3.97	7.98	3.40	10.85	16.47	12.58	10.30	6.65	12.45	104.81
1952	4.21	3.27	1.49	6.82	11.49	20.75	12.78	15.81	15.67	17.77	7.80	7.46	125.32
1953	4.03	9.37	7.87	8.22	6.61	20.27	6.51	29.44	6.88	14.20	14.65	12.27	140.32
1954	2.97	1.93	2.37	2.01	12.93	9.91	7.33	8.81	9.74	14.06	13.09	17.05	102.20
1955	23.08	4.86	2.22	7.98	12.29	11.18	12.99	20.01	14.72	15.35	9.95	12.32	146.95
1956	7.78	3.63	8.74	18.15	12.17	11.45	19.56	11.41	12.13	14.26	11.97	14.27	145.52
1957	15.10	4.70	6.53	5.27	6.16	11.48	13.82	11.80	17.60	9.33	1.96	3.65	109.40
1958	13.70	1.46	1.38	2.92	4.68	10.21	15.84	6.07	12.80	9.74	18.53	5.20	102.53
1959	7.75	7.99	9.07	4.38	11.54	4.69	18.95	11.61	11.18	11.61	10.34	11.16	120.27
1960	7.78	6.23	4.22	6.30	12.70	9.46	11.45	11.96	10.63	18.07	20.66	8.13	127.59
1961	11.65	5.66	11.15	4.75	18.08	12.33	12.70	17.25	15.10	21.16	4.42	11.27	145.52
1962	8.53	13.36	7.82	15.95	14.43	7.96	19.44	17.32	12.23	9.65	7.41	15.01	149.11
1963	11.26	12.20	11.13	4.20	7.14	8.77	13.49	28.20	10.25	16.67	7.47	10.17	140.95
1964	2.37	6.47	4.01	7.61	18.23	6.74	9.44	16.72	12.55	11.69	6.19	10.98	113.00
1965	3.32	6.00	7.63	4.25	8.12	10.88	26.47	12.39	17.73	8.42	12.02	3.69	120.92
1966	4.98	1.29	2.31	1.86	6.71	12.52	17.98	9.02	9.59	7.11	8.84	9.97	92.18
1967	12.02	6.25	5.37	11.76	16.00	16.71	14.14	16.45	11.72	12.80	10.44	7.48	141.14
1968	10.77	8.04	3.72	1.82	3.94	5.76	14.24	10.90	10.66	11.21	3.59	8.34	92.99
1969	4.10	1.24	2.08	3.03	7.69	8.78	34.71	11.58	17.03	11.48	9.76	8.32	119.80
1970	4.64	6.17	4.67	3.04	9.76	8.76	8.80	25.45	11.04	12.31	9.56	8.15	112.35
1971	10.42	10.11	13.48	12.25	12.84	13.94	14.12	12.15	13.87	15.15	10.26	9.71	148.30
1972	6.03	10.42	14.21	8.97	5.33	10.18	9.20	11.09	17.60	5.64	9.35	5.14	113.16
1973	2.14	1.00	1.54	5.62	5.98	12.35	10.11	5.13	17.64	14.92	10.57	7.03	94.03
1974	11.84	4.27	9.99	10.07	9.77	14.30	14.40	12.33	9.48	19.11	18.85	13.30	147.71
1975	19.48	1.20	3.12	10.73	9.09	10.67	8.38	11.90	11.25	12.67	6.79	10.93	116.21
1976	7.36	3.19	8.76	6.77	12.52	13.30	11.43	16.29	13.44	2.59	8.88	9.97	114.50
1977	3.94	2.18	2.42	0.91	10.36	7.49	17.21	13.99	18.73	5.76	9.47	11.64	104.10
1978	4.22	5.25	2.04	5.38	4.87	12.89	8.67	18.52	19.17	18.10	11.09	8.98	119.18
1979	3.88	3.16	7.06	3.98	8.82	21.07	14.44	19.57	9.59	12.18	7.34	13.40	124.49
1980	2.32	4.60	6.42	7.72	10.57	13.52	17.84	9.52	12.71	13.41	7.20	14.52	120.35
1981	12.90	8.00	2.89	1.10	5.05	10.77	18.54	13.61	19.03	14.22	10.12	11.01	127.24
1982	7.30	12.58	7.50	2.62	10.49	32.01	13.04	14.26	13.93	9.34	4.95	7.01	135.03
1983	1.25	0.27	2.76	1.36	3.59	6.98	16.14	16.59	12.59	8.37	13.56	5.38	88.84
1984	5.33	9.59	3.90	2.21	1.77	12.38	9.59	15.33	6.41	17.29	12.03	5.44	101.27
1985	14.46	3.27	6.70	8.83	6.81	18.65	11.52	15.49	17.34	10.31	5.79	14.32	133.49
1986	7.53	10.61	10.90	6.94	9.59	13.08	15.36	11.25	12.31	7.62	14.07	5.88	125.14

Soils and Vegetation

The soils of the four main islands can be divided into three general categories: upland soils underlain by volcanic material, upland soils underlain by schist, and bottom-land soils underlain by alluvium or mangrove swamp deposits (Smith, 1983).

The upland volcanic soils, derived from breccia and tuff, are deep and well-drained and occur throughout Gagil-Tamil, in small areas of Maap and northeast Yap, and along the central part of southern Yap (fig. 3). The surface layer has a loamy texture and the subsoil is clay. The available water capacity of these soils is generally 0.13 to 0.15 centimeter per centimeter (cm/cm,) and the effective rooting depth is about 150 cm (Smith, 1983). These acidic, clay soils (pH of 4.5 to 6.5) are mainly latosols that are distinctly red in color, and have extremely low fertility owing to rapid decomposition of organic matter and leaching of the soil. Because of the generally low fertility and high acidity, vegetation on upland volcanic soils is classified as savannah with pandanus, grasses, false staghorn fern, and brush predominating. The volcanic rocks associated with these soils store significant quantities of ground water and are discussed in the next two sections.

Generally, the upland soils underlain by schist are moderately deep and well-drained. These soils are relatively fertile compared with the volcanic soils and are slightly acidic, with pH values ranging from about 5.6 to 6.5. These soils cover most of central and northern Yap, most of Maap and Rumung, and occur in scattered areas mainly in the northeast and northern parts of Gagil-Tamil. The vegetation associated with these soils is mainly broadleaf forest, especially in northern and central Yap and parts of Rumung. Large areas of grassland and pandanus also occur on the schist soils in central Rumung, and on the island of Yap near Yabach and Taafniith, around Colonia and north to Dugor, and just north of the old airport. On Maap and Gagil-Tamil, the vegetation type is distributed about equally between the broadleaf forest and grassland. Under savannah vegetation, the schist soils generally are less fertile and have lower organic matter content than under forest vegetation.

Bottom-land soils occur along some of the stream channels and most of the coastal areas, except for an extended area along the west coast of Rumung, the west coast of Yap near Yabach and Taafniith, and the east coast of Yap around Colonia and north to Dugor. These soils include many types and range from loamy fine sand, sandy clay loam, and very gravelly silt loam to peat. The sandy loams are fairly neutral in soil reactions, but the peat and gravelly silts are more acidic. Generally, the bottom-land soils are deep and more fertile than the upland volcanic soils. Vegetation on bottom-land soils consists of coconut palms, interspersed with tall forest trees in some areas, with an understory of young trees and brush. In the villages, these areas are attractive with lush growth of several colorful species, such as hibiscus, crotons, and panax. Along much of the coast of Yap, Maap, and Gagil-Tamil islands, and most of the eastern coast of Rumung, are dense growths of mangrove in swamps within the tidal zone.

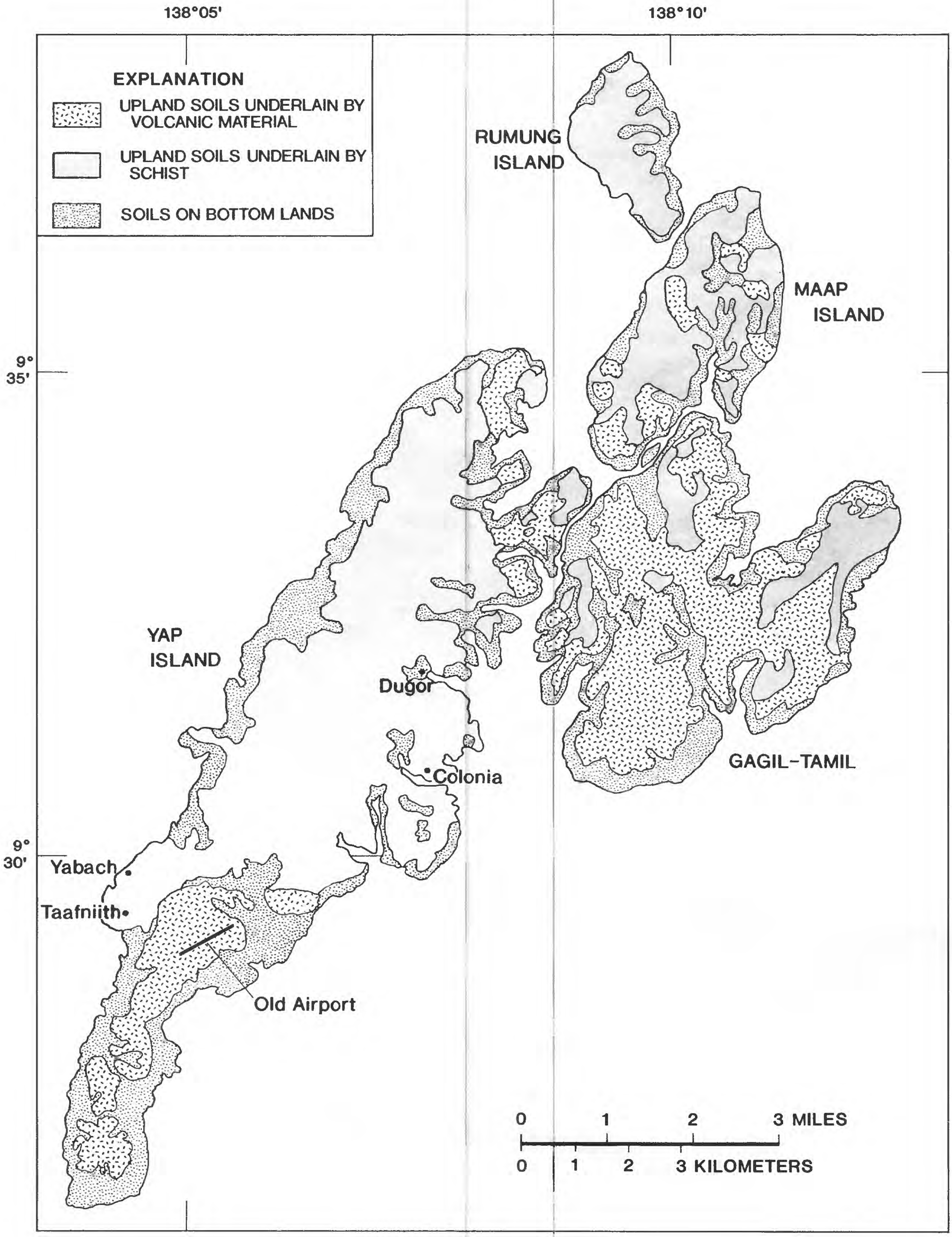

Figure 3. Yap main islands soils (modified from Smith, 1983).

Geology

The main islands of Yap, located on the western margin of a deep submarine trench, are part of a small island arc. Rocks of the Yap island arc are largely metamorphic, and thus differ markedly from most island arcs of the western Pacific. Island arcs, which parallel oceanic trenches at crustal convergence zones, commonly are formed of intermediate-composition volcanic rocks. The Mariana and Philippine arcs extend northeast and southwest of the Yap arc, respectively (fig. 4), and are sites of active volcanism and seismicity. In the Yap arc-trench system (fig. 5) there is no modern volcanism and there have been few historic earthquakes. Hawkins and Batiza (1977) suggest that the Yap arc-trench is not an active subduction zone, and that the Yap island platform is composed of metamorphosed oceanic crust and upper mantle rocks which have thrust up over (obducted) a former volcanic island arc. The few volcanic rocks present on Yap may be large fragments in this tectonic breccia.

Johnson and others (1960) did a comprehensive geologic study of the Yap main islands, which is briefly summarized here (fig. 6). The Yap main islands are composed of five main units; the Yap Formation, Map Formation, Tomil Volcanics, alluvium, and mangrove swamp deposits. The Yap Formation, which underlies the northern three-fourths of Yap island, the northwest three-fourths of Rumung, and the prominent ridge in western Gagil-Tamil, consists of pre-Miocene metamorphosed mafic-ultramafic rocks. The Yap Formation is composed of: 1) greenschist (actinolite) and amphibolite facies, which weather to fat clay, and 2) intruded serpentine dikes and sills (1 to 10 feet thick), which weather to ferruginous clay. The overburden ranges from 0 to 20 feet thick. Yap Formation outcrops typically have a well-developed crystallization schistosity caused by planar orientation of the actinolite and by segregations of the minerals plagioclase and/or epidote (Hawkins and Batiza, 1977). Many of the outcrops have a north to northeasterly trending lineation which is caused by the intersection of two planes of schistocity. Most of the outcrops are well-jointed (fractured) and spaced 6 to 12 inches apart. Breccia zones occur where the Yap Formation is cut by faults, but few zones can be traced beyond the limits of the outcrop. The Yap Formation is the basement rock on the island platform and has an undetermined thickness.

The Map Formation, which is found in the northwest part of Maap and Gagil-Tamil, is Oligocene in age. It is a fragmental rock of tectonic and sedimentary origin, which includes breccia, conglomerate, and interbedded sandstone and siltstone. On Maap island, large exposures show a massive deposit of angular to subangular fragments of actinolite schist, hornblende diorite, and serpentinite embedded in a matrix of finely crushed rock. Nearly vertical faulting of the Map Formation has complicated the structure and stratigraphy of the sedimentary rocks. It has been suggested by Johnson and others (1960) and Hawkins and Batiza (1977) that the lower part of the Map Formation was produced at the base of the Yap Formation as it was overthrust

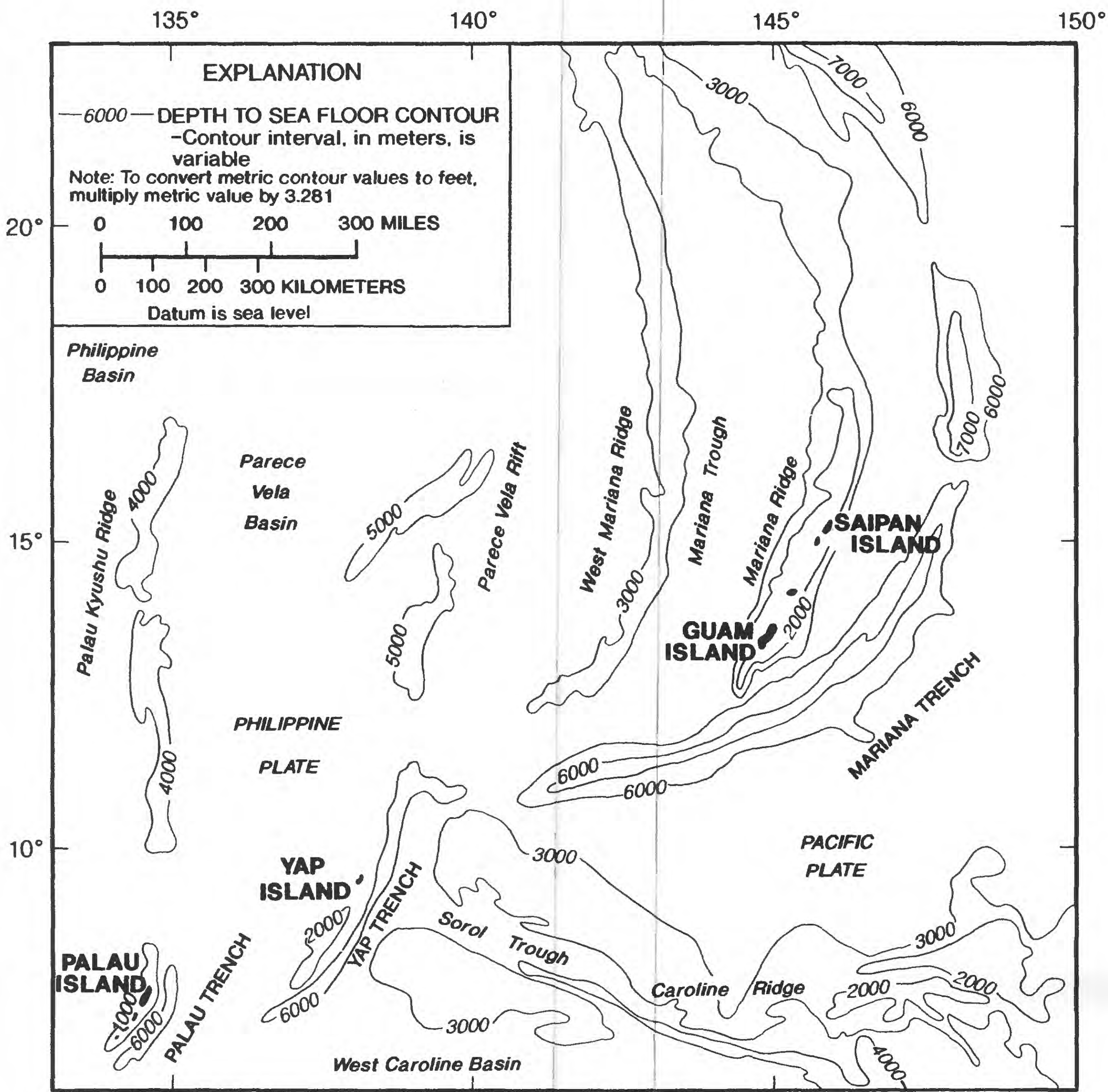

Figure 4. Location of the Yap arc-trench system in the Western Pacific (from Rytuba and others, 1988).

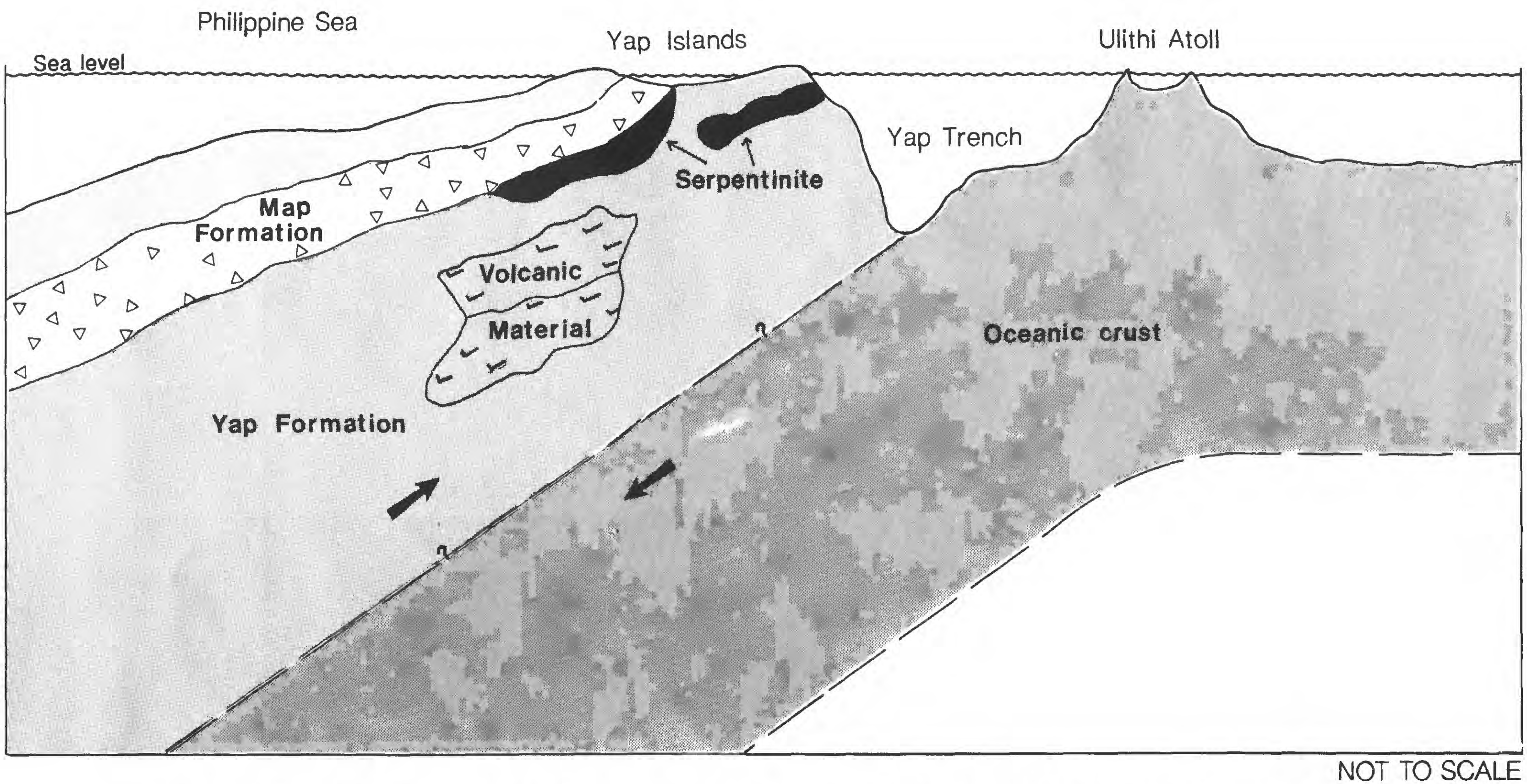

Figure 5. The Yap arc–trench system. Arrows indicate relative plate motions prior to the termination of subduction (modified from Hawkins and Batiza, 1977).

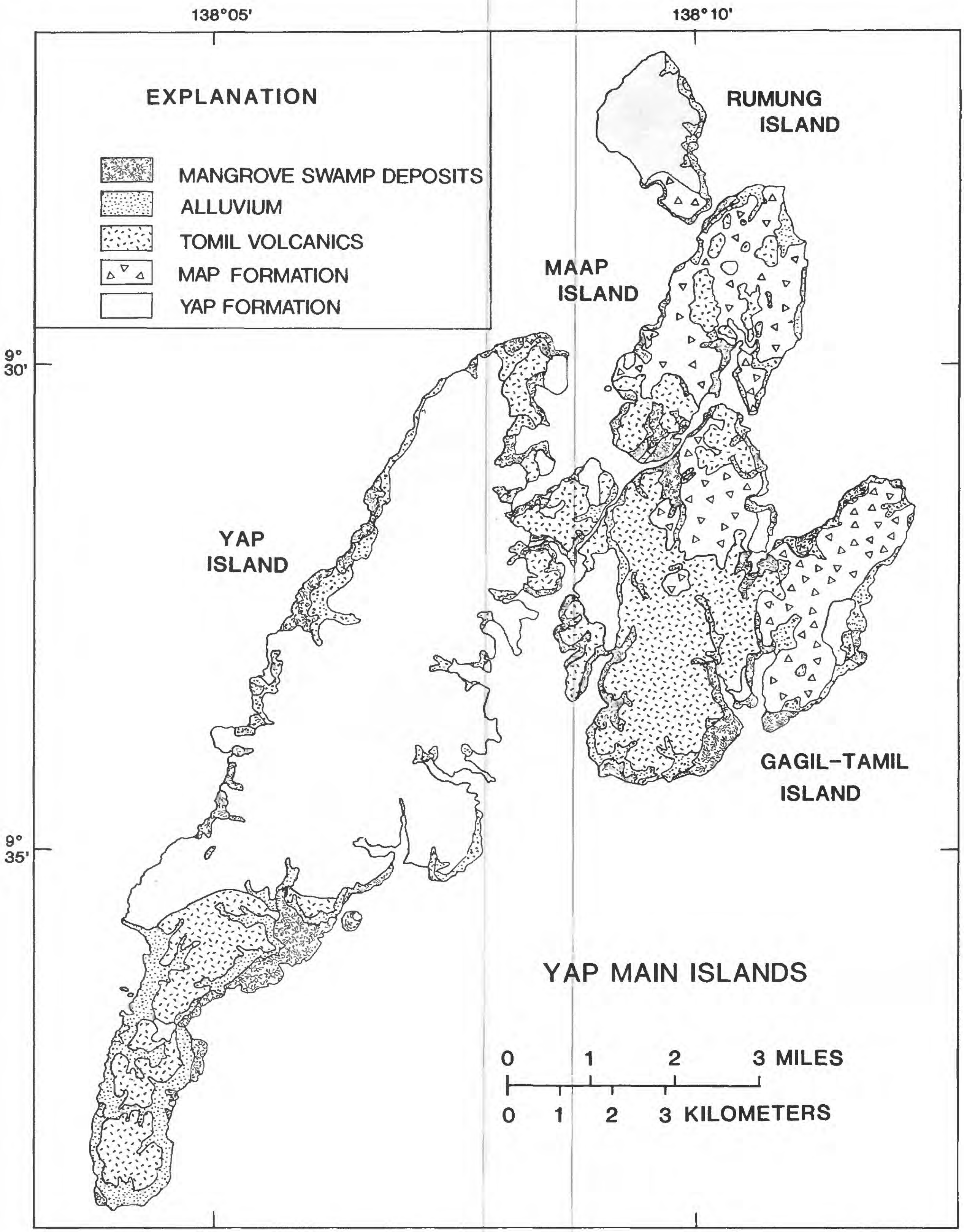

Figure 6. Geologic map of the Yap main islands (modified from Johnson and others, 1960).

from west to east and underthrust from east to west. This speculative suggestion (shown in figure 5) explains why the Map Formation is sandwiched between parts of the Yap Formation. The thickness of the Map Formation is unknown; however, it is believed to be more than 200 feet on the island of Maap (Johnson and others, 1960). On Gagil-Tamil, the formation is considered to be relatively thin as there are many outcrops of serpentine and rock of the Yap Formation.

According to Johnson and others (1960) the Tomil volcanic unit is composed of andesitic tuffs, volcanic breccias, and lava flows that unconformably overlie the Map and Yap Formations in the central and southernmost parts of the Yap main islands. Outcrops of fresh volcanic rock are rare, as almost all rock has been deeply weathered to kaolinitic clay. The clays in central Gagil-Tamil are deeply eroded and support only sparse vegetation, resulting in a wasteland of bare slopes and gullies. The unit is believed to be several hundred feet thick in central Gagil-Tamil, and considerably thinner where hilltops of the underlying Yap and Map Formations protrude through the volcanic deposits in central Gagil-Tamil, and southern and northern Yap. Hawkins and Batiza (1977) doubt that the whole area mapped as the Tomil Volcanics is andesitic volcanic rock. They interpret the Tomil Volcanics to be a mappable unit of deeply weathered fragmental rock, some of which appears to be of volcanic origin. The outcrop pattern, the restriction of volcanic rocks to low-lying areas, the presence of "windows" in the Map Formation, and the abundance of resistant outcrops of schist in the Tomil unit, lead Hawkins and Batiza (1977) to believe that the Tomil Volcanics are a thin tectonic breccia, which include fragments of andesitic volcanic breccia, rather than an extensive younger volcanic unit deposited on schist after the schist was thrust up to its present structural position.

The alluvial deposits of the Yap main islands are restricted to beaches, and to valley floors at or near sea level. Because most streams on Yap are in narrow valleys with steep gradients, no large flood plains of alluvium have developed. The largest accumulations of alluvium are on the southern tip of Yap island, northwestern Yap island, the eastern side of Gagil-Tamil, and on the east coast and north shores of Maap. These deposits are a mixture of stream-laid alluvium and beach deposits. The shores of all the islands of Yap are discontinuously bordered with mangrove swamps where a sandy black muck is accumulating.

WATER RESOURCES

Occurrence of Ground-Water

Most of the recoverable ground water in the Yap main islands is in weathered rock, talus and alluvium, or artificial land fill. Historically, ground water has been developed by shallow dug wells, and at seeps and springs. Shallow dug wells, located in low-lying areas and adjacent coastal plains, yield ground water stored in talus and alluvial deposits. Seeps and springs, commonly found in upland areas, discharge at the contact of water-bearing, weathered rock (saprolite) and underlying less permeable unweathered rock that acts as the perching member. Aquifers in the weathered Tomil Volcanics have been identified by test drilling and by streamflow analyses in the central valley of Gagil-Tamil, and by drilling in the old airport area of southern Yap island.

The ground-water reservoirs are generally larger in low-lying areas than in the upland areas. The low-lying areas are widest near the mouth of stream valleys and in gently sloping areas. Figure 7 is a generalized sketch showing the occurrence of ground water in coastal areas of Yap. Saltwater mangrove swamps generally occupy the seaward edge of coastal plains. Where coastal flats are wide, freshwater marshes commonly occupy the area inland of the mangrove swamps. In many locations, the area once occupied by a freshwater marsh and mangrove swamp has been artificially filled to provide land for villages and crops.

Natural discharge of ground water in the low-lying areas is largely by plant uptake (transpiration) from the shallow ground-water body and evaporation from the wet soil and freshwater marshes. Ground water not discharged by seeps and springs or to the atmosphere and plants by evapotranspiration slowly seeps to the sea through beach sands and other sediments at the shore.

The shallow dug wells shown in figure 7 illustrate in general terms the variable quantity and quality of ground water in different geologic units. Well DW 1 is dug into beach deposits where freshwater floats on saline ground water. The quantity of water developable from this well is high; however, the well is subject to saline-water intrusion if overpumped. The chloride concentration in ground water in wells generally decreases with increasing distance inland from the sea or mangrove swamp; however, it may increase if the well is located too close to the marsh. Well DW 2 is dug into talus and alluvial deposits on the inland side of the freshwater marsh. The yield of this well is low, and the water quality is poor owing to the organic matter generated by the nearby marsh. Well DW 3 yields water stored in the lower slopes of talus and alluvial deposits. The yield to this well is low; however, the quality of water is excellent throughout the slope area in terms of chloride concentration and organic content. Infiltration galleries constructed along the base of the slope, and dug three to five feet below the water table, would increase the yield from this area.

Figure 8 is a generalized sketch showing the occurrence of ground water in the upland areas of Yap. Many small ground-water bodies discharge water at the land surface as springs or seeps. Because storage in the ground-water bodies is generally small, the flow at most of the springs and seeps ceases shortly after rainfall. Springs and seeps fed by slightly larger ground-water bodies discharge for days, even weeks after rainfall. Water from the longer-lasting springs and seeps is commonly piped to low-lying villages; however,

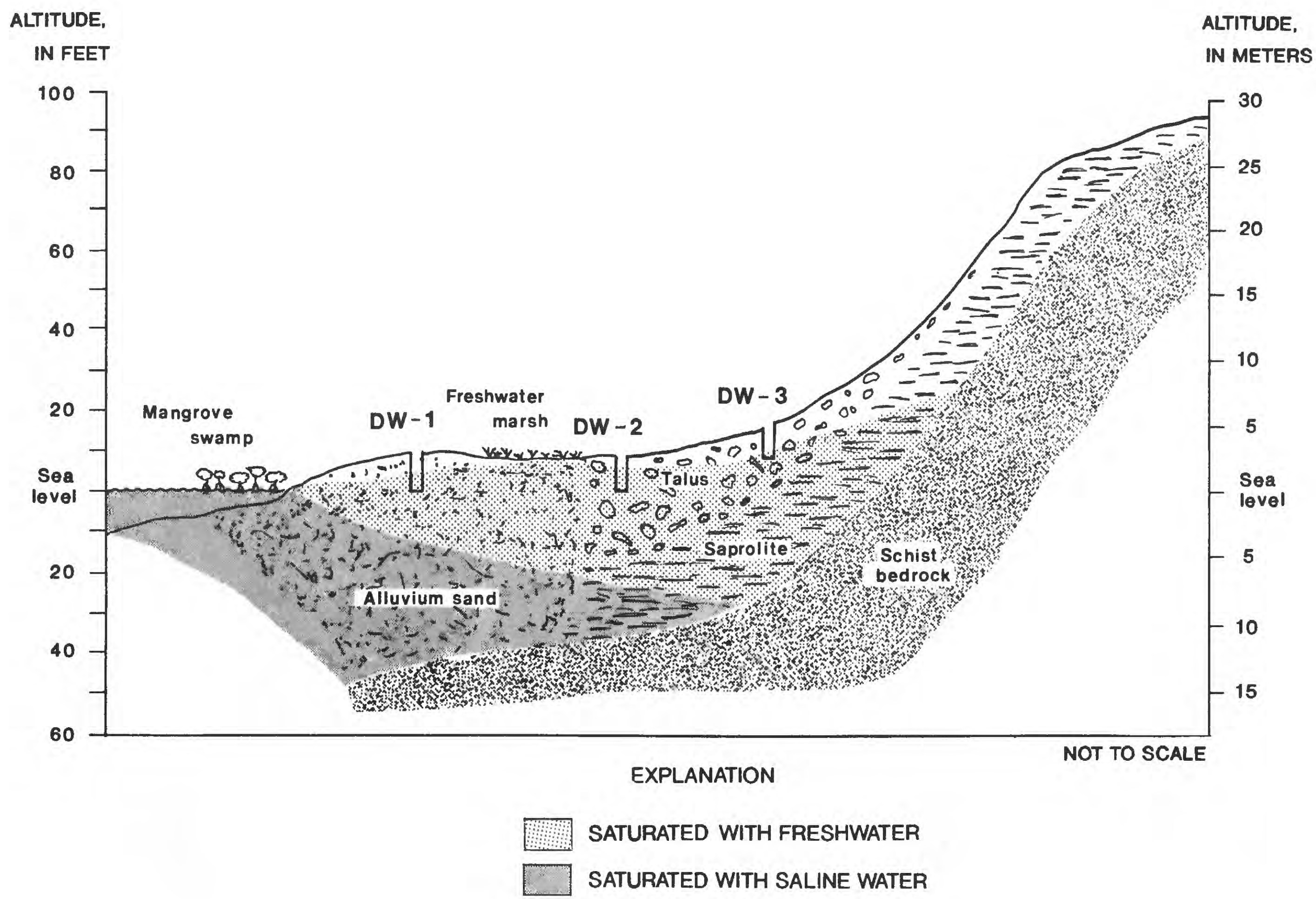

Figure 7. Diagrammatic section showing occurrence of ground water in the coastal areas of Yap main islands.

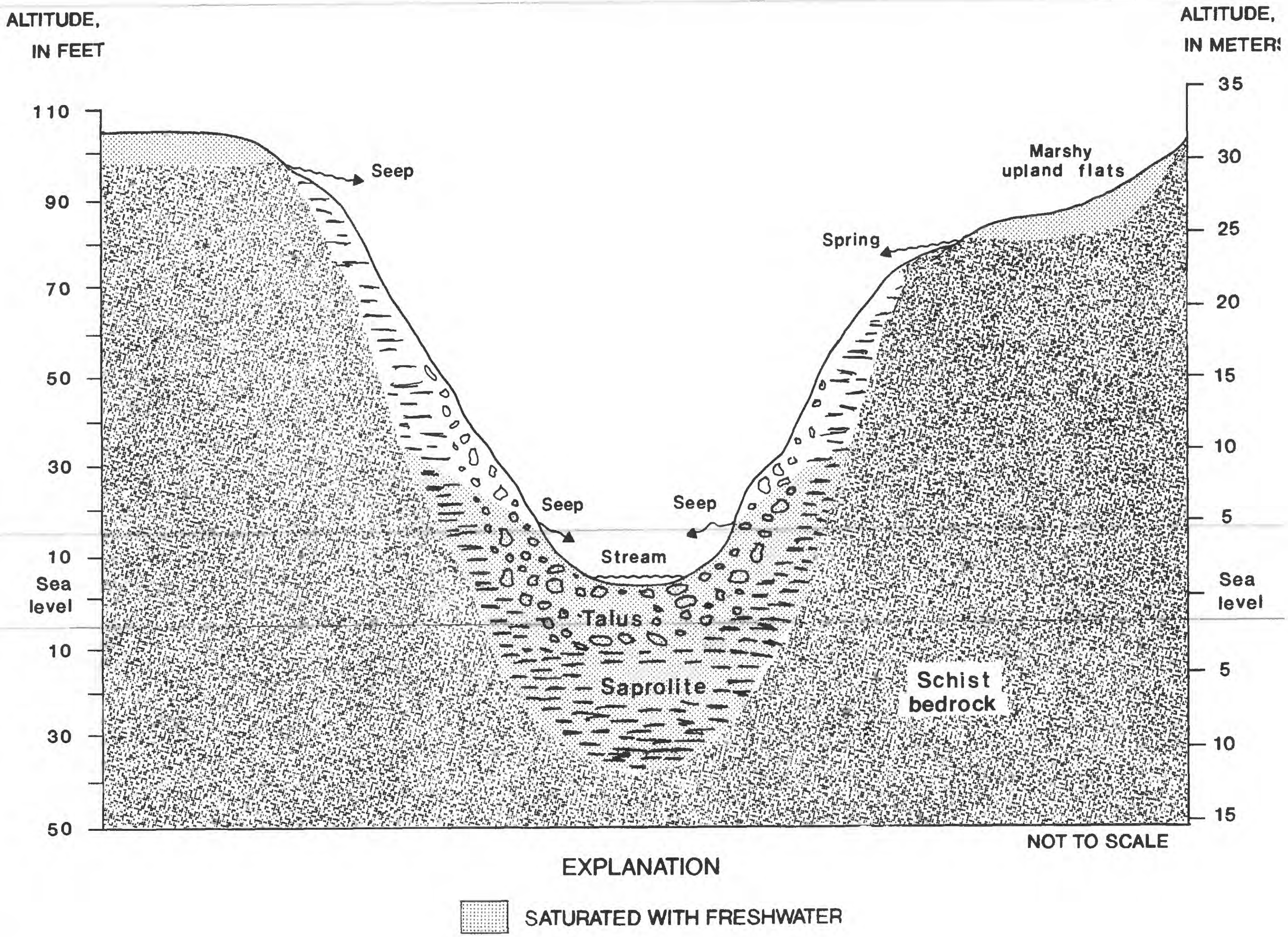

Figure 8. Diagrammatic section showing occurrence of ground water in the upland areas of Yap main islands.

the yields are often low, less than 5 gallons per minute (gal/min). Shallow wells dug into the valley fill, talus, and/or weathered rock, yield ground water with low chloride concentrations. The yield and storage of the wells could be increased by digging them as deep and as wide as practical below the water table.

Weathered rock in the Tomil Volcanics provides a permeable aquifer in which ground water is stored in significant quantities. Between 1979 and 1982, 15 exploratory and 13 production wells were sited and drilled under the supervision of Tom Nance of Lyon Associates (Nance, 1979 and 1982). Records of the wells indicate that the thickness of the volcanic aquifers of southern Yap Island and the central valley of Gagil-Tamil island range from about 50 to 70 feet and 90 to 140 feet, respectively, and individual well yields (table 3) are approximately 25 gal/min and 50 gal/min, respectively (Nance, 1982).

Table 3.--Yap Main Islands well data
[ft = feet; gal/min = gallon per minute; GT = Gagil-Tamil]

Well name	Location	Function	Altitude top of casing (ft)	Altitude of ground surface (ft)	Total depth of hole (ft)	Initial pumping rate (gal/min)	1987 pumping rate (gal/min)	Primary water-bearing material[1]
Monguch-1	GT	Production	21.38	--	72	30	50	Tomil volcanics
Monguch-2	GT	Production	26.47	--	71	30	50	Tomil volcanics
Thilung-1	GT	Production	28.16	--	88	30	50	Tomil volcanics
Thilung-2	GT	Production	34.82	--	75	30	50	Tomil volcanics
Dorfay 4-inch well	GT	Observation	29.93	--	92	12-15	15	Tomil volcanics
Dorfay 6-inch well	GT	Observation	30.92	--	145	30	--	Tomil volcanics
Mukong	GT	Observation	25.83	--	98	30	--	Soft coral
GT testhole-1	GT	Exploratory	--	50	46	5	--	Tomil volcanics
GT testhole-2	GT	Exploratory	--	30	78	5	--	Tomil volcanics
GT testhole-3	GT	Exploratory	--	20	93	5	--	Tomil volcanics
GT testhole-4	GT	Exploratory	--	25	66	<10	--	Tomil volcanics
Timlang-1	Yap	Production	42.68	42.5	30	25	16	Tomil volcanics
Timlang-2	Yap	Observation	40.43	39.4	40	--	--	Volcanics/weathered schist
Timlang-3	Yap	Production	44.22	43.2	45	25	Not pumping	Tomil volcanics
Yugamanman-1	Yap	Production	42.68	41.9	50	25	21	Volcanics/weathered schist
Yugamanman-2	Yap	Production	38.83	37.6	45	25	24	Volcanics/weathered schist
Communication Station	Yap	Observation	--	38.5	81	--	--	Silty fine sand
Test hole-1	Yap	Exploratory	--	45	41	<10	--	Volcanics/weathered schist
Test hole-2	Yap	Exploratory	--	37	50	<10	--	Volcanics/weathered schist

Table 3.--Yap Main Islands well data - Continued
[ft = feet; gal/min = gallon per minute; GT = Gagil-Tamil]

Well name	Location	Function	Altitude top of casing (ft)	Altitude of ground surface (ft)	Total depth of hole (ft)	Initial pumping rate (gal/min)	1987 pumping rate (gal/min)	Primary water-bearing material[1]
Magaaf	Yap	Production	15.9	15	68	5.9	--	Schist
Qaringeel	Yap	Exploratory	--	74.7	75.5	0.1	--	Schist
Baqel School	Yap	Exploratory	52.5	51.8	54	1.1	--	Schist
Gagil elementary	GT	Exploratory	--	37.2	50	0.1	--	Schist
Qokaaw	Yap	Exploratory	--	8	50	6	--	Alluvium
Ruuq	GT	Exploratory	39.9	38.6	75	--	--	Tomil volcanics
Monguch test hole	GT	Exploratory	41.2	39.7	96	--	--	Tomil volcanics
Waath hole at Maaq	GT	Exploratory	43.2	42.3	70	--	--	Tomil volcanics
Dechumur	GT	Exploratory	--	32	37	--	--	Tomil volcanics
Kanifaay Dispensary	Yap	Exploratory	--	36.4	61	--	--	Clayey silt/decomposed schist
Gachalaaw	Yap	Exploratory	--	31.6	60	--	--	Clayey silt/decomposed schist
Chumeg, Guroor	Yap	Exploratory	--	40.6	60	--	--	Silty clay/schist
Faraq	Yap	Exploratory	37.3	35.9	90.4	2.8	--	Sandy silt/schist
Dokleng, Lamear	Yap	Exploratory	42.8	41	91	1.8	--	Silty sand

[1] Data from Nance, 1979.

Water Demand

Priorities in water-resource development set by the Yap State Office of Planning and Budget are two-fold: 1) to establish and privatize year-round 24-hour per day potable water service in populated areas, and 2) to construct or improve village-scale water systems to meet the demand for freshwater in the less populated outlying villages.

The present and projected water demand is an important factor in designing an efficient 24-hour potable water service. The U.S. Department of Commerce, 1980 Census of Population, was used as a base from which to estimate the 1987 and year 2000 residential water demand. Because most of the Colonia Water System service area is within the Ruul municipality, an annual growth rate (rate of natural increase plus or minus net migration) of 3.3 percent (Nance, 1979) was used with the Ruul municipality (fig. 9) population to estimate the present (1987) Colonia Water System population, and to project the population to the year 2000.

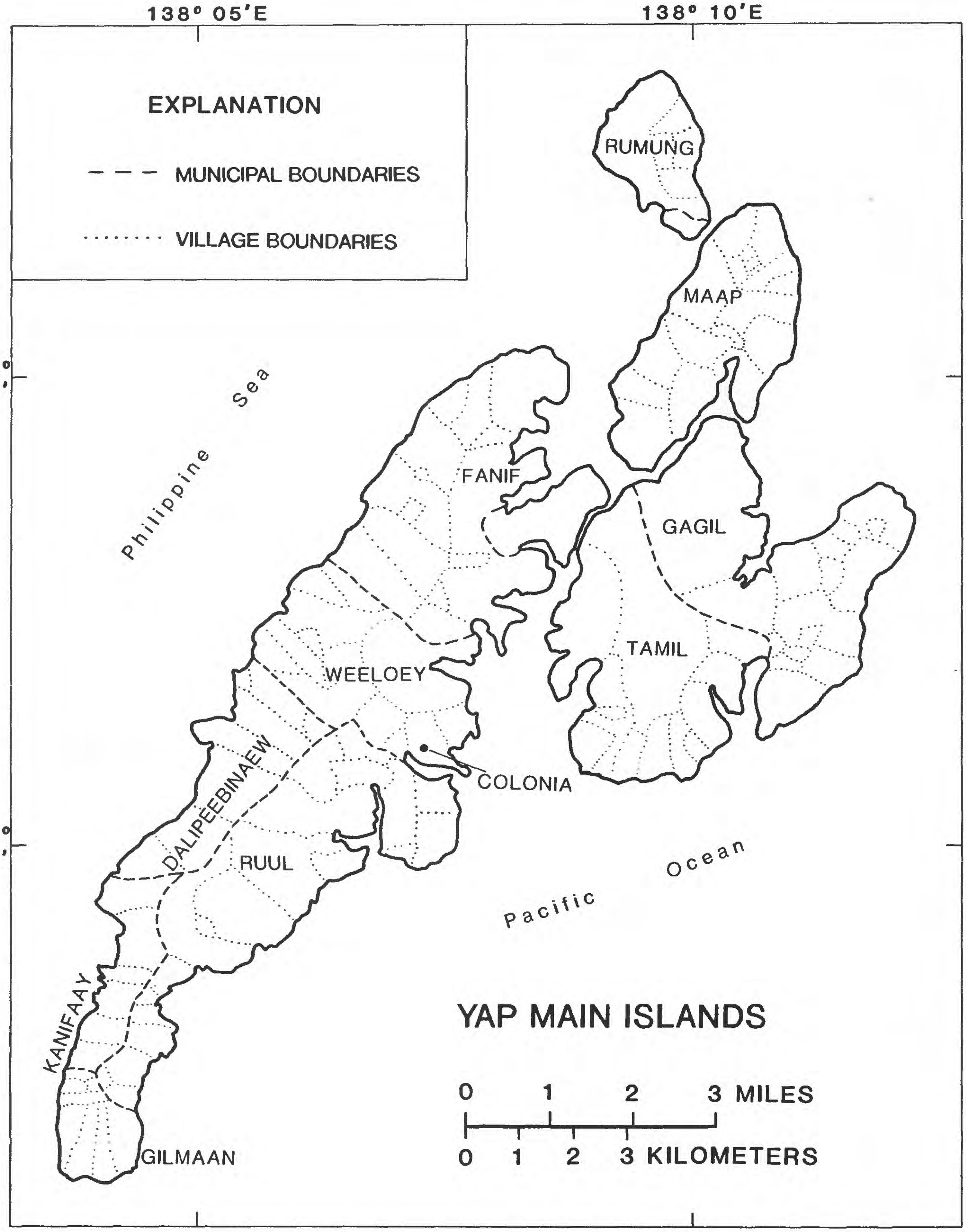

Figure 9. Yap main islands municipality locations (modified from Sunn, Low, Tom, and Hara, Inc., 1971).

Assuming a private residential water-use rate of 50 gal/d/person (gallons per day per person) from the pressurized large-scale Colonia Water System (Lyon Associates, Inc., 1980), the 1987 residential water demand is estimated to be 90,100 gal/d (gallons per day) and projected to be nearly 137,450 gal/d in the year 2000. These may be conservative estimates, as they are based on the assumption that 100 percent of the households in the Ruul municipality are connected to the system, when presently the system services only some of the villages in Ruul and a few villages in Weeloey municipality. Government residence use estimated at 100 gal/d/person, and use by government offices, schools, public facilities, and businesses at various rates as described by Lyon Associates (1980) were projected to 1987 and to the year 2000, using the same growth rates indicated by Lyon Associates, Inc. (1980). With the addition of these uses, the 1987 and the year 2000 total water demand on the Colonia Water System is estimated to be 181,000 gal/d and 261,000 gal/d, respectively.

Table 4 lists population and water demand by municipality. Because all the villages in Ruul and Weeloey municipalities are not connected to the Colonia Water System, the table cannot be used directly to sum the Colonia Water System demand. About 507,000 gal/d of potable water will be required to provide 24-hour per day water service throughout the Yap main islands in the year 2000. The municipalities of Ruul, Weeloey, Gagil, and Tamil will have the greatest water demand in the year 2000. Additionally, the Yap State Office of Planning and Budget has identified Fanif and Dalipeebinaew as rapidly growing municipalities whose water demands are not being met.

Table 4.--Population and residential water demand by municipality

[gal/d = gallon per day]

	1980		1987		2000	
Municipality	Population 1/	Water Demand 3/ (gal/d)	Population 2/	Water Demand 3/ (gal/d)	Population 2/	Water Demand 3/ (gal/d)
Fanif	392	7,840	492	9,840	750	15,000
Weeloey	926	18,520	1,162	23,240	1,773	35,460
Ruul	1,436	28,720	1,802	90,100	2,749	137,450
Dalipeebinaew	211	4,220	265	5,300	404	8,080
Kanifaay	225	4,500	282	5,640	431	21,550
Gilmaan	228	4,560	286	5,720	437	21,850
Gagil	616	12,320	773	15,460	1,179	29,475
Tamil	713	14,260	895	17,900	1,365	34,125
Maap	319	6,380	400	8,000	611	15,275
Rumung	130	2,600	163	3,260	249	6,225
Total	5,196	186,870	6,520	234,500	9,148	383,790

1/ 1980 Census of Population (U.S. Department of Commerce, 1983).

2/ Estimated population based on an annual growth rate of 3.3 percent (Quarterly Bulletin of Statistics, Trust Territories of the Pacific Islands, 1979).

3/ Residential water demand based on 25 gal/d/person in all municipalities in 1980. Ruul demand was based on 50 gal/d/person (Lyon Associates, 1980), for 1987 and the year 2000. The demand in Kanifaay, Gilmaan, and Tamil also rose to 50 gal/d/person in the year 2000. It was assumed that 100 percent of the population in these municipalities was connected to the large-scale Colonia, Gagil-Tamil, or Southern Yap Water Systems.

Presently, few household connections to the Southern Yap Water System have been made. Limited pumpage records for the wells in the old airport aquifer indicate that the present demand is about 10,000 gal/d.

About one-third of the households have been connected to the Gagil-Tamil Water System. The present demand is about 20,000 gal/d.

In villages that are serviced by small-scale seep- or spring-fed systems, the water demand is estimated at 20 gal/d/person (Nance, 1979). Assuming an average household of six people consuming 20 gal/d/person, the monthly household water consumption would be about 3,700 gal/mo (gallons per month).

Assuming the same water demand in villages served by rain-catchment systems, a roof catchment area of 500 ft^2 could supply 3,700 gal/mo if a net rainfall of 12 inches was captured. This amount of rainfall is likely to occur during July, August, September, and October, when the 38-year mean monthly rainfall is 13.83 in., 14.31 in., 13.46 in., and 12.40 in., respectively. During the remainder of the year, when the monthly rainfall means range from a low of about 5.68 inches in February to 12.09 inches in June, larger catchment areas and/or sufficient storage would be required. Van der Brug (1983) presents graphs which indicate for a 100 percent efficient, 100 ft^2 catchment area, and a total draft rate of 10 gal/d, 200 gal storage volumes would be necessary during the dry period in an average-rainfall year. For the dry period in a below-average-rainfall year, and with a reduced draft rate of 5.5 gal/d, 300 gallons of storage would be necessary. Increasing the storage volumes and catchment areas will alleviate the severity of water shortages during the dry periods each year.

Water-Supply Systems

Water-supply systems in the Yap main islands consist of three large-scale systems and 20 small village-scale systems outside the area served by the large-scale systems. The large-scale water-supply systems are the Colonia System, the Southern Yap System, and the Gagil-Tamil System (fig. 10). The village-scale systems are scattered outside the areas served by the large centralized systems (fig. 11).

Large-Scale Water-Supply Systems

Since the end of World War II, Colonia, the state capital, has faced problems of a growing population and an increasing demand for water. In 1951, an earthen dam with a storage capacity of 2 Mgal (million gallons) was built across Daloelaeb Stream at Gitaem (fig. 12). A new dam, completed there in 1975, increased the storage capacity by about 25 Mgal. Gitaem Reservoir is the source of supply for the first large-scale, centralized water system built in Yap, the Colonia system.

The Colonia Water System consists of two raw-water impoundments totaling 27 Mgal, a treatment plant with a capacity of 200 gal/min, a distribution

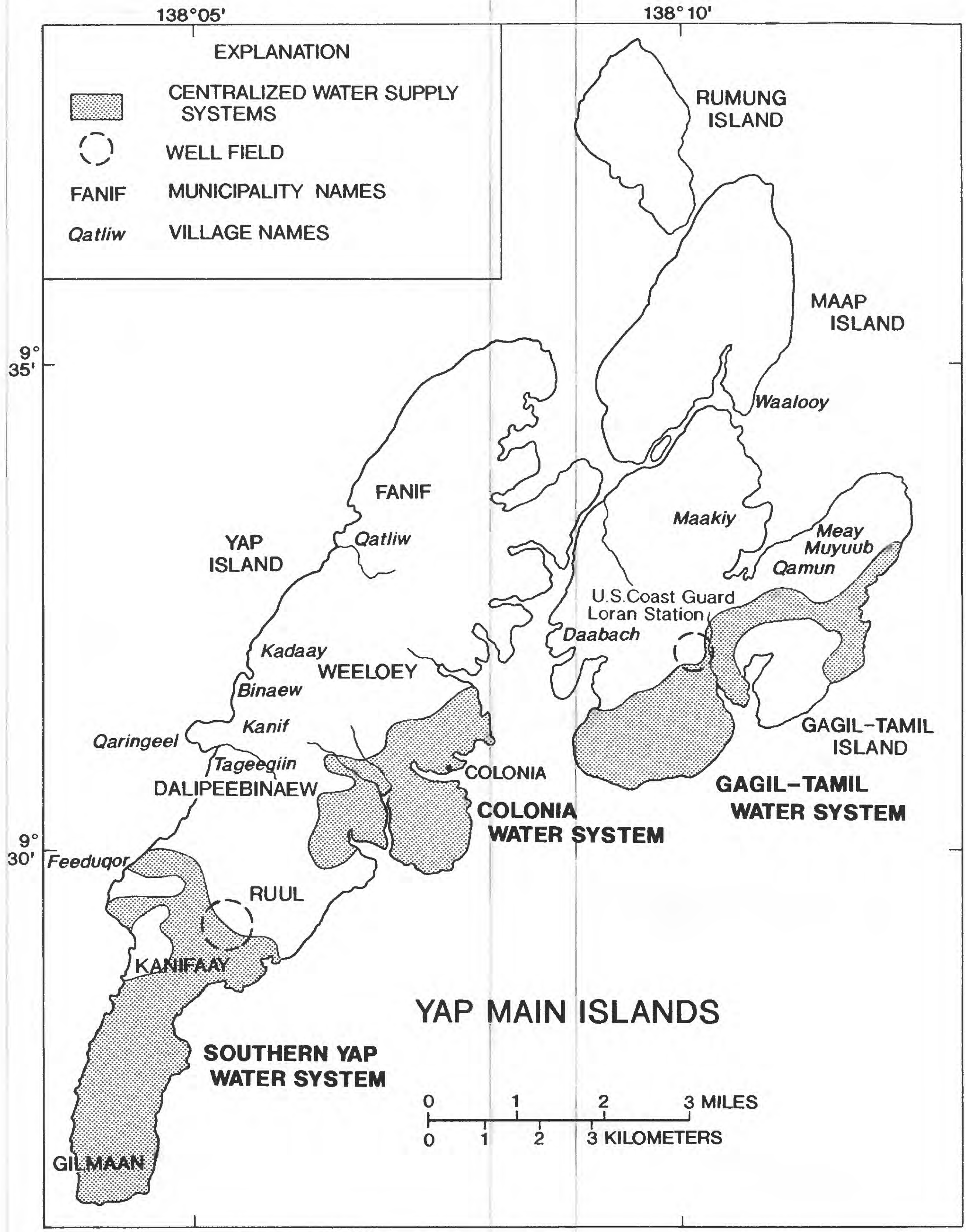

Figure 10. Location of centralized water-supply systems.

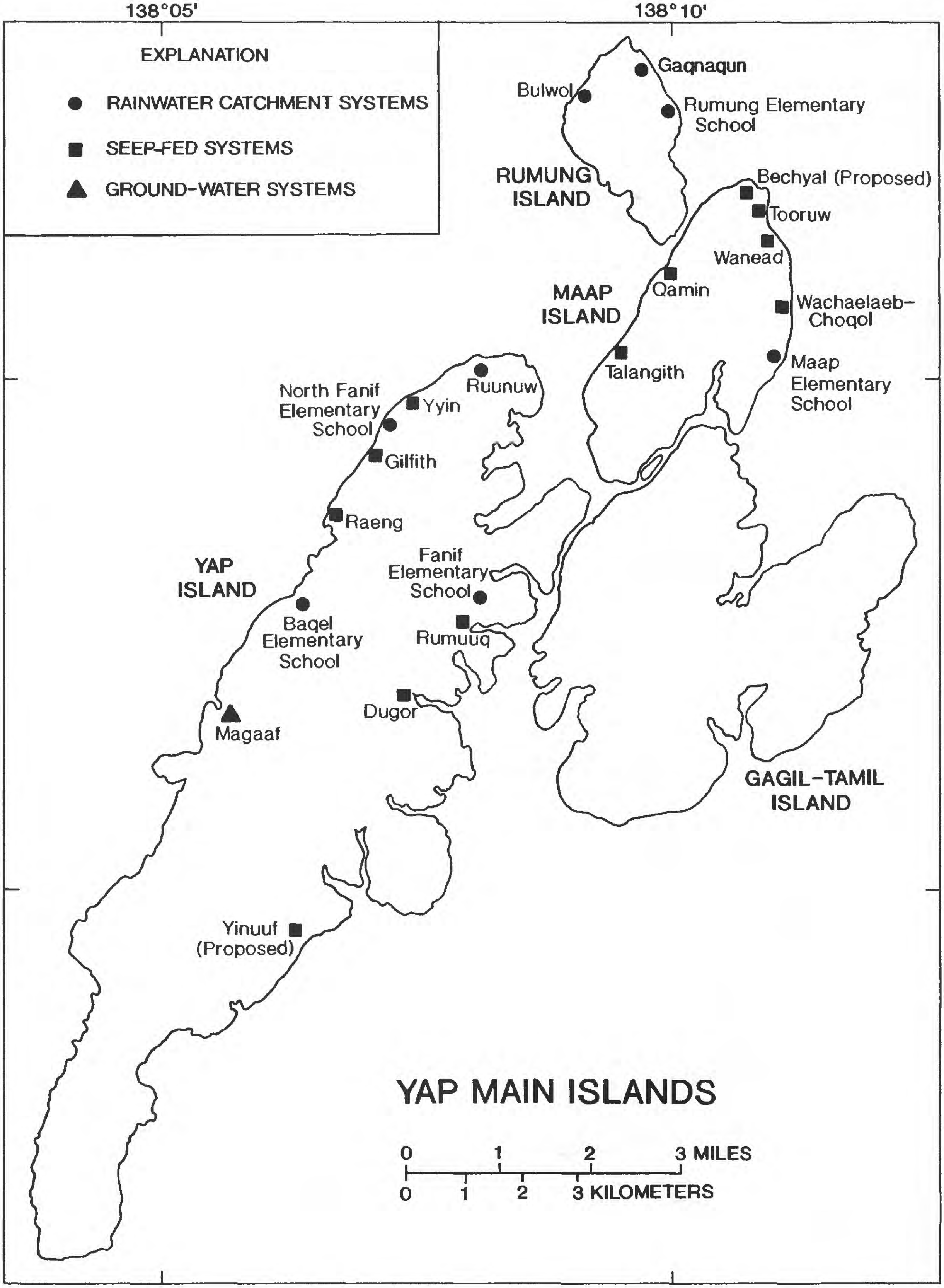

Figure 11. The village-scale water-supply systems.

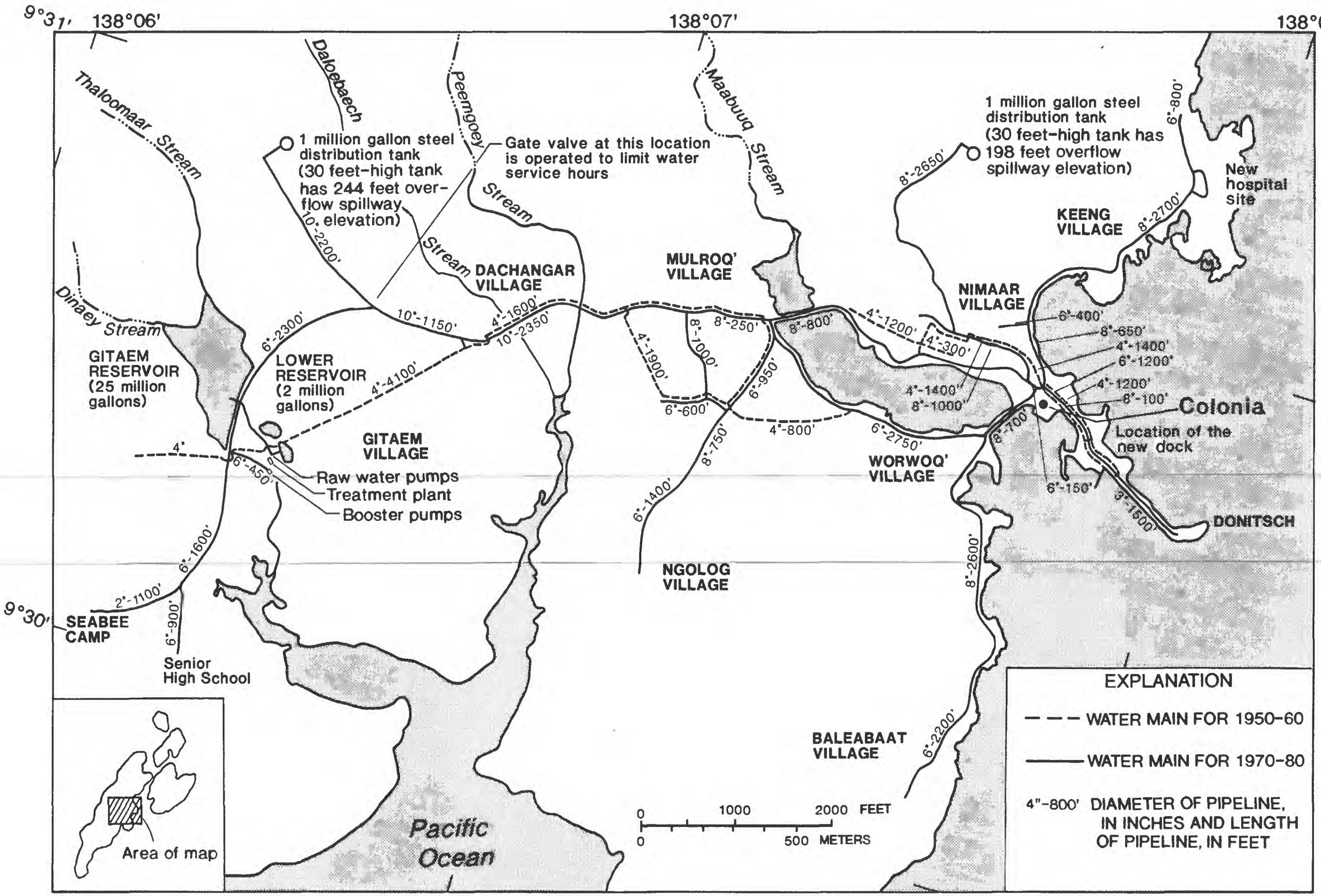

Figure 12. Colonia Water System (modified from Lyon Associates, 1980).

pipeline network, and two 1.0 Mgal tanks in the network (fig. 12). Inflow to the reservoirs is from two tributaries of Daloelaeb Stream, Dinaey, and Thaloomaar. The drainage area, which consists of open grassland in its lower part and forest in its upland area, covers 150 acres. The Colonia Water System serves Colonia and adjacent villages in Weeloey and Ruul municipalities. The system has several problems, which include excessive leakage from distribution lines, insufficient supply during severe droughts, episodes of high turbidity, unacceptable color and odor, and the potential for contamination resulting from a leaky distribution system which allows infiltration of ground water into the system between water-hour periods (Lyon Associates, 1980).

The Southern Yap Water System is supplied by ground water developed near the old airport on Yap island (fig. 13). The geologic setting and ground-water reservoir have been described by Nance (1979, 1982). According to Nance (1979), the water-bearing formation consists of deeply weathered Tomil Volcanics underlain by weathered schist of the Yap Formation. On the basis of information from driller's logs and water-level measurements, the ground-water reservoir covers an area of about 0.36 mi^2 and is approximately 40 ft thick. The central part of the ground-water reservoir overlies a small buried hill of unweathered schist (figs. 13 and 14). The depth of weathering, in both the Tomil Volcanics and the underlying Yap Formation, increases with distance from the hill.

The highest observed water levels occur in the old airport pond, north of the old runway, and the water table has an apparent gradient of about 25 ft/mi (feet per mile) to the north (fig. 15). The gradient in the southerly direction has not been determined. Ground-water discharges at seeps and streams in gulches north, northwest, and south of the area of high water levels, and by evaporation from the pond.

Five production wells, drilled in 1981, tap the old airport aquifer. Nance (1982) estimates that the five production wells are capable of producing a combined yield of 194,400 gal/d. Four of these wells, Timlang-1, Timlang-3, Yugamanman-1, and Yugamanman-2, are outfitted with pumps designed to produce an average rate of 25 gal/min per well. The wells in the old airport aquifer serve the Southern Yap Water System, which distributes water to the villages south of the airport, and to Feeduqor, but excludes Yinuuf which is to be supplied by a spring-fed system (figs. 10 and 11). In 1987, the main distribution lines had been laid; however, only a few household service connections had been made.

Operators of the Southern Yap Water System do not record individual well pumping rates or keep complete records of total pumpage; however, the present demand on the system is estimated at about 10,000 gal/d. This demand is met by replenishing a 100,000-gal storage tank every two or three days. The combined average pumping rate of all four wells in October 1986 was observed to be 77 gal/min; 23 gal/min less than the designed pumping rate.

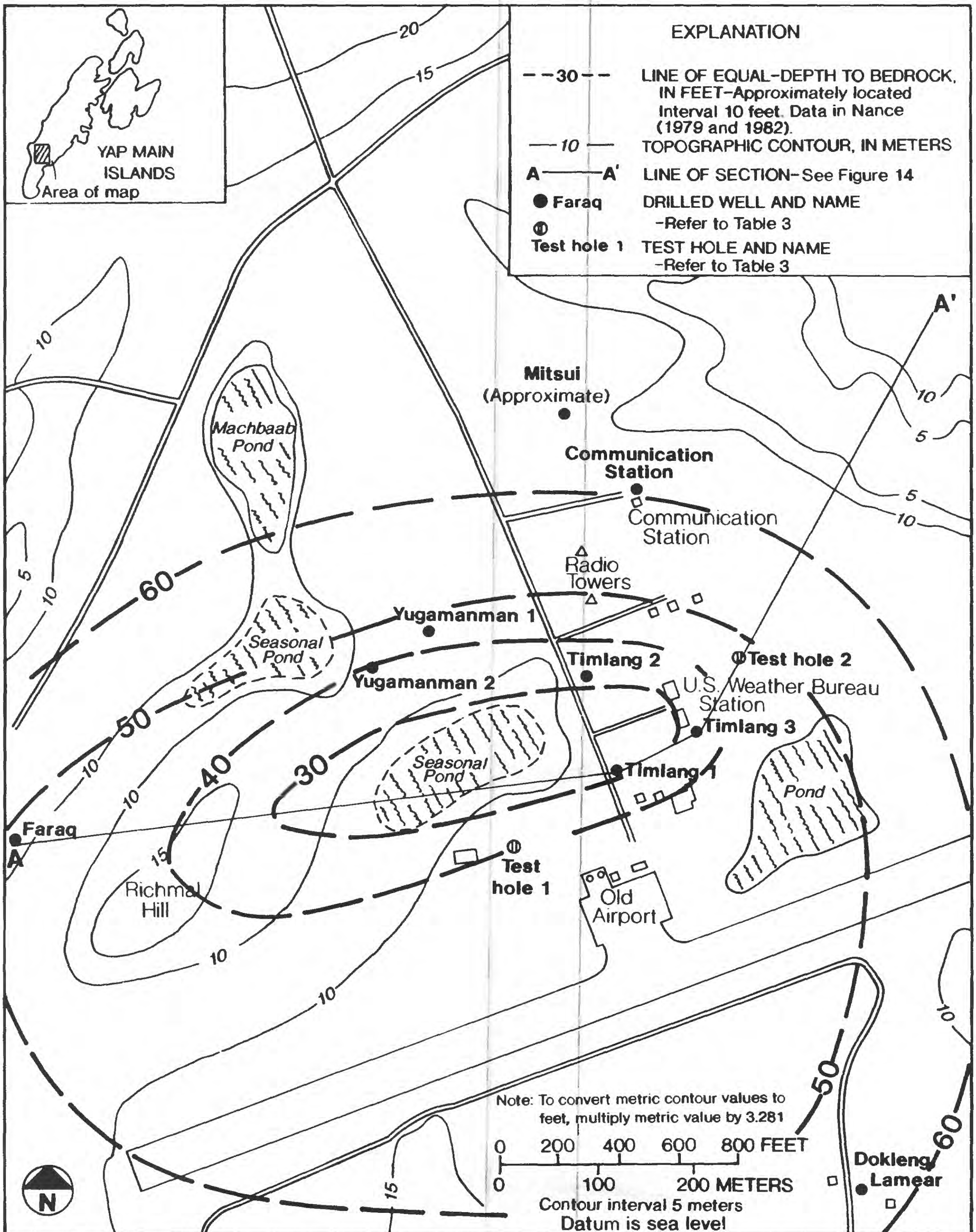

Figure 13. Approximate depth to bedrock (Yap Formation) in the old airport aquifer, Southern Yap Water System.

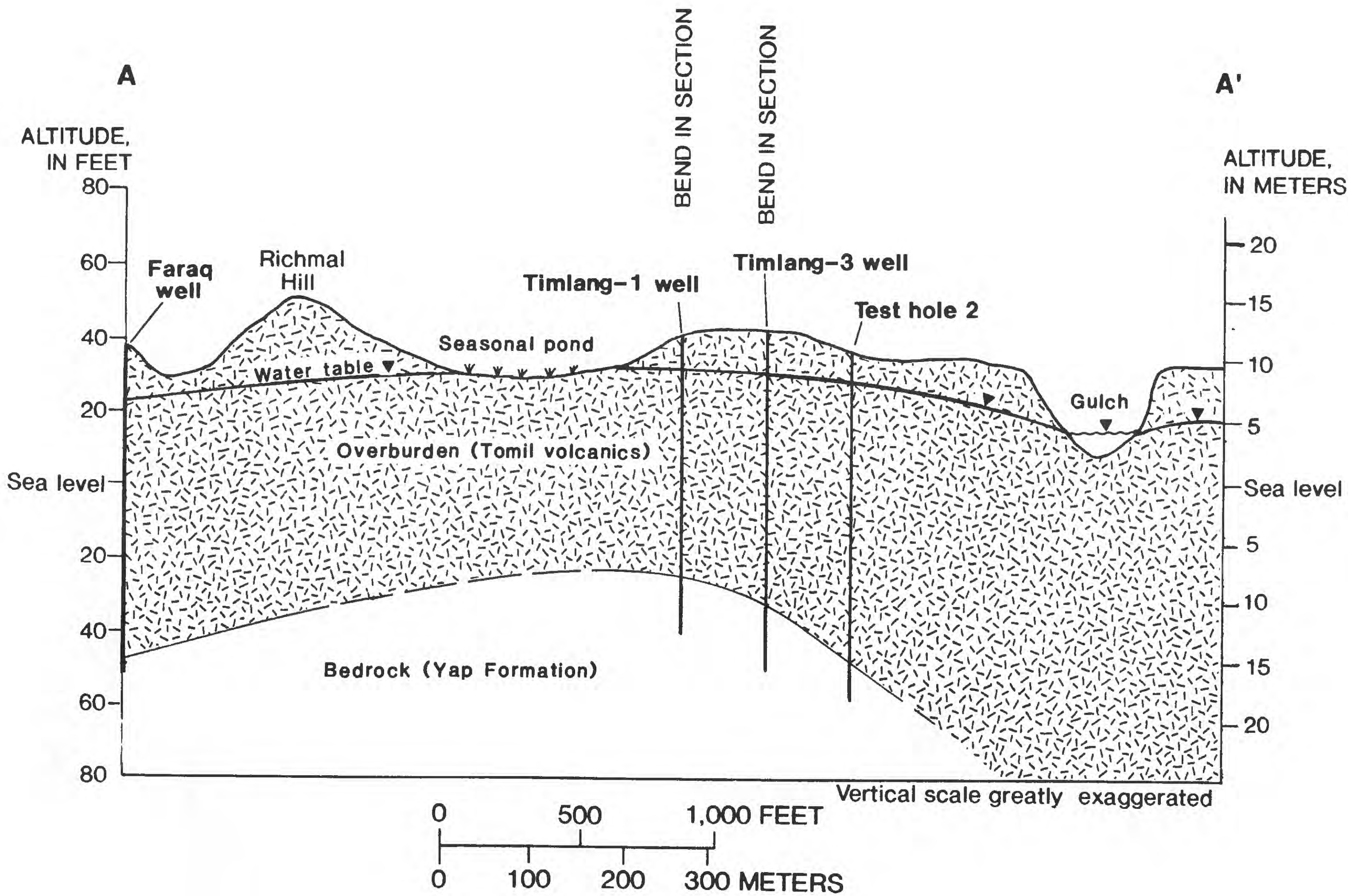

Figure 14. Hydrogeologic section A-A' of the old airport aquifer.

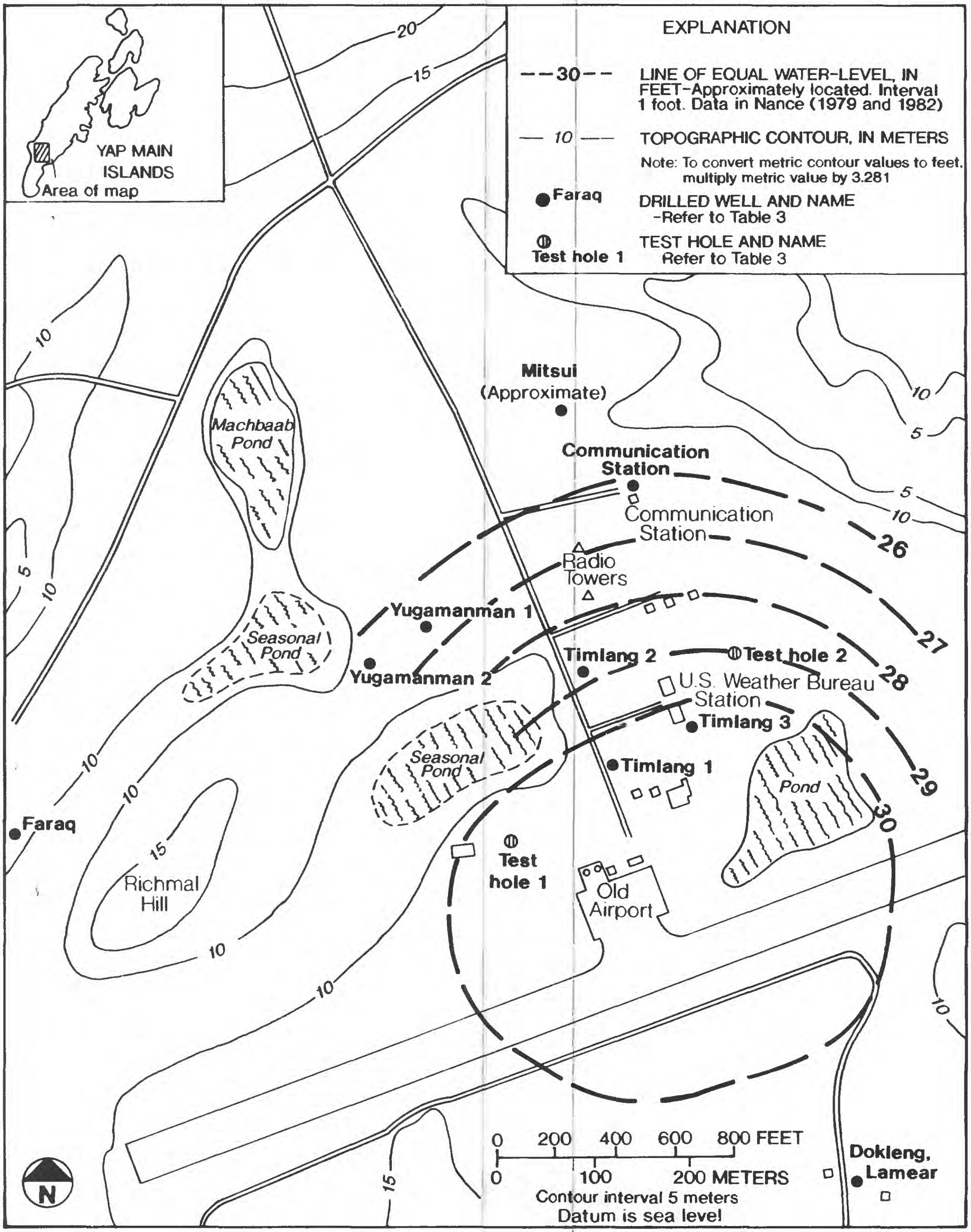

Figure 15. Water levels of the old airport aquifer.

An 8-hour pumping test was run on March 3, 1987, after the pumps had been left idle for four days. At the start of the test, Timlang-1, Yugamanman-1 and Yugamanman-2 wells produced 16, 21, and 24 gal/min, respectively, for a combined rate of 61 gal/min. The pump at Timlang-3 was inoperable. The combined pumping was reduced to 45 gal/min after 3 hours when Timlang-1 quit pumping because of excessive drawdown in the well. Steel tape water-level measurements revealed that the bottom of the Timlang-1 well contained a reddish brown sludge. Total pumpage was 23,600 gallons for the 8-hour period.

There has been a significant loss in yield from the Timlang wells since construction. The well yield might have been reduced by chemical incrustation or biofouling of the well screen and formation materials around the intake part of the well. Well rehabilitation, restoring a well to its most efficient condition, by various treatments or reconstruction methods might be necessary. Ongoing performance evaluations of wells are needed if well failures are to be avoided.

Ground water from the central valley in Gagil-Tamil supplies the Gagil-Tamil Water System (fig. 16). The geologic setting and ground-water reservoir have been described by Nance (1979, 1982). Monguch, Dorfay, and Mukong Streams, within the central valley, are perennial, fed by ground-water discharge. The water-bearing formation is composed of deeply weathered Tomil Volcanics underlain by unweathered schist of the Yap Formation. A part of the schist bedrock has been eroded in the area adjacent to Mukong Stream for at least a half mile upstream from the estuary. In this area the volcanics are underlain by 20 or more feet of coral limestone. The coral is as permeable or more permeable than the weathered volcanics.

The Gagil-Tamil aquifer is thin and confined by a silt-clay confining layer. .It covers an estimated 173 acres. As in the old airport aquifer, a significant part of the ground-water body overlies an elongated buried hill of schist bedrock (figs. 16 and 17). The higher yielding wells apparently straddle the buried hill. The water-level gradient is steep, about 120 feet per mile (ft/mi), and slopes southeastward toward the three perennial streams (fig. 18). The gradient of the land surface is about 300 ft/mi in some places.

Seven production wells tap the Gagil-Tamil aquifer. The Monguch, Thilung, and Mukong wells can yield as much as 50 gal/min, but the two Dorfay wells are poorer producers. Nance (1982) estimates that the seven production wells are capable of producing a combined yield of 396,000 gal/d. Presently, four wells (Monguch-1, Monguch-2, Thilung-1, and Thilung-2) are connected to the Gagil-Tamil Water System. These wells are outfitted with pumps capable of producing at average rates of 50 gal/min per well, or a potential combined yield of 288,000 gal/d.

The Gagil-Tamil Water System operators do not keep complete records of individual well pumping rates or total pumpage. However, the producing wells do not appear to have experienced a loss in yield since construction. Nonetheless, an ongoing performance evaluation of wells is needed if well failures are to be avoided.

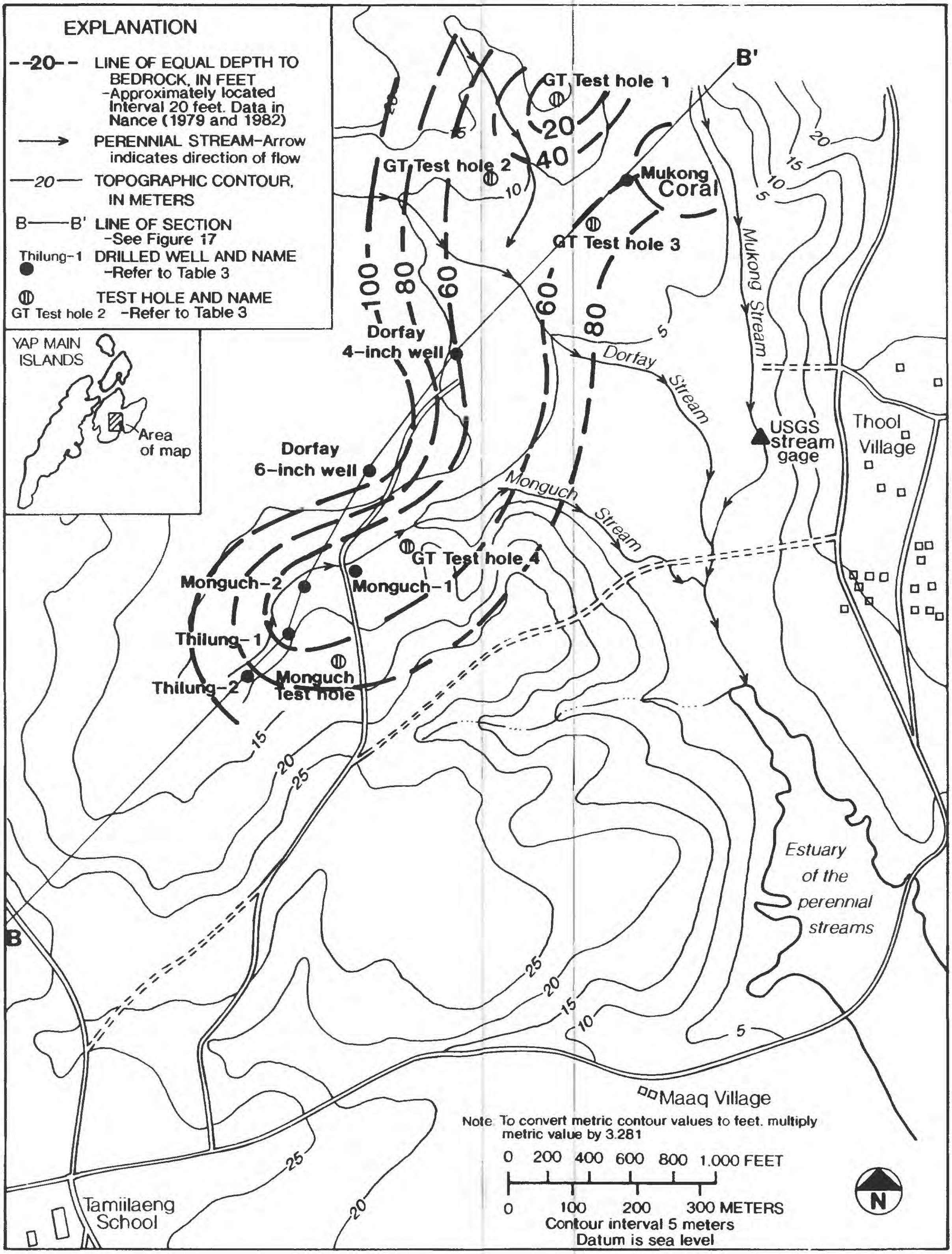

Figure 16. Approximate depth to bedrock (Yap Formation) in the Gagil-Tamil aquifer, Gagil-Tamil Water System.

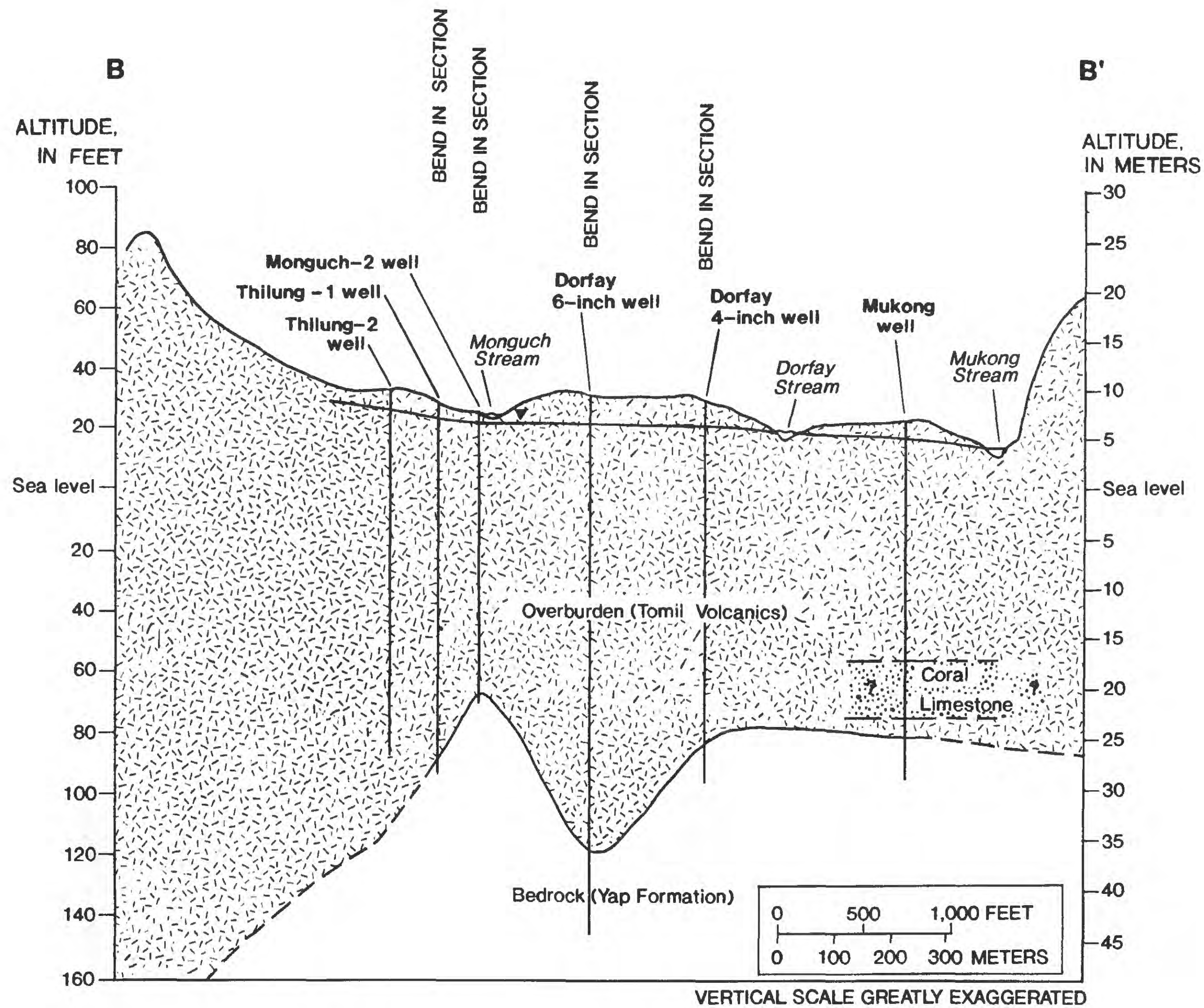

Figure 17. Hydrogeologic section B-B' of the Gagil-Tamil aquifer.

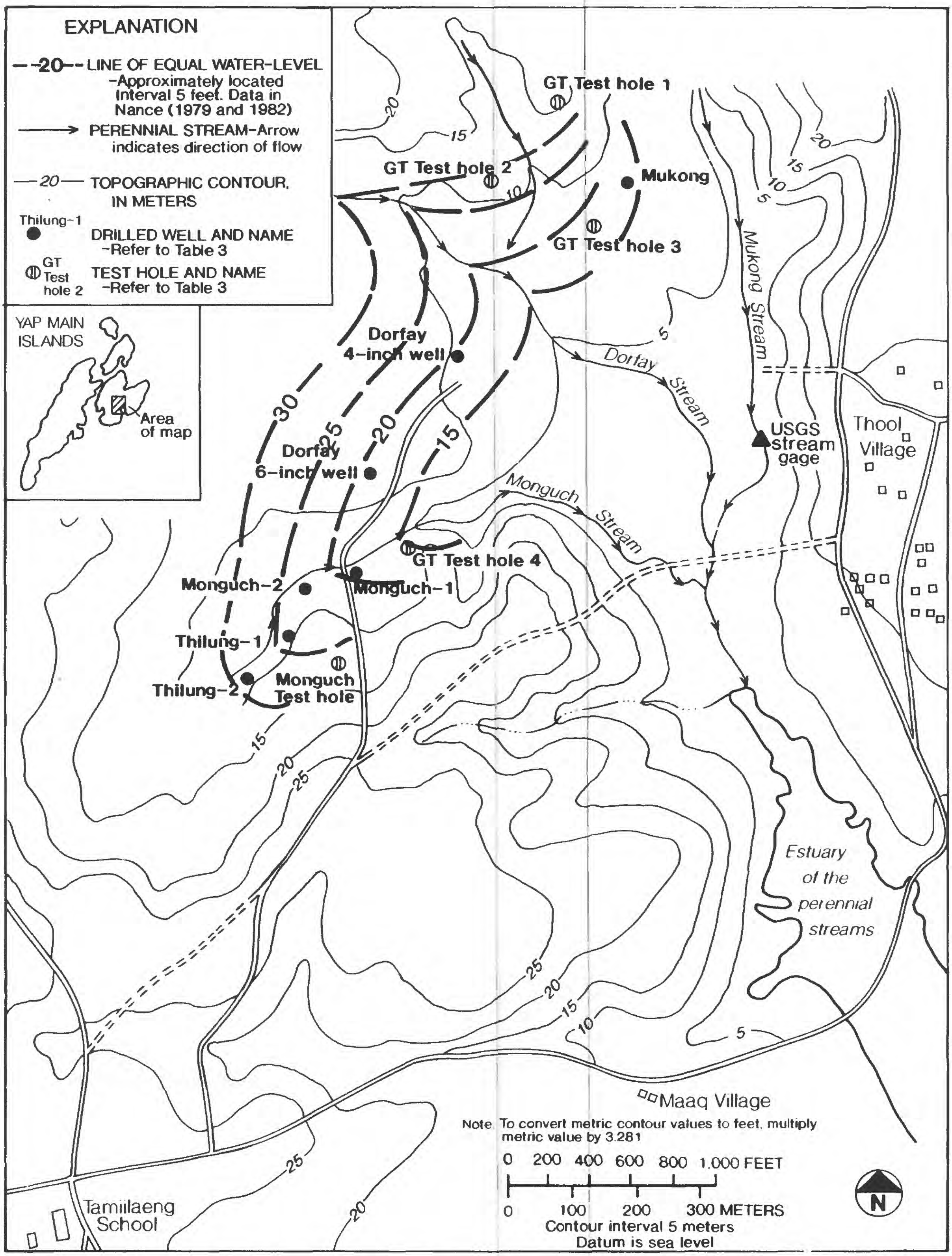

Figure 18. Water levels of the Gagil-Tamil aquifer.

In 1987 the demand on the system was approximately 20,000 gal/d with about one-third of the households in the service area connected to the system. When all individual household connections are complete, and assuming that the entire population of Gagil and Tamil municipalities are being serviced at a demand of 50 gal/d/person (Lyon Associates, 1980), the demand may reach 127,200 gal/d in the year 2000.

The Gagil-Tamil Water System serves all of Gagil-Tamil except for the villages of Daabach, Maakiy, Qamun, Muyuub, Meay, and the old U.S. Coast Guard Loran Station (fig. 10). Because the projected water demand (127,200 gal/d) for Gagil-Tamil in the year 2000 includes these areas and is less than one-half the present potential combined yield of the Gagil-Tamil aquifer, it is feasible that the area served by the Gagil-Tamil Water System could be expanded to include northern Gagil-Tamil, Maap, and the rapidly growing villages of Rumuuq and Dugor on the island of Yap (fig. 11). The projected water demand in the year 2000, assuming a 3.3 percent population growth rate and 50 gal/d/person (Lyon Associates, 1980), is 33,700 gal/d for the combined villages of Rumuuq and Dugor, and 30,550 gal/d for the island of Maap. If the Gagil-Tamil Water System was expanded to include these areas, then the total projected demand in the year 2000 would be 191,450 gal/d, which is less than the present potential combined yield of 288,000 gal/d.

Village-Scale Water-Supply Systems

Twenty village-scale water-supply systems were identified outside the area served by the three large-scale systems. The village-scale systems can be divided into spring-fed or rainwater-catchment systems, except for the Magaaf well water system in Dalipeebinaew municipality, Yap (figs. 9 and 11). A typical spring-fed system consists of a sump at the spring connected to a storage tank and distribution lines to the village (fig. 19). Most rainwater-catchment systems utilize a guttered roof of a community building (elementary school or dispensery) for a catchment surface and a concrete tank for storage.

The Magaaf well water system is capable of producing 5 to 10 gal/min during several hours of each day. Water developed from the well is pumped to a storage tank located on a hill above Kanif village. From the storage tank, water is distributed to the villages of Kadaay, Magaaf, Binaew, Kanif, Qaringeel, and Tageegiin (figs. 10 and 11). Yield to the Magaaf well comes from schist bedrock (Yap Formation) and the nearby stream (Nance, 1982). Because there are months each year when the stream is dry, the well yield declines during the dry season. Additional water supplies are, therefore, needed to meet the water demand in this rapidly growing municipality.

Residents prefer rainwater as a source of freshwater because it is considered to be virtually pure, containing small quantities of dissolved constituents. Additional sources of freshwater have been developed to meet the demand during the dry season and drought periods. The failure of

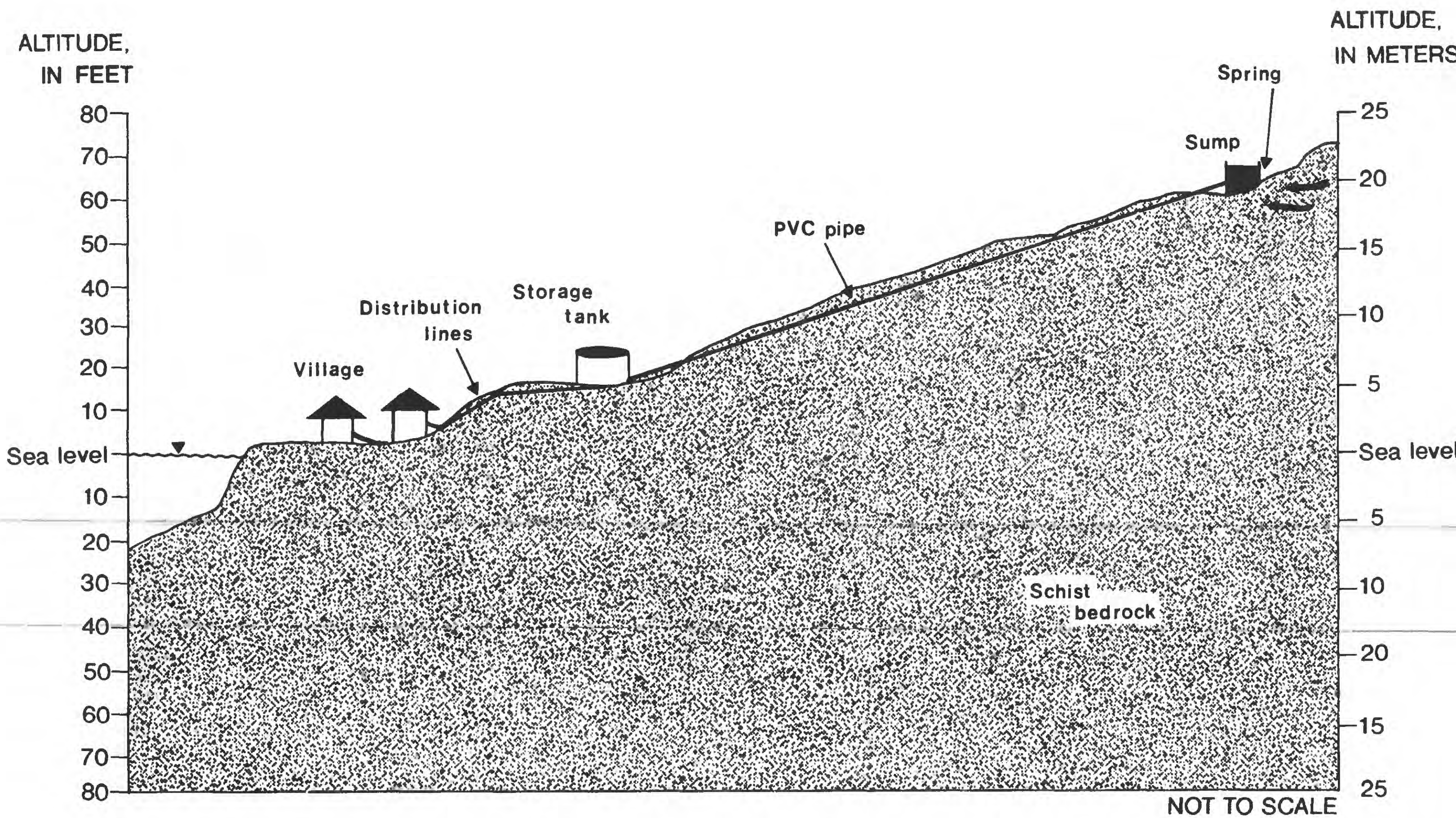

Figure 19. Diagrammatic section of a typical spring-fed village-scale water-supply system in the Yap main islands.

individual rainwater-catchment systems during the dry season commonly is the result of inefficient catchment areas and undersized storage facilities. In most of the villages, shallow dug wells and seeps have been developed to augment individual rainwater-catchment systems. The water derived from seeps is low in dissolved solids; however, the quantity is small, ranging from 0 to 8 gal/min. Shallow wells dug into the coastal plain yield water of variable quantity and quality. Quantity is dependent on the formation into which the well is dug and the well design. Quality is dependent on the proximity of the well to the ocean and land-use practices. Sources of ground-water contamination include seawater intrusion, overland benjos (outhouses), garbage pits, dish- and clothes- washing water, livestock waste, and crop fertilizer.

Descriptions of 12 spring-fed systems are given in table 5, and their locations are shown in figure 11. Village population figures supplied by YAPCAP (Yap Community Action Program, Edward Brettin, oral communication, 1987) together with the demand of 20 gal/d/person estimated by Lyon Associates (1980) were used to estimate the water demand at each spring-fed system. Dry-season yields were determined by volumetric measurements of discharge at the spring-fed sump, and wet-season yield figures were estimates made by experienced field personnel from YAPCAP.

Table 5. Description of seep- or spring-fed village-scale water-supply systems

[N.D. = not determined; gal/d = gallon per day; gal = gallon]

Village, Municipality	Population 1/	Water demand 2/ (gal/d)	Yield (gal/d) wet season 3/ dry season	Sump (gal)	Storage (gal)	Description
Talangith, Maap	35	700	N.D. 1,400	1,800	--	Angiya seep discharges at soil/rock interface; infiltration gallery feeds sump which supplies the village distribution lines.
Qamin, Maap	91	1,820	11,520 4,600	--	23,900	Wudee seep feeds a 8,600 gallon holding tank; water is pumped to a 15,900 storage tank which supplies the village distribution lines.
Bechyal, Maap 4/	26	520	N.D. 600	--	--	Proposed seep development; additional source needed for proposed tourist development; shallow ground-water development possible.
Tooruw, Maap 4/	29	580	1,500 500	1,800	15,000	Binyuw seep in taro patch; infiltration gallery feeds a sump located in the streambed; sump is connected to storage tank which supplies the village distribution lines; additional freshwater supply needed.
Wanead, Maap	68	1,360	17,800 8,000	270	8,600	Perennial seep at head of a ravine inland from Wanead village; 1,900 ft of pipe connect the sump and storage tank which supplies the village distribution lines.

Table 5. Description of seep- or spring-fed village-scale water-supply systems - Continued

[N.D. = not determined; gal/d = gallon per day; gal = gallon]

Village, Municipality	Population 1/	Water demand 2/ (gal/d)	Yield (gal/d) wet season 3/ dry season	Sump (gal)	Storage (gal)	Description
Wachaelaeb/ Choqol, Maap 3/	65	1,300	5,500 N.D.	8,600	--	Perennial seep in taro patch; infiltration gallery feeds a sump located in the streambed; sump supplies distribution lines in Wachalaeb and part of Choqol village. Rationing needed in the dry season; additional freshwater supply needed.
Raeng, Fanif	36	720	N.D. N.D.	540	5,700	Paaran seep: hillside seep through fractured schist; sump is connected to storage tank which supplies the village distribution lines; "never goes dry".
Gilfith, Fanif	50	1,000	N.D. N.D.	700	8,600	Archeq seep: hillside seep; sump is connected to storage tank which supplies the village distribution lines; system needs a sand filter.
Yyin, Fanif	47	940	9,800 N.D.	N.D.	8,600	Qawach seep: hillside seep; sump located in streambed downstream from the source; sump is connected to storage tank which supplies the village distribution lines (10-15 homes).
Rumuuq, Fanif 4/	238	>4,760	>8,000 3,000	N.D.	23,000	Mayche spring: located in Qaabach, Tamil; hillside seepage at approximately 40 ft elevation; linked to Rumuuq village system by a polyethylene pipe; additional freshwater supply needed.
Dugor, Weeloey 4/	204	4,080	3,000 N.D.	270	3,800	Magbuy seep: hillside seep; sump is connected to storage tank which supplies the village distribution lines; rationing needed in the dry season, additional freshwater supply needed.
Yinuuf, Ruul	60	1,200	20,000 8,640	--	8,600	Auw spring located in a small ravine inland of Yinuuf village; small earth-fill dam ponds water; spring development not complete.

1/ Village population figures from 1984 mapping survey.

2/ 20 gal/d/person (Lyon Associates, 1980).

3/ Wet season yields are YAPCAP estimates.

4/ Additional freshwater supplies needed to meet the present water demand.

By comparing the dry season yield with the water demand, the villages of Bechyal, Tooruw, Wachaelaeb-Choqol, Rumuuq, and Dugor were identified as places in need of additional freshwater supplies. Because of the inadequacy of the present systems in Rumuuq and Dugor villages, and their large, rapidly growing populations, these two villages are proposed as sites to be served by either the Colonia or Gagil-Tamil Water System.

Descriptions of rainwater-catchment systems at seven villages are given in table 6, and locations of the systems are shown on figure 11. Most catchment systems require rationing during dry seasons, because of inadequate catchment areas and insufficient volumes of storage. Specifically, at Gaqnaqun, Rumung, Maap Elementary School, and North Fanif Elementary School, only part of each roof area has gutters, so that a large part of the rainfall, as much as half, is not caught. In addition, there is further loss of water due to lack of security at storage tanks.

Table 6. Description of village-scale rainwater catchment systems

[gal/d = gallon per day; gal = gallon; ft^2 = square foot]

Village, Municipality	Population	Water Demand 1/ (gal/d)	Catchment (ft)	Storage (gal)	Comments
Bulwol, Rumung	12	240	240	5,000	Built by Yap Community Action Program.
Gaqnaqun, Rumung	20	400	450	24,000	Roof needs repair; only half the roof is guttered; storage tank needs cleaning and a locking valve.
Rumung Elementary School, Rumung 2/	61	1,220	1,900	24,000	Pipeline distributes to Riy village; rationing needed during the dry season.
Maap Elementary School, Maap 2/	76	1,520	5,000	3,800	Gutters catch 3/4 of rainfall, and need to be replaced. Rationing needed during dry season.
North Fanif Elementary School, Fanif	30	600	2,100	3,800	Serves school and nearby dispensary, improve catchment gutters.
Ruunuw, Fanif 2/	37	740	255	23,000	Pipeline distributes to Ruunuw village; rationing needed during dry season.
Fanif Elementary School, Fanif	61	1,220	--	8,600	

1/ 20 gal/d/person.

2/ Additional freshwater supplies needed to meet the present water demand.

In spite of current and long historical use of rainwater-catchment systems, the quality of water obtained from rainwater-catchment systems in Micronesia has received little attention. In the only bacteriological evaluation of water obtained from rainwater-catchment systems in Micronesia, Dillaha and Zolan (1983) recommended that users boil catchment water before drinking because coliform organisms, some at very high and potentially dangerous levels, were found in many catchments. However, Dillaha and Zolan (1983) showed that rainwater-catchment systems provide relatively high quality water for domestic purposes; 56 percent showed no fecal coliforms, and 37 percent had no total coliforms present. Using a standard of less than or equal to five coliforms present, 75 percent of the rainwater-catchment systems met the standard for fecal coliforms and 58 percent met the standard for total coliforms.

One of the authors of this report, Anthony, is presently studying the deposition of toxic metals, such as lead, in rainwater-catchment systems as a function of system design and maintenance. This study is being conducted on Ulithi atoll, Yap State, and Mwoakilloa and Pingelap atolls, Pohnpei State.

To improve the efficiency and water quality of rainwater-catchment systems on the Yap main islands the following are suggested:

- Low corrosion materials, such as aluminium, are desirable for roof catchment surfaces and guttering. The present use of corrugated metal sheet is not suitable.
- Trees that overhang collection surfaces can be removed to minimize entry of organic matter into tanks.
- A foul flush and/or a filter device can be employed in rainwater-catchment systems to remove contaminants before water enters the storage tank. A foul flush device diverts the early runoff of dirty water from a roof at the beginning of a storm. Early runoff typically contains a high concentration of dust, leaves, and other debris that has collected on a roof since the last rainfall event.
- Filter devices, such as prefabricated drain boxes with perforated plates or coarse sand filters can be used.
- Maintenance of roofs, gutters, pipes and tanks can be carried out regularly to ensure maximum efficiency of collection and to minimize chances of bacteriological contamination.
- Rainwater used for human consumption can be boiled as a further water-quality control.

Chlorination of rainwater tanks, although practiced in some places, is not seen as the answer for the Yap main islands, partly because of the need for monitoring of chlorine levels in each tank, and the extra operational requirements for the local population. Improvements to the established rainwater-catchment systems along with the construction of additional storage tanks, would be sufficient system improvements to satisfy the village water demands.

Chemical Characteristics of Water

The main chemical characteristics of surface, spring, and ground-water sources in the Yap main islands appear to be related to the mineralogy of the host rock and soil. The composition of stream water is variable, both with time and location. Important factors that vary with time and location are the relative contribution of runoff and ground water, climate, the amount of organic matter present, the extent of physical mixing of the water, and the amount of suspended matter. A number of factors affect the chemical character of ground water, such as the chemical composition of recharge water, the abundance and type of organic matter present in the host rock, contact with the atmosphere, and proximity to the ocean. Based on major-ion data, all surface-, spring-, and ground-water sources meet World Health Organization (World Health Organization, 1971) drinking water standards. However, water-quality testing for bacteria need to be carried out to determine whether these waters are safe to drink before boiling.

The source of most of the water in streams is quick runoff from rainfall. Rainwater contains very small amounts of various dissolved constituents. Rainwater in proximity to the ocean, however, may acquire significant amounts of salts deposited from sea spray. As water from rainfall passes through soil and rock, it reacts with inorganic and organic matter, and various ions and compounds are taken into solution. Minerals contribute such cations as sodium, potassium, magnesium, and calcium, and such anions as chloride, sulfate, and bicarbonate. Organic materials affect the content of oxygen, carbon dioxide, and nutrient elements such as nitrogen and phosphorus. The water continually changes composition as it encounters new conditions. Eventually part of the rainwater enters a stream, either as surface runoff or as ground water issuing at springs and seeps.

In general, the composition of stream water depends on the type of soil and rock that the water has passed through, and whether the main source of water in the stream is from direct runoff or ground water. Ground water usually contains more dissolved material than surface runoff, because it has closer and longer contact with organic material and minerals in the soil and rock particles. Generally, there is a fairly direct relation between the chemical composition of a given ground-water body and the mineralogy of its host rock or soil.

Water-quality samples have been collected from wells, streams, and springs on the Yap main islands by the U.S. Geological Survey from 1979 to the present; these data are sparse and conclusions drawn from them are only tentative. Field determinations of temperature, pH, and specific conductance were made by techniques outlined by Presser and Barnes (1974). Samples for analysis of major ions were collected and treated according to procedures described by the U.S. Geological Survey (1977), and analyzed according to analytical methods described by Fishman and Friedman (1985).

Chemical analyses of water from seven wells and nine streams are summarized in table 7. All wells are in the Tomil Volcanics; two in the Gagil-Tamil aquifer and five in the southern Yap airport aquifer. Of the nine streams, four are in the Tomil Volcanics on Gagil-Tamil island, four are in the Yap Formation (schist) on Yap island, and one is in the Map Formation (tectonic breccia) on Maap island. The mean values and standard deviations of temperature, pH, and major-ion concentrations are listed in table 7.

Table 7. Summary of chemical data from surface- and ground-water sources in the Yap Islands

[GT = Gagil-Tamil; Q = discharge; cfs = cubic feet per second or ft^3/s; x = mean; s = standard deviation; mg/L = milligrams per liter; n = number of analyses]

	Units	GT Wells (n = 3) x	s	GT Streams (n = 18) x	s	Old Airport Wells (n = 12) x	s	Yap Streams (n = 12) x	s	Maap Streams (n = 3) x	s
Temperature	°C	28.6	0.75	27.1	0.72	29.1	0.23	26.1	0.77	27.3	0.35
pH		7.04	0.45	6.4	0.46	6.5	1.0	7.5	0.31	7.5	0.07
Alkalinity, total as $CaCO_3$	mg/L	29.3	3.59	17.9	10.21	16.1	14.98	32.1	11.46	36.0	6.08
Sulfate, dissolved SO_4	mg/L	1.7	0.15	3.1	2.37	3.5	4.6	3.9	4.04	7.0	7.07
Chloride, dissolved Cl	mg/L	6.7	0.21	6.2	1.0	7.3	2.49	10.9	4.16	16.0	1.73
Silica, dissolved SiO_2	mg/L	63.3	8.38	8.4	3.42	9.1	15.61	18.2	3.45	19.7	0.58
Magnesium, dissolved Mg	mg/L	3.2	0.12	2.3	1.45	1.8	1.59	5.9	1.35	6.3	0.29
Calcium, dissolved Ca	mg/L	3.7	0.44	3.0	1.92	3.5	2.16	3.9	2.3	6.4	0.35
Iron, dissolved Fe	mg/L	0.015	0.02	0.52	0.6	0.4	0.63	0.25	0.09	0.32	0.1
Manganese, dissolved Mn	mg/L	0.002	0.01	0.11	0.13	0.06	0.08	0.007	0.01	0.03	0.02
Sodium, dissolved Na	mg/L	7.3	1.47	4.4	0.78	6.1	1.31	5.8	1.02	10.2	0.76
Potassium, dissolved K	mg/L	1.6	0.29	0.2	0.14	0.4	0.16	0.2	0.1	0.3	0.58
Solids, dissolved, sum of constituents	mg/L	98.0	16.97	40.6	14.24	42.6	30.29	70.0	11.94	85.7	5.51
Q(cfs)		--	--	1.32	0.81	--	--	1.14	2.43	0.28	0.22

Ground water in the Gagil-Tamil and old airport aquifers contains a greater amount of total dissolved solids than surface water on Gagil-Tamil island. Both the ground water and surface water are slightly acidic, pH equals 6.4 to 7.04, which is probably related to the acidic soils (latosols) of the Tomil Volcanics. The Tomil Volcanics compose the geologic setting for both aquifers and streams on Gagil-Tamil. The Tomil Volcanics, composed of andesitic rocks, have been deeply weathered to kaolinitic clays, releasing sodium cations and dissolved silica. The process by which water dissolves rocks can be expressed in terms of chemical equations. The reaction of carbon dioxide and water supplies hydrogen ions:

$$CO_2(aq) + H_2O = HCO_3^- + H^+ \quad (1)$$

Andesites, which are rich in plagioclase feldspar, are changed to clay minerals (kaolinite) in a reaction with hydrogen ions:

$$\underset{\text{feldspar}}{2NaAlSi_3O_8} + \underset{\text{carbonic acid}}{9H_2O + 2H^+} = \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + \underset{\text{Na ions}}{2Na^+} + \underset{\text{dis. } SiO_2}{4H_4SiO_4} \quad (2)$$

The dissolved silica content in the ground water depends on the ease and extent of breakdown of silicate minerals in the host rock. Concentrations are a function of contact time and the exposed surface area of the mineral. Because of the longer and more intimate contact of ground water with organic material and with soil and rock, ground water in the Gagil-Tamil and old airport aquifers has a greater amount of total dissolved solids, and dissolved silica and sodium concentrations than surface water sampled on Gagil-Tamil.

Iron concentrations exceeding 0.1 milligrams per liter (mg/L) are noted in all of the stream water sampled and in the ground water of the old airport aquifer. Manganese concentrations exceeding 0.05 mg/L are noted in the sampled stream water of Gagil-Tamil and in the ground water of the old airport aquifer. These concentrations are not high enough to cause water-quality problems; however, periodic monitoring should continue. Iron and manganese are minor elements in water and pose no real health hazard; however, they can cause considerable problems in water supplies for either domestic or industrial use. Iron and manganese can appreciably affect the taste of beverages, and can stain laundered clothes and plumbing fixtures. Iron can also promote the growth of bacteria. The World Health Oranization recommends a desirable level of 0.1 and 0.05 mg/L, and a maximum permissible level of 1.0 and 0.5 mg/L for iron and manganese, respectively (World Health Organization, 1971).

The rocks of the Yap Formation are composed of ultramafic parent material that has been recrystallized to greenschist facies by regional metamorphic processes. The silicate minerals that compose these rocks are rich in magnesium and have a high sodium to potassium ratio. Considering the compositional similarities of the Yap and Map Formations, it is not surprising that the chemical characteristics of sampled stream water flowing over these formations is similar. These waters have a pH of 7.5, moderately high concentrations of total dissolved solids (70-85 mg/L), high sodium to potassium ratio, and high magnesium concentrations in comparison to the other water types listed in table 7.

Chemical data, collected during February 1987, from five springs which discharge water from the soil-rock interface in the Yap and Map Formations are listed in table 8. The pH of these waters ranges from 7.2 to 8.0. Higher alkalinity and total dissolved solids in sampled springs as compared with sampled ground water and streams suggest an additional input of CO_2 to spring waters. The input of CO_2 to spring waters is derived from the decay of vegetation and root respiration in the soil zone. High sodium, magnesium, and dissolved silica concentrations suggest that spring waters are actively dissolving their host rock.

Table 8. Chemical data from springs in the Yap Islands
(Samples collected in February 1987)

[mg/L = milligrams per liter]

		Yinuuf, Yap	Dugor, Yap	Yabach, Yap	Qamin, Maap	Talangith, Maap
Temperature	°C	25.5	27.5	26.5	27.5	28.0
pH		7.20	7.98	7.34	7.70	7.27
Alkalinity, total as $CaCO_3$	mg/L	108.0	172.	89.	92.	289.0
Sulfate, dissolved SO_4	mg/L	4.9	2.3	4.2	2.1	5.5
Chloride, dissolved Cl	mg/L	16.0	14.	16.	18.	29.0
Silica, dissolved SiO_2	mg/L	40.0	49.	45.	42.	50.0
Magnesium, dissolved Mg	mg/L	18.0	25.	12.	11.	34.0
Calcium, dissolved Ca	mg/L	13.0	24.	12.	18.	51.0
Iron, dissolved Fe	mg/L	0.33	0.014	0.005	0.046	0.012
Manganese, dissolved Mn	mg/L	0.082	0.001	0.007	0.014	0.014
Sodium, dissolved Na	mg/L	12.0	12.	13.	14.	26.0
Potassium, dissolved K	mg/L	0.2	0.4	0.2	0.8	0.9
Solids, dissolved, sum of constituents	mg/L					
Nickel, dissolved Ni	mg/L	0.004	0.001	0.003	0.002	0.001
Chromium, dissolved Cr	mg/L	0.001	0.001	0.002	<0.001	<0.001

Except for the high iron concentrations noted in all of the sampled surface water and in the ground water of the old airport aquifer, and the high manganese concentrations noted in the sampled stream water of Gagil-Tamil, and in the ground water of the old airport aquifer, the overall quality of water in the Yap main islands is good. The concentration of all chemicals analyzed are within maximum permissible levels recommended for domestic use by the World Health Organization (1971). Bacterial analyses were not performed. Water-quality problems that were not studied include; biological and heavy metal contamination of rainwater-catchment system waters, biological contamination of shallow dug well waters, and the potential contamination of the Colonia Water System reservoir waters from leachate derived from the Yap State sanitary landfill.

Water Balance

A water balance has been calculated for each of seven stream basins where continuous streamflow data are available (fig. 20). The water-balance calculations indicate how water from rainfall is distributed among the components of the hydrologic cycle: runoff, evapotranspiration, and ground-water recharge. The water-balance equation:

Rainfall - Runoff - Evapotranspiration = Change in Soil Storage + Recharge

and a bookkeeping method developed by Mather (1978), with monthly rainfall, streamflow, and pan evaporation data, were used to calculate, month by month through the period of record, the quantity of water in each of the components of the hydrologic system.

Because of the short term of record available from the U.S. Geological Survey station, only the rainfall data collected by the National Weather Service (formerly the U.S. Weather Bureau) at the old airport (table 2) are used for the water-balance calculations made in this report. Rainfall recorded at the old airport station is assumed to be distributed homogeneously over the selected drainage areas used in the water-balance calculations.

Pan evaporation data have been collected at the Weather Service station at the old airport since 1978 (table 9). Mean annual pan evaporation at the station during the 7-year period, 1979 to 1985, was 75 inches. Data for 1978 and 1986 were incomplete and could not be used for the mean annual calculation. These data have been applied homogeneously throughout the Yap main islands and are assumed to equal potential evapotranspiration.

Table 9. Monthly and annual pan evaporation data for Yap

(Source: U.S. National Oceanic and Atmospheric Administration)

[e = Estimated value; M = 10 or more daily values are missing; -- = No record]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Total
1978	--	--	--	--	--	--	5.58	6.70	5.15	5.33	5.06	7.23	--
1979	6.52	6.74	7.49	8.21	7.41	5.90	5.55	6.33	6.15	8.60	6.11	6.11	81.12
1980	5.41	6.16	6.96	6.87	6.32	5.97	6.25	5.96	4.78	6.54	5.24	5.55	72.01
1981	3.99	5.56	7.48	7.69	8.41	4.36	5.31	6.65	7.01	5.56	4.91	5.35	72.28
1982	6.58	5.60	7.12	7.56	5.58	5.70	6.82	7.75	5.70	5.88	5.76	6.37	76.42
1983	7.17	7.66	9.04	8.08	8.68	6.16	5.30e	4.85e	4.67e	5.64e	4.73e	5.83	77.81e
1984	5.55	5.95	7.90	8.23	8.85	5.39e	6.45e	4.87	5.55	5.03	6.04e	6.24	76.05e
1985	5.01e	6.53	7.31	6.45e	6.09e	5.24e	6.31	6.26e	5.41e	5.47	5.98	4.99e	71.05e
1986	6.40e	4.64e	6.48e	6.85	5.96e	5.36e	M	6.78e	5.30e	M	5.83e	6.79	--

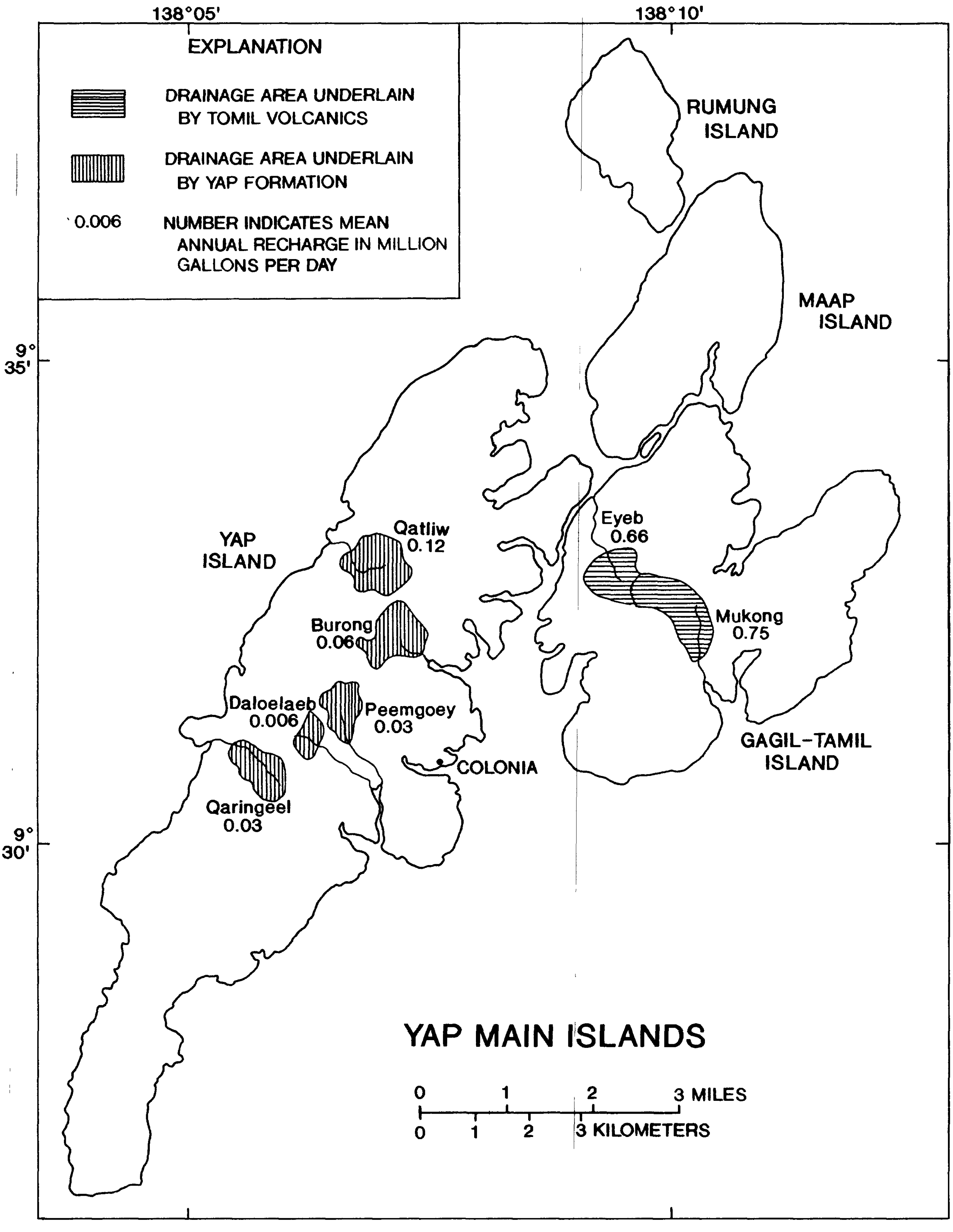

Figure 20. Mean annual recharge of the Yap main islands.

Continuous streamflow data are available for the nonperennial streams of Peemgoey, Qatliw, Qaringeel, Burong, and Daloelaeb, and the perennial streams, Mukong, and Eyeb. Because Mukong and Eyeb Streams are perennial, data for these two streams were analyzed differently from the others to determine runoff values for the water-balance equation. A discussion of the techniques used for both nonperennial and perennial streams follows.

The monthly water-balance calculations produce average ratios of runoff, actual evapotranspiration, and ground-water recharge as a percentage of rainfall. These ratios can be used to estimate the water balance in ungaged basins, and to estimate the ground water possibly available for development if basin characteristics of topography, geology, vegetative cover, and soil infiltration characteristics are similar.

It is necessary to note that the period of record for streamflow and pan evaporation data is short, and the monthly basis of calculation lacks sensitivity to daily fluctuations in the system that are often extreme. In keeping with these data and with the scope of this investigation, a monthly water balance is suitable. The monthly balance tends to increase the estimate of actual evapotranspiration and decrease the estimate of ground-water recharge when compared with daily calculations (Mather, 1978). For the purpose of locating sites for ground-water exploration, it is desirable to use a method that will yield a conservative estimate of ground-water recharge. With these precautions in mind, the estimates of ground-water recharge determined in the water-balance calculations are used to indicate areas that appear to be most favorable for ground-water development.

Nonperennial Stream Basins

Water budgets were calculated for the Peemgoey, Qatliw, Qaringeel, Burong, and Daloelaeb Stream basins. All the basins are underlain by rocks of the Yap Formation having low permeability; consequently ground water does not contribute significantly to streamflow. Streamflow in the basins occurs during periods of precipitation and lasts for only short periods of time thereafter. To calculate the water balance, the following parameters had to be determined: 1) the area of the drainage basin above the gage site, 2) the average effective rooting depth and available water capacity of the basin, and 3) the maximum soil storage.

First, the outline of the contributing area above the stream gaging site was traced on the soil map of the basin prepared by the Soil Conservation Service (Smith, 1983). The soil types within the basin were outlined, and each soil type's effective rooting depth and available water capacity were determined from tables prepared by the Soil Conservation Service (Smith, 1983). The proportional areas within the basin covered by each soil type, and the rooting depths and available water capacities of the soil types were averaged to determine an average effective rooting depth and available water capacity for the basin.

The rooting depth multiplied by the available water capacity (the difference between the quantity of soil water at field capacity and at the wilting point) yields the maximum soil storage. This maximum soil-storage value must be known, because AE (actual evapotranspiration) is subtracted from this storage. Generally, AE (the amount of water evaporated from soil and plant surfaces, and transpired by plants) is limited by the amount of water in soil storage. Depending on the amount of water in soil storage, the actual evapotranspiration rate sometimes equals the maximum (potential) rate, and when the amount in soil storage decreases, the actual rate of evapotranspiration decreases to below the potential rate. The pan evaporation data (table 8) are equated to PE, the potential, or maximum evapotranspiration rate as the pan coefficient is assumed to be 1.0 in humid areas where strong, positive advection is not common (Dr. Paul C. Ekern, Hydrologist, University of Hawaii, oral communication, 1987). It is recognized that AE sometimes exceeds pan evaporation for vegetation at the mature stage of growth (Chang, 1968), that is a pan coefficient greater than 1.0. However, there are data that show pan coefficients of less than 1.0 for crops at a mature stage of growth. Without data from native vegetation in Yap, a pan coefficient of 1.0 is a reasonable assumption.

After the maximum soil storage for the basin is determined, the water balance can be calculated. First, net precipitation (rainfall - runoff) is compared with potential evapotranspiration (PE). If the net precipitation is greater than, or equals PE, then actual evapotranspiration (AE) equals PE and this quantity is subtracted from net precipitation. If there is a remainder, it goes into soil storage. If the quantity in soil storage is greater than the maximum soil storage quantity, the excess recharges the ground-water body. If the quantity in storage is less than the maximum soil storage quantity, there is no recharge to ground water. Any quantity remaining in soil storage is carried over into the next month. If the quantity of net precipitation plus any soil storage carried over from the previous month is less than PE, then AE equals this quantity, and nothing is contributed to soil storage.

Water balances calculated for Peemgoey, Qatliw, Qaringeel, Burong, and Daloelaeb Stream basins are shown in tables 10 to 14. Calculated rates of annual recharge ranged from less than 1 percent of rainfall in Qaringeel basin to 11 percent in Qatliw basin. Calculated recharge rates were generally between 1 to 5 percent of rainfall for all basins except Qatliw, which for three years of available data, the average was nearly 8 percent. All of these recharge rates are low, because of the low permeability of the rock underlying the basins, and because of the rapid runoff that is generally characteristic of the soils in the basins. The average runoff/rainfall ratio in these basins combined is 50 percent. Therefore, the possibility of large ground-water supplies in the five basins is not indicated by these data. Figure 20 indicates the mean annual recharge calculated for each of the stream basins.

Table 10. Water balance in Peemgoey Stream basin

[AE = actual evaporatranspiration; Mgal/d = million gallons per day]

Year	Rainfall (inches)	Runoff (inches)	AE (inches)	Recharge (inches, Mgal/d)	Recharge/ Rainfall (percent)
1979	124.49	58.19	62.25	4.00, 0.03	3
1980	120.35	53.02	60.89	4.25, 0.03	3.5
1981	127.24	67.57	55.63	4.27, 0.03	3
3-yr mean	124.03	59.59	59.59	4.17, 0.03	3

Table 11. Water balance in Qatliw Stream basin

[AE = actual evaporatranspiration; Mgal/d = million gallons per day]

Year	Rainfall (inches)	Runoff (inches)	AE (inches)	Recharge (inches, Mgal/d)	Recharge/ Rainfall (percent)
1982	135.03	67.00	64.12	3.91, 0.06	3
1983	88.84	32.71	46.25	9.88, 0.15	11
1984	101.27	44.74	47.10	9.43, 0.14	9
3-yr mean	108.38	48.15	52.49	7.74, 0.12	7

Table 12. Water balance in Qaringeel Stream basin

[AE = actual evaporatranspiration; Mgal/d = million gallons per day]

Year	Rainfall (inches)	Runoff (inches)	AE (inches)	Recharge (inches, Mgal/d)	Recharge/ Rainfall (percent)
1979	124.49	60.62	60.61	3.26, 0.04	3
1980	120.35	62.10	54.03	2.05, 0.02	2
1981	127.24	72.48	53.83	2.61, 0.03	2
1982	135.03	68.72	66.30	0.50, 0.01	0.4
1983	88.84	46.09	41.88	0.48, 0.01	0.5
1984	101.27	49.40	46.64	5.62, 0.06	6
6-yr mean	116.20	59.90	53.88	2.42, 0.03	2

Table 13. Water balance in Burong Stream basin

[AE = actual evaporatranspiration; Mgal/d = million gallons per day]

Year	Rainfall (inches)	Runoff (inches)	AE (inches)	Recharge (inches, Mgal/d)	Recharge/ Rainfall (percent)
1979	124.49	57.32	61.00	6.17, 0.07	5
1980	120.35	54.14	60.15	3.88, 0.04	3
1981	127.24	66.15	56.04	5.75, 0.06	5
1982	135.03	73.86	61.33	2.38, 0.03	2
1983	88.84	34.32	46.41	5.36, 0.06	6
1984	101.27	40.99	50.70	9.51, 0.10	9
6-yr mean	116.20	54.46	55.94	5.51, 0.06	5

Table 14. Water balance in Daloelaeb Stream basin

[AE = actual evaporatranspiration; Mgal/d = million gallons per day]

Year	Rainfall (inches)	Runoff (inches)	AE (inches)	Recharge (inches, Mgal/d)	Recharge/ Rainfall (percent)
1979	124.49	67.84	53.40	3.25, 0.01	3
1980	120.35	65.69	49.93	0.97, 0.003	1
1981	127.24	80.60	46.23	1.48, 0.005	1
3-yr mean	124.03	71.38	49.85	1.90, 0.006	1.5

Perennial Stream Basins

Water balances were calculated for Mukong and Eyeb Stream basins, which are underlain by fairly permeable rocks of the Tomil Volcanics. Perennial streamflow in these basins reflects the greater permeability of the volcanics as compared with the Yap Formation. Part of the streamflow is supplied by ground-water discharge at places where the stream channel intersects the water table. This part of the streamflow is called baseflow and was calculated for both the Mukong and Eyeb Streams using graphic streamflow charts of daily discharge and baseflow-separation techniques described by Chow (1964).

The water budgets for these basins were calculated in a manner similar to that used for the nonperennial basins. The only difference was that baseflow, that part of streamflow contributed by ground-water discharge to the stream, was subtracted from streamflow to obtain runoff before following the procedure outlined for nonperennial streams. Tables 15 and 16 show the results of the water-balance calculations for Mukong and Eyeb Streams.

Table 15. Water balance in Mukong Stream basin

[AE = actual evaporatranspiration; Mgal/d = million gallons per day]

Year	Rainfall (inches)	Runoff (inches)	AE (inches)	Recharge (inches, Mgal/d)	Baseflow (inches, Mgal/d)	Recharge/ Rainfall (percent)	Baseflow/ Rainfall (percent)
1981	127.24	24.91	65.38	36.95, .88	29.68, .71	29	23
1982	135.03	47.99	76.42	12.60, .30	31.62, .75	9	23
1983	88.84	9.48	52.47	25.97, .62	23.53, .56	29	26
1984	101.27	16.95	65.12	20.03, .48	33.16, .79	20	33
1985	133.49	23.30	71.05	37.25, .89	40.17, .96	28	30
5-yr. mean	117.17	24.53	66.09	26.56, .63	31.63, .75	23	27

Table 16. Water balance in Eyeb Stream basin

[AE = actual evaporatranspiration; Mgal/d = million gallons per day]

Year	Rainfall (inches)	Runoff (inches)	AE (inches)	Recharge (inches, Mgal/d)	Baseflow (inches, Mgal/d)	Recharge/ Rainfall (percent)	Baseflow/ Rainfall (percent)
1982	135.03	56.34	68.53	9.25, .14	42.49, .65	7	31
1983	88.84	17.50	51.13	17.45, .27	28.49, .43	20	32
1984	101.27	28.45	61.21	12.82, .19	44.14, .67	13	44
1985	133.49	41.12	70.42	15.16, .23	58.84, .90	11	44
4-yr. mean	114.66	35.85	62.82	13.67, .21	43.49, .66	12	38

Included in these tables are the calculated amounts of baseflow that indicate the minimum ground water discharging from the system. Because the long-term flow out of the ground-water system cannot be higher than the flow into the system, the baseflow values also represent the minimum recharge in the basins. The baseflow, or minimum recharge was measured directly from the streamflow hydrographs, using a baseflow separation technique (Linsley and others, 1958). A straight line is drawn from the point of rise in the hydrograph to a point on the recession segment located at ($Area^{0.2}$) days after the time of peak flow. Drainage area is in units of square miles. The area under this line represents the baseflow part of the measured streamflow and the area above this line represents storm runoff. For long periods during the dry season, there are no peaks in the hydrographs and it is clear that the streamflow is being sustained by ground-water contributions.

A possible source of error in computing recharge from this direct method might be the accuracy of the stream rating table which relates stream gage height to stream discharge. However, the stream ratings are generally well defined at low gage heights.

Because the recharge values are expected to be higher than the baseflow values in tables 15 and 16, additional explanations for the results might be considered. In computing recharge from the water balance, there are several sources of error owing to the uncertainties in estimating average basin rooting depths, available water capacities, maximum soil storage values, and in the assumption that rainfall is distributed homogeneously over the islands. Additionally, monthly water balances tend to underestimate recharge (Mather, 1978), and this may explain why the calculated recharge is less than baseflow. Also, it is possible that some ground water supplying the baseflow may come from outside the basin boundary used in the calculations. That is, topographic boundaries may not coincide with ground-water flow boundaries. In 1981 and 1983, the calculated recharge in the Mukong basin was greater than the baseflow, indicating there is validity in the use of the water-balance calculation with short-term data, and the calculation is a useful analytical approach. Considering the potential errors in recharge estimates using the water-balance calculations, the baseflow values are considered to be more representative of the ground-water recharge in the basins, and more reliable as estimates of minimum ground-water flow through the basins. The baseflow values for Eyeb and Mukong basins are shown as the mean annual recharge in figure 20.

A good indication of the minimum baseflow, or ground-water flow that may be available for development in the Mukong Stream basin, is the baseflow of 0.56 Mgal/d in the drought year of 1983. The probability is about 3 percent that less than the 1983 drought rainfall may occur in any given year. Recognizing baseflow is a function of rainfall, the 1983 baseflow can be considered near the potential minimum. In a high rainfall year such as 1985, the calculated baseflow nearly doubled to 0.96 Mgal/d. The 5-year average baseflow is 0.75 Mgal/d or 27 percent of the 5-year mean rainfall. A statistical probability analysis that would generate the probability that a given annual baseflow amount would occur is not possible from the short term of streamflow record.

The 4-year average baseflow for Eyeb basin is 0.66 Mgal/d. A minimum baseflow value is 0.43 Mgal/d in the 1983 drought year, and a maximum value is 0.90 Mgal/d in 1985, a high rainfall year. The 4-year average baseflow/rainfall ratio is 38 percent. These values are estimates of the quantity of ground-water flowing through the Eyeb basin and possibly available for development. Because 1983 was such a low-rainfall year, the 0.43 Mgal/d baseflow value is considered a good estimate of the minimum ground-water flow through this basin.

For Eyeb basin there is a larger discrepancy between the average recharge, 0.21 Mgal/d, and baseflow of 0.66 Mgal/d that can be attributed to the same reasons stated in the discussion of the Mukong basin. Additionally, the larger discrepancy may exist, because part of the Eyeb Stream basin is underlain by the less-permeable rock of the Yap Formation, which could explain the lower ground-water recharge value and the consistently higher runoff/rainfall ratio as compared with the Mukong basin. It is also possible that the Eyeb Stream rating curve is not as well defined as the Mukong's, and that the high-stage end of the Eyeb Stream rating curve is not accurately defined. Thus, there could be erroneously high runoff values that would affect the water balance calculations by reducing the net precipitation, and therefore, recharge values.

In both the Mukong and Eyeb Stream basins, the recharge values calculated from the water balance, and baseflow values measured from the hydrographs, establish a range of the amount of ground water that is flowing through these basins. Because the calculated ground-water recharge did not consistently exceed the baseflow values in the Mukong basin, and never exceeded the baseflow values in the Eyeb basin, and because the baseflow values are determined more directly, and are thus, less subject to error, the baseflow values are considered to be more reliable estimates of the minimum ground water flowing through these basins. Because of the heterogeneity in distribution of porosity and permeability in the subsurface geology, firm estimates of the amount of water that can be practically developed by wells cannot be stated without subsurface exploration.

GROUND-WATER EXPLORATION PROGRAM

Proposed Exploratory Drilling and Aquifer Testing

The primary purpose of a proposed ground-water exploration program is to locate additional sources of water to supplement the Colonia Water System. To meet the demand for freshwater in the less populated, outlying villages, several exploratory drill sites have been located along the east and west coasts of Yap island, and the east coast of Maap island. A priority list of well sites to be drilled will be formulated by the Yap State government. Figure 21 shows the general areas of the proposed exploratory drilling sites. Table 17 is a list of proposed exploratory drilling sites. The following discusses each area in detail.

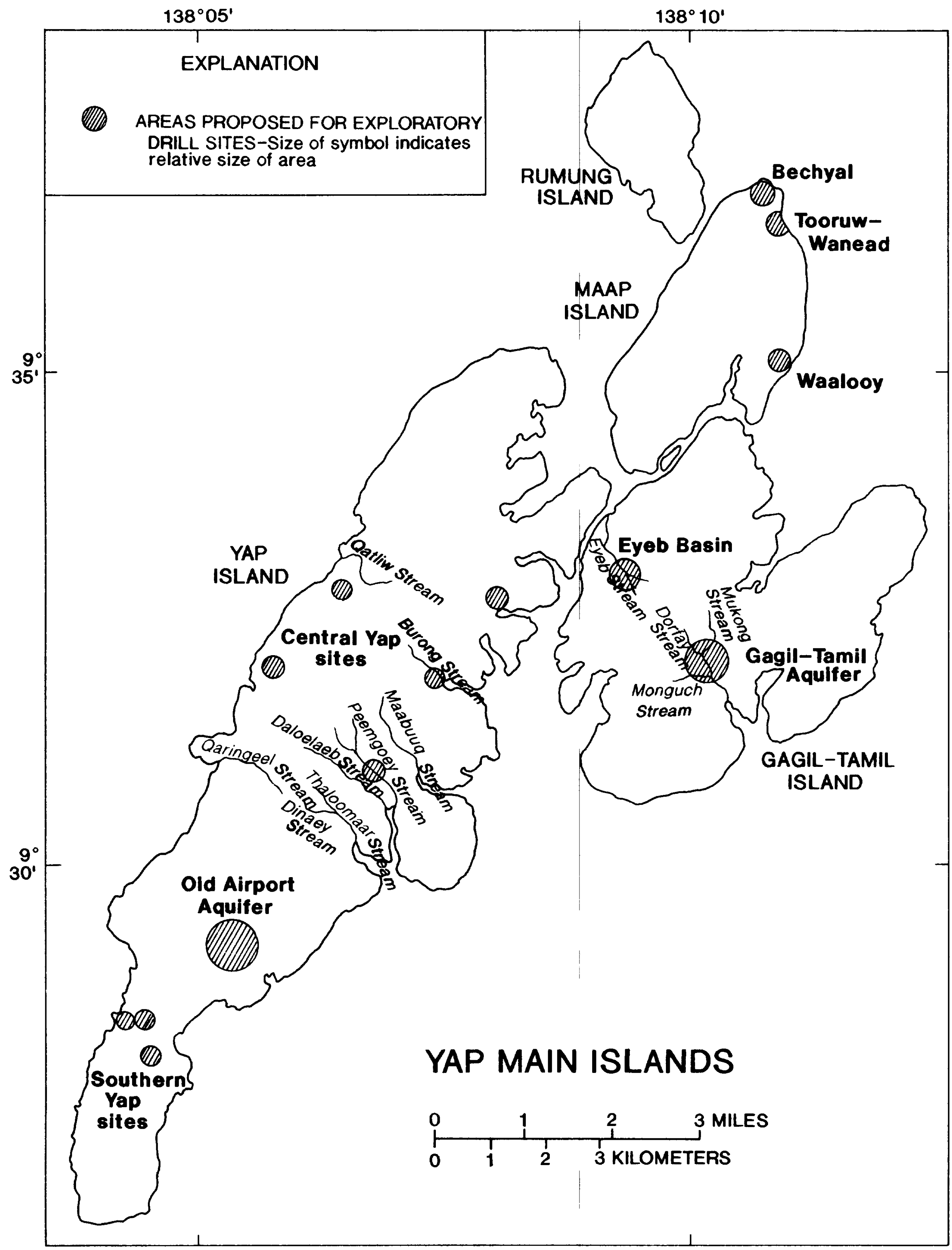

Figure 21. Proposed exploratory drill sites.

Table 17. List of proposed exploratory drilling sites

Area	Number of drill sites	Depth (feet)	Geologic Formation
Old airport aquifer, Yap	5	100	Tomil Volcanics
Southern plateau, Yap	3	100	Tomil Volcanics
Eyeb Stream basin, Gagil-Tamil	2	100	Tomil Volcanics
Gagil-Tamil aquifer, Gagil-Tamil	2	150	Tomil Volcanics
Central Yap	5	100	Yap Formation
	1	150-200	Yap Formation
Bechyal, Maap	5	50	Coastal Deposits
Tooruw-Wanead, Maap	5	50	Coastal Deposits
Waalooy, Maap	5	50	Coastal Deposits

The most permeable rocks in the Yap main islands are the Tomil Volcanics. Known reservoirs of ground water in this formation are in the old airport area on Yap and in central Gagil-Tamil. Other areas in which the Tomil Volcanics are likely to contain ground-water reservoirs include the Eyeb Stream basin on Gagil-Tamil island and the southern plateau of Yap island.

Old Airport Aquifer Area

Five sites within the old airport aquifer area have been selected for drilling exploratory holes as a means of determining the extent of the aquifer. These sites, shown in figure 22, are distributed along the perimeter of the existing well field, and are intended to tap ground water that discharges into gulches north, northwest, and south of the well field, and that evaporates from adjacent ponds.

The flow of ground water in the old airport aquifer appears to be radial, away from the pond area and from the summit of the buried mound of schist that is shown by contour lines in figure 13, toward the gulches surrounding it. The mound slopes away from this area so that the thickness of the ground-water reservoir is generally the greatest near the margins of the valleys. The test holes would be drilled near the valley margins to determine the extent of the ground-water reservoir. Additional production wells at test hole sites might be able to capture water that is being lost to the surrounding gulches, and might be able to draw down the water table enough to dry up the ponds in the area and eliminate the losses by evaporation from the ponds. Aquifer tests using the test holes will provide new information on the water-bearing properties of the aquifer and could aid in the design of a more optimal development plan for the ground-water reservoir.

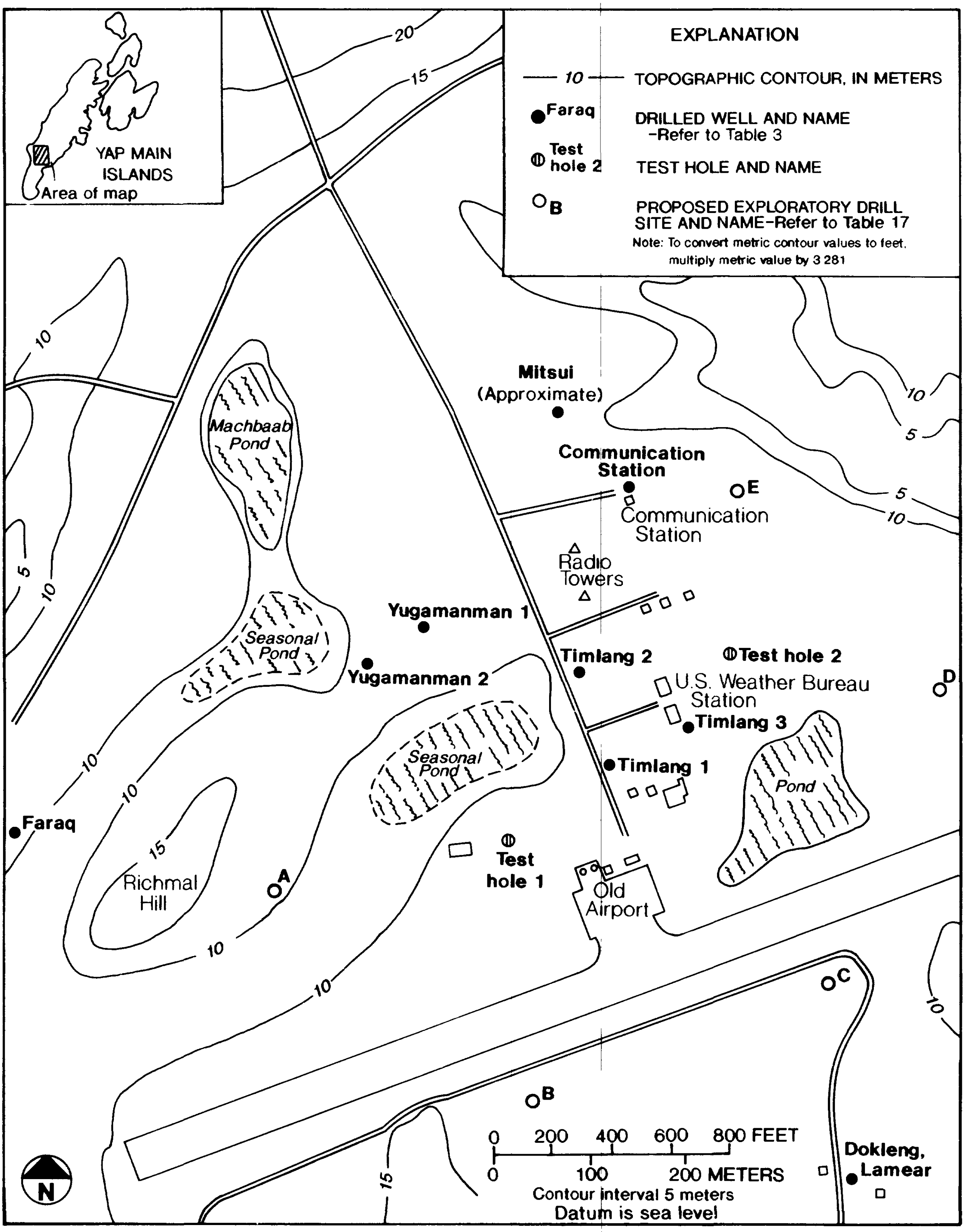

Figure 22. Exploratory drill sites in the old airport aquifer area.

Storage in the aquifer can possibly be regulated profitably by pumping heavily and lowering the water table during dry periods, and by pumping at low rates during rainy periods, thus allowing replenishment of the water removed from storage. With the new wells and appropriate aquifer management, the aquifer yield could be greater than the present combined well yield of 144,000 gal/d estimated by Nance (1982).

Water withdrawn from the old airport aquifer area presently supplies the Southern Yap Water System, which serves villages in southern Yap. If new wells in southern Yap can provide supplies greater than the local demand, water from the old airport aquifer could be available for diversion to the Colonia Water System.

Southern Yap Plateau

Three exploratory drilling sites proposed for the southern plateau of Yap island are shown in figure 23. The sites are along the road extending between Malaay and Ngariy villages where thick sections of weathered Tomil Volcanics are believed to exist.

The geology of the southern plateau is similar to that of the old airport aquifer area: Tomil Volcanics underlain by schist of the Yap Formation. Three 1-inch test borings were drilled in 1979 along the main road, which trends southward from the old airport to Magachgil. The borings revealed 12 to 45 feet of residual soils derived from the Tomil Volcanics underlain by 10 to 15 feet of decomposed schist underlain by unweathered schist (Nance, 1979). On the basis of water-level measurements in relation to rainfall, the yield was estimated to be too low to warrant ground-water development by drilled wells. The ground-water level rise in response to rainfall recharge at the Kanifaay dispensary and Chumeg, Guroor was 20 to 24 feet during a 3-month period of 57 inches of rain, suggesting limited storage in the soil mantle. However, it is important to realize this 3-month rainfall of 57 inches occurred at the end of the dry season and represents nearly half of the average annual rainfall.

Figure 24 is a hydrogeologic section that extends from the southern tip of Yap Island to the old airport area along line C - C' in figure 23. Thick sections of weathered Tomil Volcanics are shown to exist beneath the old airport area and in the vicinity of Gachalaaw. These sections overlie valleys in the bedrock topography. Proposed exploratory drill sites are along the road between Malaay and Ngariy villages, perpendicular to the cross section. These holes will test the water-bearing properties of this thicker formation of weathered Tomil Volcanics. It is possible that new wells at these sites may be able to supply the water needs of the Southern Yap Water System.

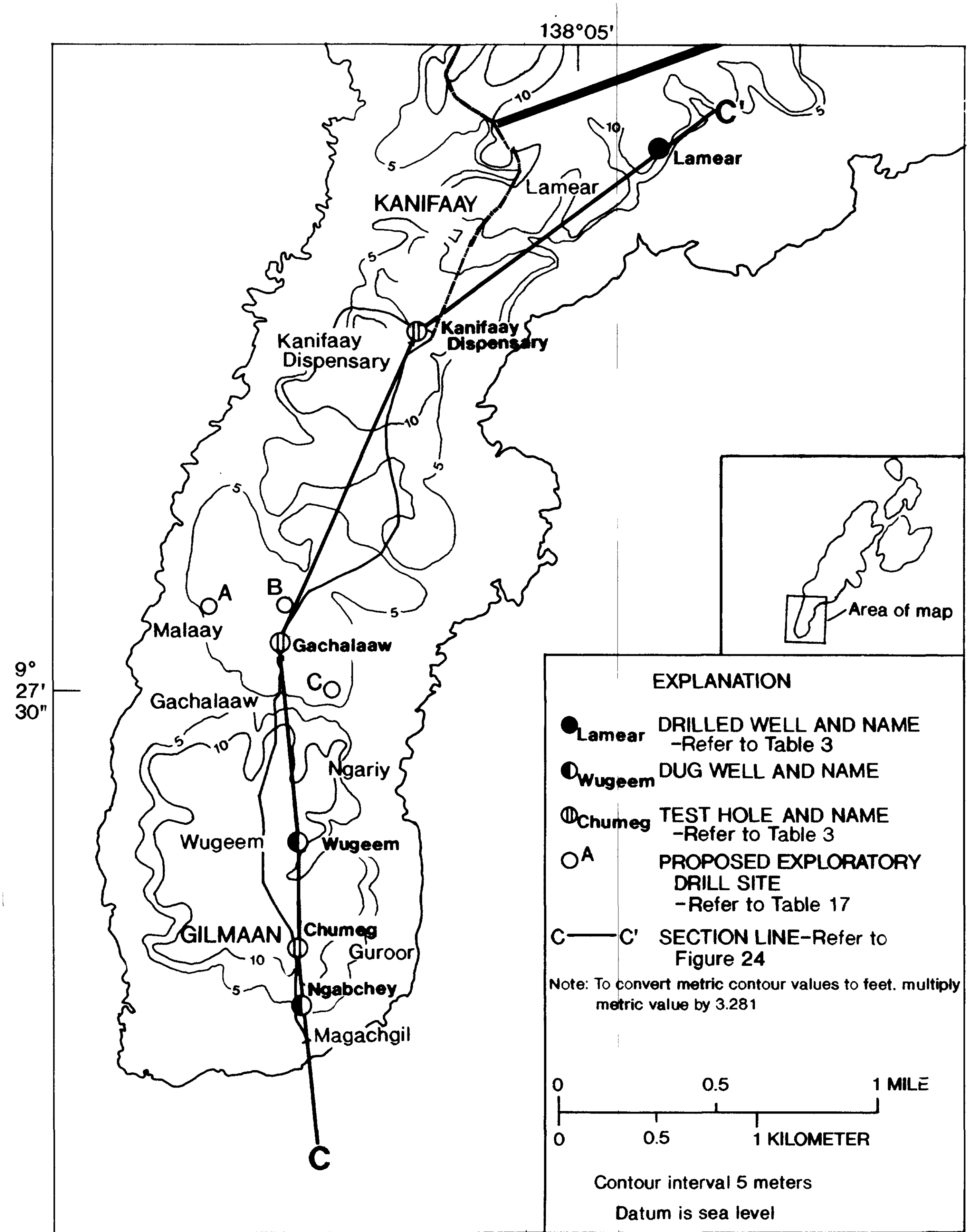

Figure 23. Exploratory drill sites on the southern Yap plateau.

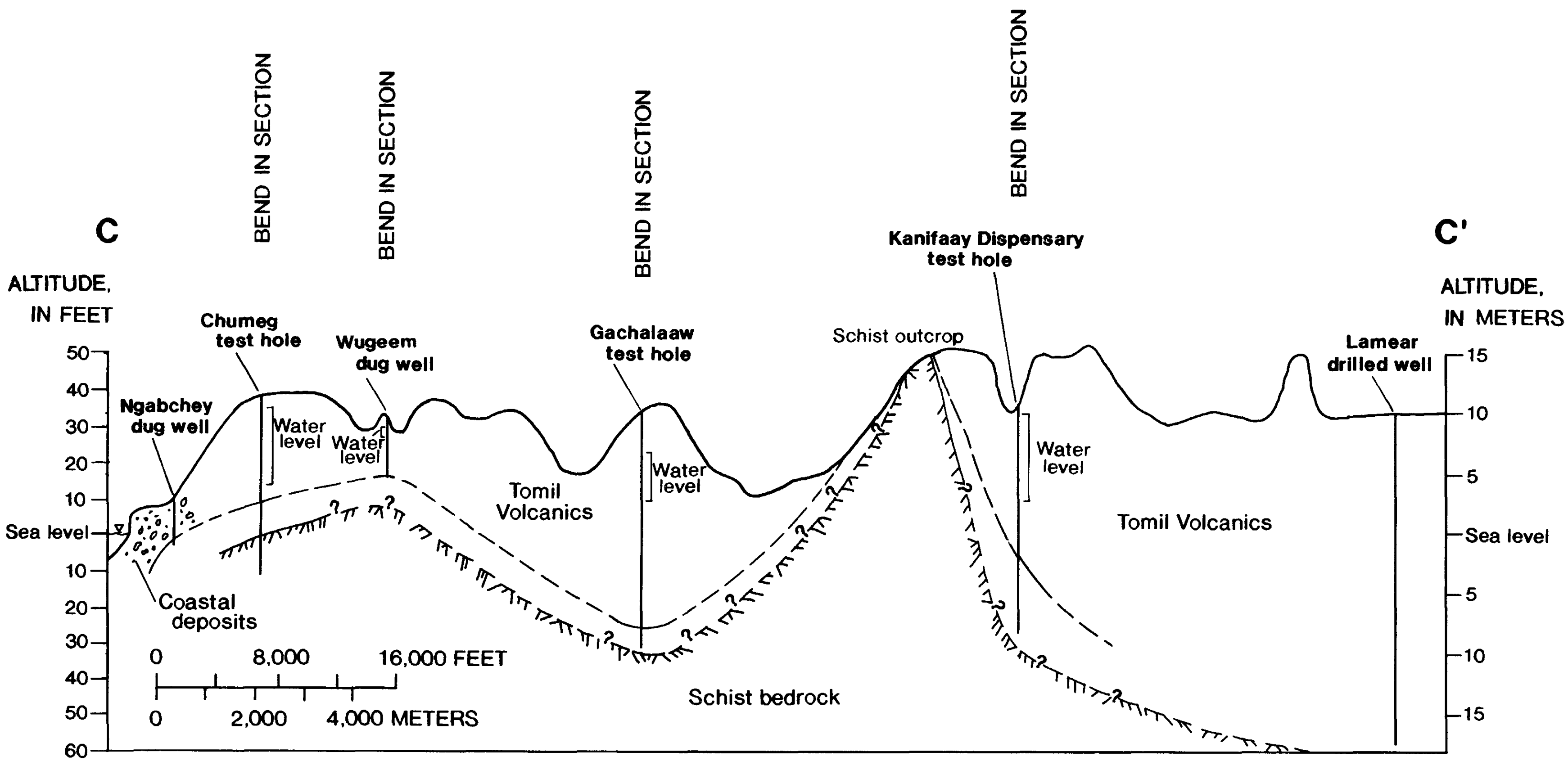

Figure 24. Hydrogeologic section C–C' of the southern Yap plateau.

Eyeb Stream Basin

One of the most promising areas for additional ground-water development is in the Eyeb Stream basin, Gagil-Tamil island. Two exploratory drilling sites are proposed in the gently-sloping area southeast of the U.S. Geological Survey gaging station (fig. 25). Figure 26 is a generalized sketch of the hydrogeologic setting of Eyeb Stream basin.

The drainage area is underlain predominantly by the deeply weathered Tomil Volcanics. The perennial dry-season flow of Eyeb Stream indicates that ground water is discharging into the stream. From the basin water balance presented in table 16, it is estimated that the minimum ground-water flow, or baseflow, is about 0.4 Mgal/d using the 1983 value. A possible consequence of pumping at wells in this area is that the stream, at times, may go dry.

Although the present demand for water in the area is low, the ground-water body or bodies that feed Eyeb Stream should be investigated because water developed in the Eyeb Stream basin in excess of local need could be used to augment supplies in Colonia or the rapidly growing village of Rumuuq, Yap (fig. 11).

Gagil-Tamil Aquifer

Two exploratory drilling sites are proposed in the Gagil-Tamil aquifer area. The sites shown in figure 27 were selected to explore the coral and Dorfay Stream parts of the Gagil-Tamil aquifer.

Site A is located east of the Mukong well and west of Mukong Stream. The well would be drilled to the top of the unweathered schist bedrock or to a depth of 150 feet, whichever is reached first. The well will provide information on the water-bearing properties of the overlying weathered Tomil Volcanics and the 30- to 50-foot thick coral limestone lying beneath the Tomil Volcanics. The limestone may prove to be an important aquifer.

Site B is at an altitude of about 25 feet on the east side of Dorfay Stream. The well would be drilled to the top of the unweathered schist bedrock. The information from this well will help determine the potential yield of wells in the area underlying Dorfay Stream.

Although the present demand for water in Gagil-Tamil is being met, the exploratory holes will help to determine the full potential of the aquifer.

Central Yap

Most of the rocks in the Yap main islands consist of metamorphic rocks of the Yap Formation. In places where the Yap Formation is not exposed at the surface, a thin layer of the Map Formation and/or Tomil Volcanics overlie these basement rocks. Because of its widespread occurrence, there is a need to determine the water-bearing properties of the Yap Formation.

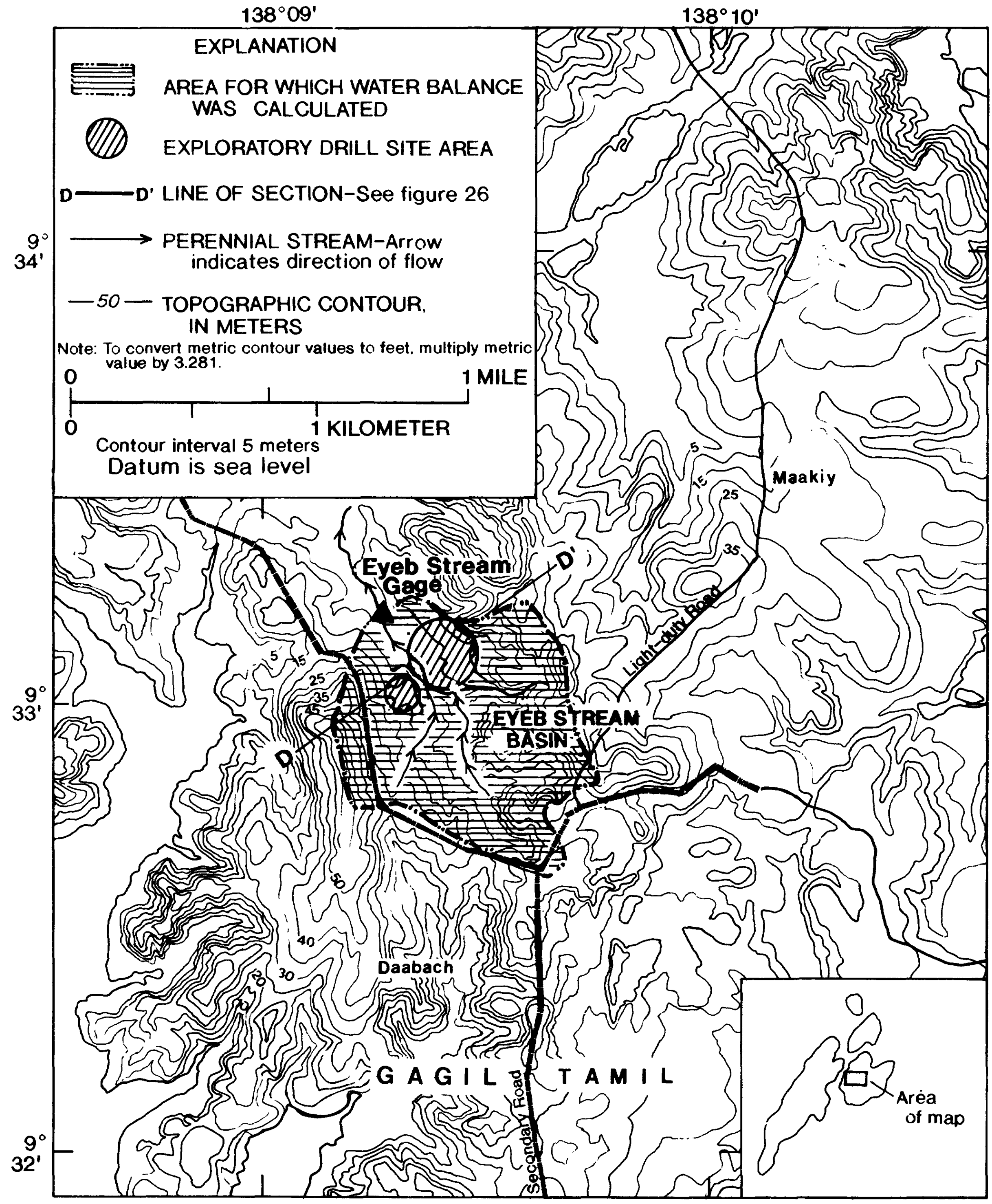

Figure 25. Exploratory drill sites in Eyeb Stream basin.

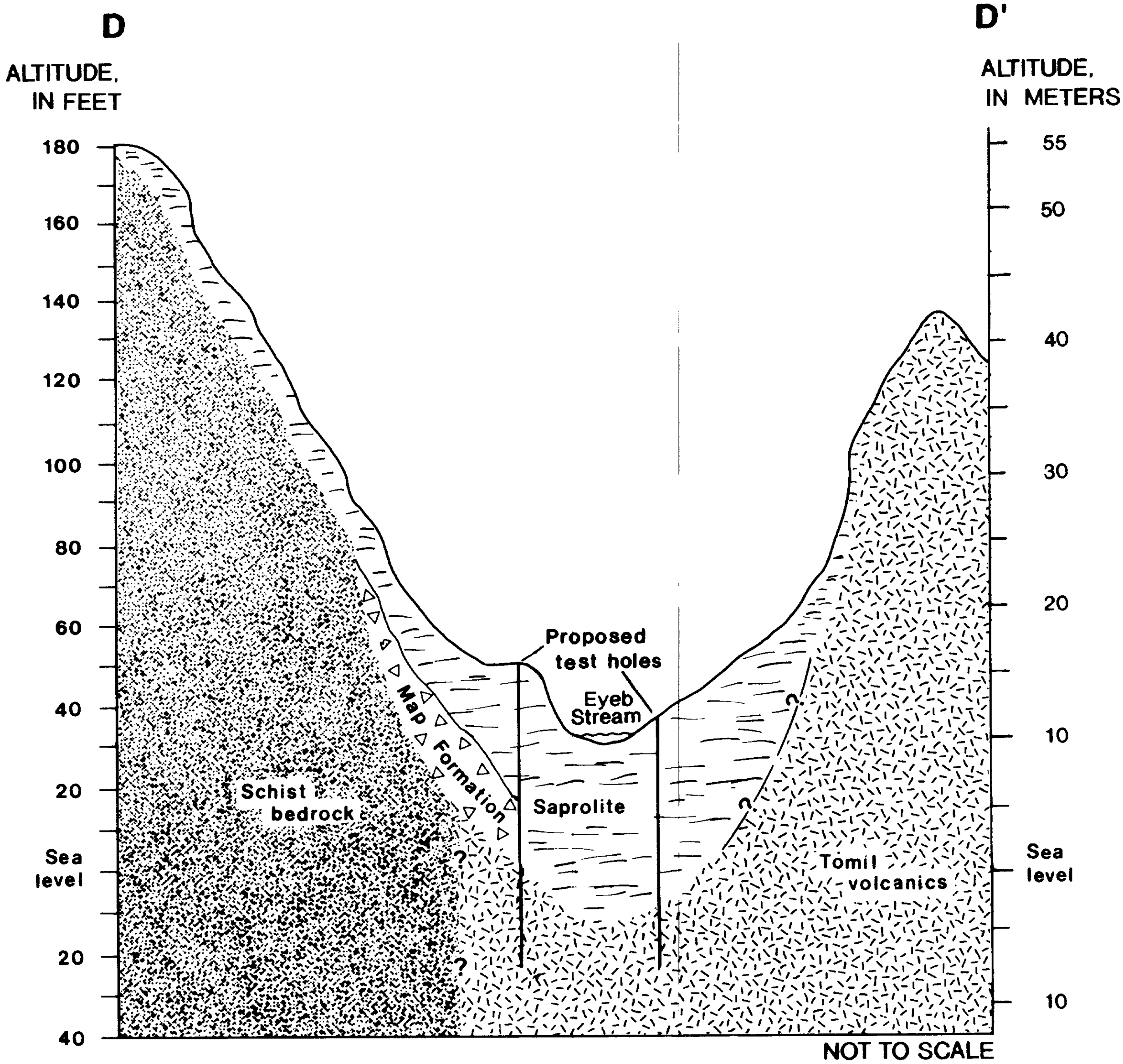

Figure 26. Diagrammatic section of the hydrogeologic setting of Eyeb Stream basin.

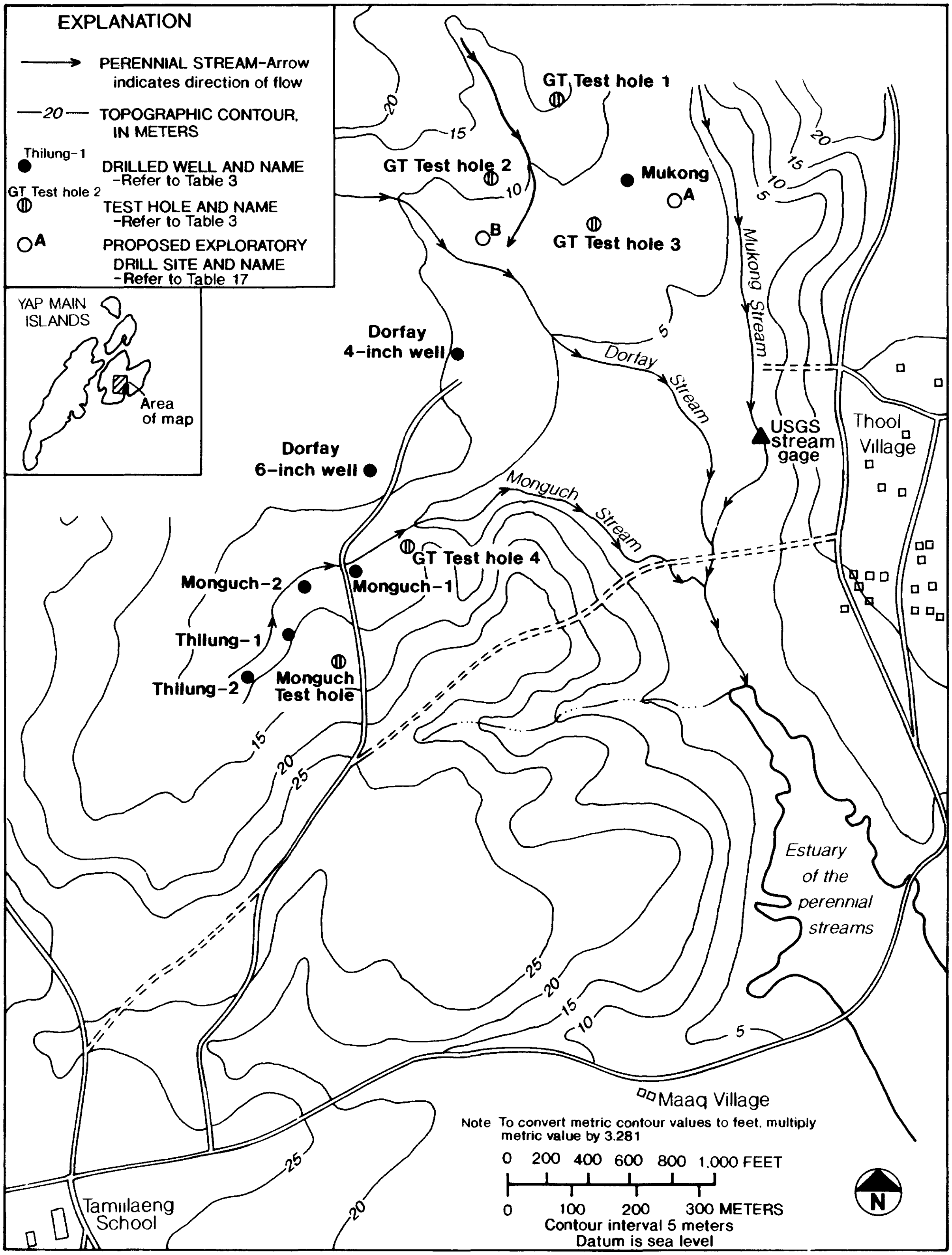

Figure 27. Exploratory drill sites in the Gagil–Tamil aquifer area.

The Yap Formation is mostly massive schist that appears very tight when fresh, and likely to yield very little water to wells drilled in it. There is some increase in the permeability when the rock becomes weathered, and where it is deeply weathered, such as in valleys, it may store developable quantities of ground water. However, because the weathered zones are surrounded by tight unweathered schist, the reservoirs of ground water are probably isolated and small. The water-balance calculations indicate fairly low amounts of ground-water recharge, 1 to 7 percent of rainfall, in basins draining the Yap Formation. Because of the low permeability of the rock, most of the rainfall runs off before it can infiltrate and recharge the ground water.

Because of the concentration of population around Colonia, additional sources of water are needed for the Colonia Water System. The surface-water reservoir at Gitaem supplies the Colonia Water System, and is dependent largely on wet-season rainfall on a small watershed area of 150 acres. The reservoir's storage capacity is not sufficient to meet the system's demand during some dry seasons, as became evident during the drought of 1983 when the reservoir went completely dry. Therefore, exploratory drilling within the Colonia area is proposed.

Three major stream basins, Maabuuq, Peemgoey, and Daloelaeb are found within the vicinity of Colonia. Of these, the Peemgoey Stream basin appears to be the most reasonable area to explore for ground water since Daloelaeb Stream basin has a sanitary landfill in it and drill sites are not easily accessible in the Maabuuq basin.

The proposed exploratory drill site shown on figure 28, is within the Peemgoey Stream basin at an elevation of 30 feet above sea level. A power line road provides easy access to the site. A generalized sketch of the hydrogeologic setting of Peemgoey Stream basin can be found on figure 8. The drill site overlies valley-fill sediments and at some depth, weathered bedrock that grades into unweathered schist bedrock (Yap Formation). A well drilled within this basin will provide needed information on water-bearing properties of the Yap Formation.

On the basis of the water-budget calculations for the area bounded by dashed lines in figure 28, the average annual ground-water recharge to the Peemgoey basin is estimated to be 3 percent of the mean annual rainfall of 120 inches or 3.6 inches integrated over the basin area. This amount converts to about 11 million gallons per year (Mgal/yr) or 30,000 gal/d. It is difficult to predict what part of this recharge can be developed with drilled wells because the hydraulic characteristics of the schist are poorly known.

In 1979, three wells were drilled into the Yap Formation (Nance, 1979) at Magaaf, Qaringeel, and at the Baqel School near Qatliw on the west coast of Yap (figs. 10 and 11). Transmissivities ranged from virtually 0 to 250 gal/d per foot, a low figure, but enough to supply a village-scale water system. Overlying the schist was 10 to 20 feet of soil and decomposed rock. Depths to unweathered schist ranged from 20 to 66 feet. A pattern of highly-fractured

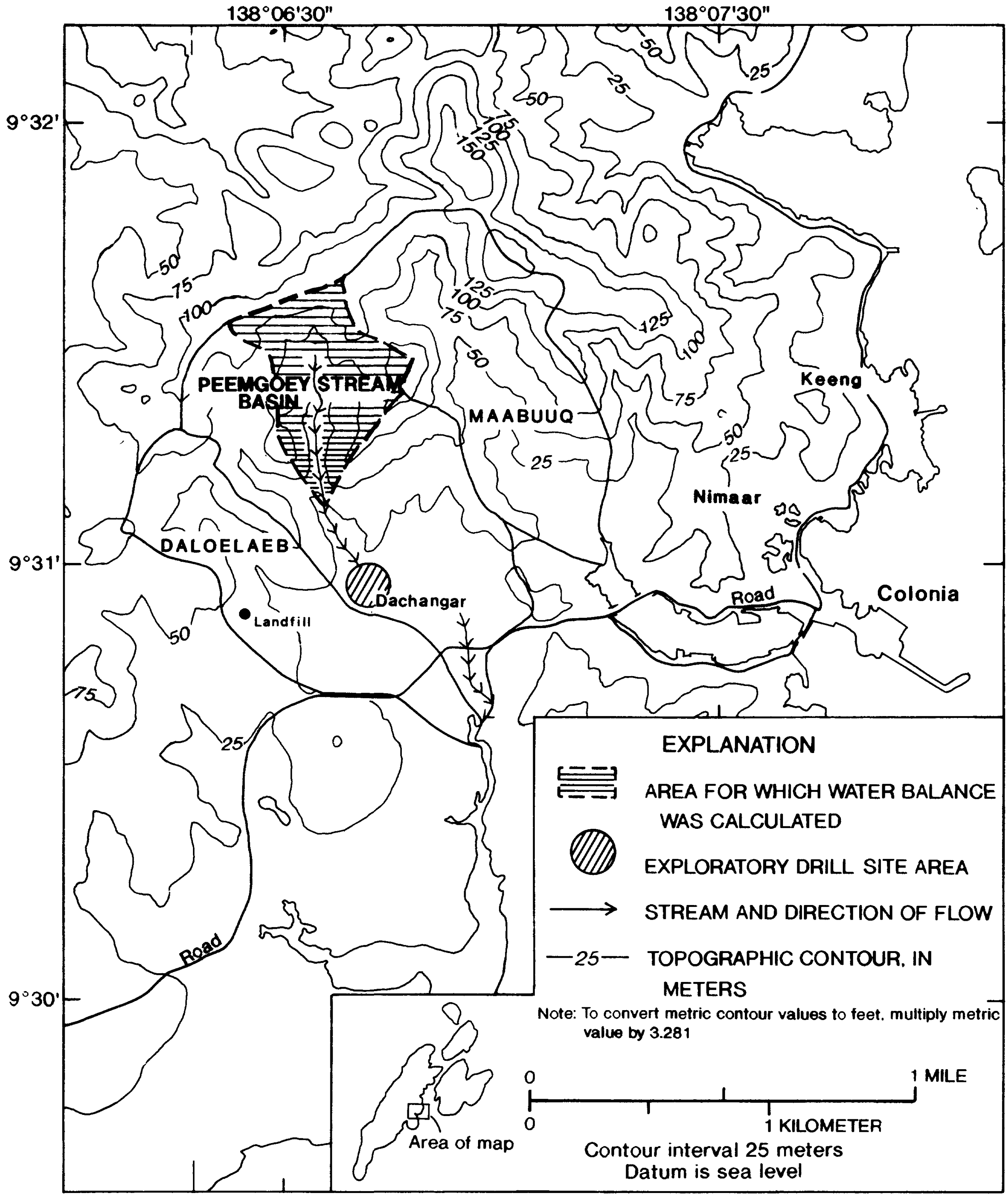

Figure 28. Exploratory drill site in the Colonia area.

layers occurring below less-fractured layers was found at all three sites. The proposed test hole in Peemgoey Stream basin will be drilled to a depth of 150 to 200 feet to provide information on the water-bearing properties of the rocks on the east coast of Yap island.

At present there are no deep wells in the Yap Formation. The proposed 150- to 200-ft hole in Peemgoey Stream basin, pump tested at the base of the alluvium and saprolite, and at the bottom of the hole (unweathered rock), could provide permeability and yield values for the alluvium and saprolite, and the schist bedrock separately. This information will have significant transfer value in other areas underlain by schist bedrock.

Many of the villages in the central part of Yap island are underlain by schist and are in need of an additional water supply to supplement existing small village-scale systems. Four coastal sites for exploratory drilling along the northwest and northeast side of central Yap have been selected and are shown in figure 29. Three of the sites were selected on level ground within stream valleys where road access can be provided. Wells drilled at these sites are likely to yield less than 10 to 15 gal/min. However, a 10 to 15 gal/min well, such as the Magaaf well, may produce enough water to supplement a small village-scale system.

To take advantage of the potential transfer value, the four exploratory drill sites in central Yap would be drilled after the proposed deep hole penetrating the Yap Formation in Peemgoey Stream basin.

Bechyal, Wanead, and Waalooy Coastal Areas

Several areas for exploratory drilling along the northeast coast of Maap island have been selected and are shown in figure 21. Bechyal, Tooruw/Wanead, and Waalooy villages are built on coastal deposits (alluvium, sand) that probably support small bodies of fresh ground-water floating on saltwater. In September 1986, shallow dug wells in Wanead and Waalooy villages yielded ground water containing less than 25 mg/L chloride. On the basis of the factors of high rainfall, estimated evapotranspiration losses, and land area, the prospect of tapping ground water of low chloride concentration with shallow wells is good.

To obtain estimates of the size of the ground-water bodies, it is suggested that a minimum of five well points be installed to depths of about 30 feet in each valley. Chloride samples could be collected as the wells are driven to determine the salinity profile at each site.

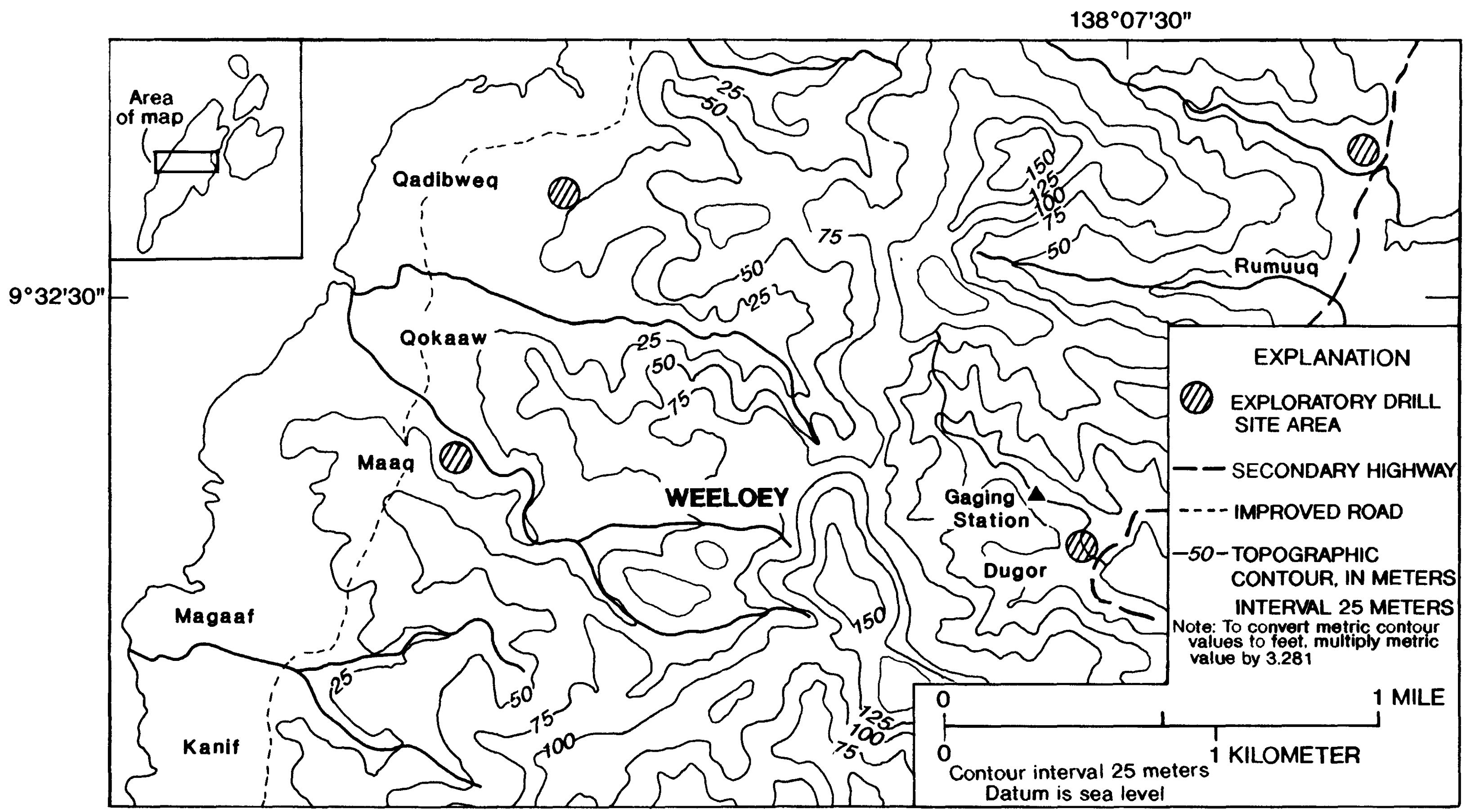

Figure 29. Exploratory drill sites in central Yap.

Hydrologic Monitoring

The following hydrologic monitoring program is currently being undertaken by the U.S. Geological Survey in cooperation with the Yap State government.

Streamflow is being measured at five gaging stations on Qatliw, Qaringeel, Burong, Mukong, and Eyeb Streams. Low-flow measurements are being made at five sites on Dinaey, Thaloomaar, Peemgoey, Monguch, and Dorfay Streams. One water-quality sample per year is taken at the Eyeb and Mukong Stream gaging station sites.

Ground-water data are collected at several sites. Continuous water-level records are collected at Dorfay and Timlang-2 wells. Miscellaneous water-level measurements are made at 10 wells: Yugamanman-1, Yugamanman-2, Timlang-1, Timlang-3, Communication station well-2, Monguch-1, Monguch-2, Thilung-1, Thilung-2, and the Mukong well. Water-quality samples are collected from Yugamanman-1, Yugamanman-2, Timlang-2, Mukong, Monguch-1, Monguch-2, and Thilung-2.

Rainfall data are being collected at two sites. Continuous rainfall measurements are made at the U.S. Geological Survey gage at the old U.S. Coast Guard Loran station, and at the U.S. Weather Bureau gage at the old airport.

SUMMARY AND CONCLUSIONS

A ground-water exploration program has been proposed to help alleviate the water shortages that occur every year on the four Yap main islands. It is of primary importance to locate additional sources of water to supplement the Colonia Water System. New sources of ground water could be located and possibly developed by drilling wells along the southern Yap plateau, located south of the old airport, and in the Mukong and Eyeb Stream basins on Gagil-Tamil. These areas overlie a volcanic formation that is currently being developed by wells elsewhere on the islands. Water developed from these new sources could be used to augment the supplies for the centralized Colonia, Southern Yap, and Gagil-Tamil Water Systems, and allow these systems to expand to service more villages.

The Colonia area is underlain by schist, a massive rock that is likely to yield little water to wells. Exploration for ground water in the Colonia area will accomplish two objectives. The first objective is to locate additional sources of water to supplement the Colonia Water System. The second objective is to provide information on the water-bearing properties of the schist. Schist is present throughout the main islands, and the transfer value of such information could be important for the development of future water supplies.

Shallow wells in coastal alluvial deposits are planned for villages along the northeast coast of Maap island. These wells will supplement village water systems currently supplied by rain catchment and/or small springs, and might provide enough water for a small tourist development in the remote areas of the Yap main islands.

This study has provided information that will be useful to a planned program of water-system improvements and ground-water exploration to accomplish the Yap State government's goal of supplying the four main islands with a 24-hour per day water system in the populated areas, and improving village-scale water systems in remote areas. With a mean annual rainfall of more than 120 inches, increasing rain-catchment areas and storage volumes could improve water supplies in outlying villages. Ground-water exploration is integral to this endeavor, and the proposed exploratory drilling sites could provide information on potential new areas for ground-water development as well as sources of additional and useful geohydrologic data.

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