ST/ESA/121

Natural Resources/Water Series No. 12

GROUND WATER IN THE PACIFIC REGION

United Nations

ST/ESA/121

Department of Technical Co-operation for Development

Natural Resources/Water Series No. 12

GROUND WATER IN THE PACIFIC REGION

United Nations
New York, 1983

NOTE

Symbols of United Nations documents are composed of capital letters combined with figures. Mention of such a symbol indicates a reference to a United Nations document.

ST/ESA/121

UNITED NATIONS PUBLICATION

Sales No. E.83.II.A.12

03800

FOREWORD

The Economic and Social Council, by resolution 675 (XXV) of 2 May 1958, requested the Secretary-General to take appropriate measures for the establishment, within the Secretariat, of a centre to promote co-ordinated efforts for the development of water resources. It also singled out ground-water problems as one of the priority subjects in the development of a programme of studies, which was initiated in 1960 with the publication of Large-scale Ground Water Development. 1/ By resolution 1761 B (LIV) of 18 May 1973, the Economic and Social Council requested the Secretary-General to take the necessary measures, within the budgetary limitations, to improve and strengthen the existing United Nations services for the analysis, evaluation and dissemination of world-wide data on natural resources, including water resources.

As regards ground water, a first comprehensive review of the African continent was published in 1972 and 1973 under the title Ground Water in Africa 2/ as a synthesis of material available in the records and files of the United Nations. The material of the second and third volumes in this series, Ground Water in the Western Hemisphere 3/ and Ground Water in the Eastern Mediterranean and Western Asia, 4/ was drawn from country papers which were prepared by hydrogeologists and by ground-water engineering specialists of the countries concerned. Due to the abundance of interesting and specialized information obtained on a country basis and to the necessarily limited format of the publications, it was not possible - nor was it appropriate - to present a broad overview of the occurrence and development of ground water in those two regions, as was the case with part I of Ground Water in Africa.

As regards the Pacific region, which includes exclusively island countries and a country - Australia - which in itself is a continent, such an overview appears even less possible and less appropriate. However, in the introduction which follows, the general features of the area in terms of geological and physiographical structure, and climate, with special attention given to the smaller islands of various types: atolls, raised atolls and high-rise islands, have been briefly described.

It is hoped that this publication, the first to provide a comprehensive view of the ground-water resources of the Pacific region, will contribute to their development and conservation, especially in the smaller island countries which are experiencing increasing difficulties in making adequate water supplies available to their populations, and that, to some extent, it will serve the purposes of the International Drinking Water Supply and Sanitation Decade, which was launched by the Secretary-General of the United Nations on 10 November 1980.

The United Nations wishes to acknowledge the valuable contributions made to this publication by such government organizations as the Australian Water Resources Council; the Mineral Resources Department of Fiji; the Bureau de Recherches Géologiques et Minières (France); the Institute of Hydraulic Engineering of the Ministry of Public Works of Indonesia; the Directorate of Environmental Geology of the Directorate General of Mines of Indonesia; the Geological Survey of Japan; the Geological Survey of New Zealand; the Department of Minerals and Energy of Papua New Guinea; the Natural Resources Council of the Philippines; the Ministry of Natural Resources of Solomon Islands; the United States Geological Survey; and the Water Resources Research Center of the University of Hawaii. The United Nations also wishes to acknowledge the valuable contributions of the consultants and specialists who prepared country papers, in particular, Professor J. Avias, Mr. M. C. Baekisapa, Mr. C. Brands, Mr. J. H. Carter, Dr. J. Coudray, Dr. I. N. Gale, Mr. P. Ihnen, Mr. D. Kammer, Dr. D. Kear, Dr. L. S. Lau, Mr. J. F. Mink, Dr. T. Murashita, Dr. B. Soenarto, Mr. R. Villot, Dr. W. Wagner and Dr. D. Wilson. The final draft was reviewed by Dr. L. S. Lau, Director of the Water Resources Research Center of the University of Hawaii.

Notes

1/ United Nations publication, Sales No. 60.II.B.3.

2/ United Nations publication, Sales No. E.71.II.A.16.

3/ United Nations publication, Sales No. E.76.II.A.5.

4/ United Nations publication, Sales No. E.82.II.A.8.

CONTENTS

CONTENTS (continued)

List of tables

CONTENTS (continued)

List of figures

List of maps

CONTENTS (continued)

CONTENTS (continued)

Explanatory notes

The following symbols have been used in the tables throughout the report:

Three dots (...) indicate that data are not available or are not separately reported.

A blank indicates that the item is not applicable.

A full stop (.) is used to indicate decimals.

Use of a hyphen (-) between dates representing years, e.g., 1975-1978, signifies the full period involved, including the beginning and end years.

Reference to "dollars" ($) indicates United States dollars.

Details and percentages in tables do not necessarily add to totals because of rounding.

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The term "country" as used in the text of this report also refers, as appropriate, to territories or areas.

INTRODUCTION

The Pacific Ocean, so named by Magellan, is the largest and deepest body of water in the world. It extends from north to south over a distance of about 13,000 km from the Bering Straits - the gate of the Arctic Ocean - to the Southern Ocean, the conventional limit of which is considered to be parallel 40° S. The maximum breadth, from east to west, between the western shores of the western hemisphere and the shores of insular Asia, is about 15,000 km (see map 1).

The Pacific Ocean covers an area of about 160 million km^2, that is, more than the total land surface of the world, and contains more than 30,000 islands, most of which are located south of the equator.

The main geographical units are the continent of Australia, the largest island in the world; the island of New Guinea; the large islands that compose the following four countries: Japan, the Philippines, Indonesia (the fifth most populated country in the world) and New Zealand; and the summits of a number of volcanic submarine ridges and plateaux, which emerge in the form of high-rise islands, mostly of volcanic rock, and low-rise islands, which are mainly of coralline limestone. Most of the ridges have a general north-west/south-east direction (Midway-Hawaii; Marshall-Kiribati-Tuvalu; Solomon Islands-Vanuatu; Cook Islands-Austral Island; Line Island-Tuamotu).

Regarding geological conditions, the following group divisions may, by and large, be made:

(a) The Austral continent: Australia, where practically all geological periods are represented by sedimentary formations;

(b) Japan, the Philippines and New Zealand, where most of the geological periods are represented by sedimentary rocks, but where volcanics are also substantially represented, as well as Neogene-Quaternary formations;

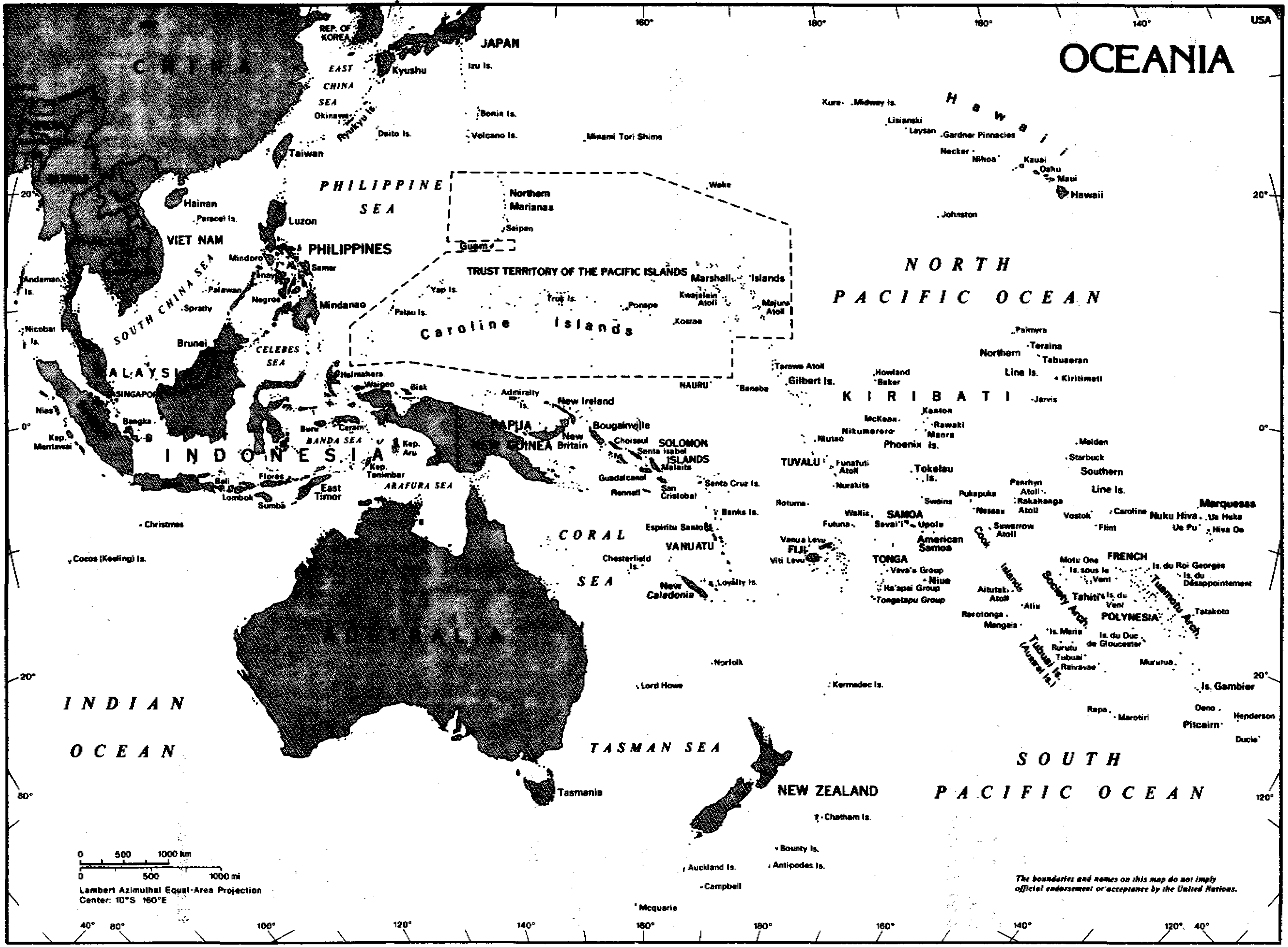
(c) Large islands in Indonesia and the island of New Guinea, where volcanics and sedimentary rocks (limestone, sandstone and marl) mainly of Cenozoic-Quaternary, largely prevail;

(d) Small islands, for example, in Hawaii, Fiji, Micronesia and French Polynesia, where Cenozoic-Quaternary volcanics are overwhelmingly present, as well as coralline limestone and debris;

(e) Coralline atolls: Micronesia, Kiribati, Tuvalu, the Tuamotu archipelago and the outer Cook Islands.

An atoll is normally composed of a ring of coralline reefs surrounding a shallow water lagoon. The soil elevation of the islands or islets above mean sea level is in the range of 2-5 m. Some atolls have risen to a few tens of metres in height, with the result that the lagoon area has emerged and the overall structure presents itself as a solid limestone island with a depressed central area and a coastal ridge.

MAP 1



MAP NO. 3098 Rev. 2 UNITED NATIONS
DECEMBER 1982

[Map 1. Oceania]

As far as hydrogeological conditions are concerned, except in the case of the larger countries or areas, three types of aquifer prevail: those related to volcanic rocks; those related to limestones, especially coralline limestone; and those related to unconsolidated alluvium and coastal deposits.

Climatic conditions are quite diverse. Freezing temperatures and humid weather conditions are experienced in the Aleutian Islands, while hot, dry weather (average temperature 26° to 28° C) prevails in the north-west of Australia. The jungles of the Philippines, Indonesia and Papua New Guinea are extremely hot and humid. In general, the smaller islands enjoy mild and humid weather. Rainfall on the volcanic summits of some islands may be as high as 10 m per year. The south-eastern coastal regions of Australia enjoy a mediterranean type of climate.

In the sub-tropics, westerly winds prevail; in the tropics, trade winds cool the equatorial area. Devastating hurricanes occur in tropical areas north and south of the equator. They are named typhoons in the central and western Pacific and in Japan, baguios in the Philippines and willy-willies in Australia.

On the atolls, dramatic water shortage conditions may develop in periods of drought, that is, three to four months without significant rainfall. In the past, when the local supply of drinking water and fresh coconuts was almost exhausted, the inhabitants would leave by pirogue (canoe) for other islands in order to survive.

The populations of the Pacific are extremely diverse. In Japan, the Mongoloid-Asian group is represented; in the Philippines and Indonesia, the population is of diverse Malayan types with Chinese components, especially in the Philippines. In Australia and New Zealand, the population is mainly of European origin. In the Hawaiian islands populations of diverse origins are found: Japanese, Chinese, European and Polynesian.

The populations of the smaller islands of the central and southern Pacific belong to three main groups:

(a) The Micronesians to the north (Mariana Islands, Caroline Islands, Kiribati), who are related to the Malaysian-Philippino group;

(b) The Melanesians to the south (the island of New Guinea, Fiji, Solomon Islands, Vanuatu, New Caledonia);

(c) The Polynesians within the triangle made up of Hawaii, Tonga and Easter Island, and in New Zealand (where they are known as Maoris).

Some aborigine groups which have existed through the last millenium practically unchanged are to be found in Japan (the Ainus), the Philippines, Indonesia and Australia, including the island of Tasmania. In Fiji, Indians constitute half the population.

Insularity is the prevailing and common characteristic of all the countries of the area, large and small. Land borders between countries are a rarity limited to the islands of Bornea and New Guinea.

The smaller islands of the Pacific in the Oceania group (the Micronesian, Melanesian and Polynesian islands) have a population in the range of 3.5 million, which has traditionally lived on fish, coconuts, root crops (giant taro) fruit, pigs and chickens, and which was completely isolated from the outside world until the end of the eighteenth century.

The arrival of voyagers from the west had a number of adverse effects on the inhabitants: they were exposed to diseases to which they were highly vulnerable, and alcoholism became a serious problem. They were killed in conflicts that ensued or were deported. In the Marquesas Islands, for example, the population fell from about 60,000 to 5,000 in less than a century. Not least of the ill effects was that the people came in contact with ways of life which local economies could not sustain. As a result "emerging" small island countries are experiencing enormous difficulties in trying to reach self-sufficiency, at least in certain areas.

Subsidies from the former colonial powers - present "protector" countries which have retained foreign affairs and defence responsibilities - and assistance from bilateral, multilateral or international organizations constitute an essential component of fragile local economies. Another is the migration of the best elements of the labour force to areas where opportunities for employment exist, thus generating income for their families in the homeland. Main local resources are tourism and agricultural products which are heavily dependent on the uncertain availability of surface water, except in some areas of Samoa and Fiji. The assessment of ground-water resources and the determination of the optimal ways to develop and use them are therefore an essential element of the economic development plans of the small islands of the Pacific.

In the course of the past 10 years or so much knowledge has been acquired on the precarious hydrological systems of the coralline atolls and on the overall water conditions in the smaller islands. It is hoped that within the framework of the International Drinking water Supply and Sanitation Decade more will be done through co-operative efforts with the major countries present in the area and with the United Nations system as a whole to permit further development of those water resources so as to secure the future of the people in the beautiful land of their ancestors. The experience that has already been gained in Hawaii in respect of the hydrology of volcanic rocks and the management of water resources in volcanic islands will probably also have benefited many other volcanic islands.

The spectacular development achieved in recent years in the knowledge of ground-water resources in the Philippines, Indonesia and Australia, will probably be pursued and accelerated, while in Japan the monitoring and control of subsidence and pollution will remain among the main activities of hydrogeologists.

Therefore, in the years ahead, the exploration, assessment, development and management of ground-water resources in the Pacific area are likely to become essential activities related to economic development, as they are in the rest of the world but with a special character owing to the large number of small islands, the occurrence of a specific geographical feature, the atoll, and the abundance and complexity of volcanic terrains.

ALEUTIAN ISLANDS

(Alaska, United States of America)

Area: about 28,500 km^2

Population: about 10,000 (United Nations estimate, 1977)

The Aleutian Islands consist of an archipelago, 2,240 km long and less than 100 km wide, which extends from the western tip of the Alaska Peninsula towards the coast of Asia. The total area of 28,500 km^2 is chiefly distributed among 33 islands, each with an area in excess of 65 km^2. The largest island, Unimak, at the tip of the Alaska Peninsula, embraces more than 4,000 km^2. The population is concentrated in the eastern part of the chain.

Conditions of ground-water occurrence

The islands are the extension of the Aleutian Range, which is part of the Pacific Mountain System covering the southern portion of the Alaska Peninsula. They are chiefly products of Quaternary volcanism imposed on older Cenozoic rocks. Fifty-seven Quaternary volcanoes have been identified, 27 of which are still active. Topography is rolling to rugged with mountain summits rising to 2,750 m above sea level. Wave-cut platforms are common below an elevation of 180 m. Normally the coast is bordered by low sea cliffs.

A northern maritime climate characterized by persistent high cloudiness and abundant moisture envelops the chain. Temperatures are always cool but are rarely severely cold at sea level. The annual average temperature is 4° C, but the average minimum January temperature is only minus 2° C. The highest monthly average of 11° C occurs in July and August. In the most easterly islands the snow line lies at 915 m and in the westerly islands at 1,370 m. The Aleutian Islands fall outside the range of permafrost. Average annual rainfall varies from 1,520 mm in the east to 760 mm in the west. On the island of Shemya, where 2,900 mm of snow fall each year, annual precipitation of water is 1,105 mm.

Surface drainage is short and run-off is swift. Where porous permeable volcanic rocks occur, streams flow only during heavy rains. Many small ice-created lakes exist. Glaciers are rare but periglacial processes dominate erosion. The islands are not forested. Grass, shrubs, wild flowers, mosses and lichens grow on the rolling hills, and ferns are common in valleys.

The northern half of the archipelago is formed of a linear chain of volcanoes of late Cenozoic age. The southern portion consists of emerged tilted fault blocks composed of early Cenozoic volcanic rocks that were locally metamorphosed. Granitic intrusions occur on a few of the islands, among them the sizeable island of Unalaska. Sedimentary rocks include glacial deposits, mud flows, landslides, alluvium and beach deposits.

Volcanic rocks are predominantly the basic varieties and include marine and subaerial lavas in addition to pyroclastics. Dykes and sills are common. Assemblages of argillite, greywacke and metamorphosed rocks are sometimes visibly associated with basic and acidic igneous intrusions.

Ground-water resources and development

Ground water was probably not necessary for the inhabitants of prehistoric Aleut settlements. Streams, lakes and high precipitation served their needs. Few attempts have been made to develope a supply of ground-water. Wells and galleries have been constructed on Shemya and Amchitka for military use, and a few wells may exist elsewhere. However, ground-water exploitation has not generally been successful.

Except on Amchitka, where, in preparation for undersea nuclear tests, hydrogeological studies were conducted, no extensive ground-water surveys of the islands have been made. The Aleutian Islands are not likely to be more densely inhabited in the future than they are at present.

The ground water that has been developed is extracted from volcanic rocks. The aquifer struck by a well drilled on Shemya is dense, unfractured and of low permeability. In the Pribilof Islands, which are composed of basaltic lavas, the rock is permeable but the Ghyben-Herzberg lenses are thin and therefore difficult to exploit. A considerable hydrogeological effort would have to be undertaken before the ground-water potential of the archipelago is known. At present, apparently, no significant effort is being made to investigate or explore for ground water in the Aleutian Islands.

Conclusions

Most of the Aleutian Islands are uninhabited. Several of the easterly islands have military bases and a few Aleut villages but these communities are not pressed for a water supply. Significant population and economic expansion is not foreseen. However, should the population increase and spread for some reason, ground water in Quaternary volcanic rocks would proably be the most reliable water supply.

Selected references

The most extensive hydrogeological bibliography for the Aleutian Islands deals with the island of Amchitka. At least 25 reports, most of them in the United States Geological Survey 474 series, have been issued.

Regional studies are few and are chiefly concerned with geology. No hydrogeological maps have been made, but reconnaissance geological maps of each island have been published by the United States Geological Survey.

Principal regional titles

Péwé, T. L. 1975. Quaternary geology of Alaska. Professional Paper 835, United States Geological Survey.

United States Geological Survey (multiple papers and authors). Investigation of Alaska Volcanoes. Bulletin 1028, United States Geological Survey.

Wharhaftig, C. 1965. Physiographic divisions of Alaska. Professional Paper 482, United States Geological Survey.

Zenoen, C., and G. S. Anderson. 1978. Summary appraisal of the nation's ground-water resources - Alaska. Professional Paper 813-P, United States Geological Survey.

AMERICAN SAMOA

(Territory administered by the United States of America)

Area: 197 km^2

Population: 34,000 (United Nations estimate, 1977)

American Samoa comprises a group of seven islands in the South Pacific Ocean, lying at approximately, longitude 170° W and latitude 14° S (see map 2). The largest island, Tutuila, has an area of 137 km^2, while the next largest, Ofu, has an area of only 5.2 km^2. Of the total estimated population, more than 30,000 people live on the main island of Tutuila. One of the islands, a tiny coral atoll, is uninhabited since there is not enough fresh water to support life.

Conditions of ground-water occurrence

The five major islands inherited a rugged, mountainous topography from their volcanic origin. The maximum elevation in the group is a peak on the island of Ta'u at 969 m. The highest point on Tutuila is 653 m, on Aunu'u it is 85 m, on Ofu, 494 m, and on Olosega, 638 m. The two small atolls, Rose Island and Swain's Island, lie near sea level. Erosion has created small, often deep, narrow valleys on the volcanic islands. Areas of gently sloping or flat land, caused by erosion, are small and scattered. The largest sector of relatively level land is the Tafuna-Leone Plain on the island of Tutuila. It encompasses 35 km^2, and was formed by volcanic extrusive rocks that covered an older eroded surface. The coastline is irregular and frequently precipitous. Where breaks occur they are small, consisting principally of marine sand and volcanic gravel at the edge of a narrow coastal shelf.

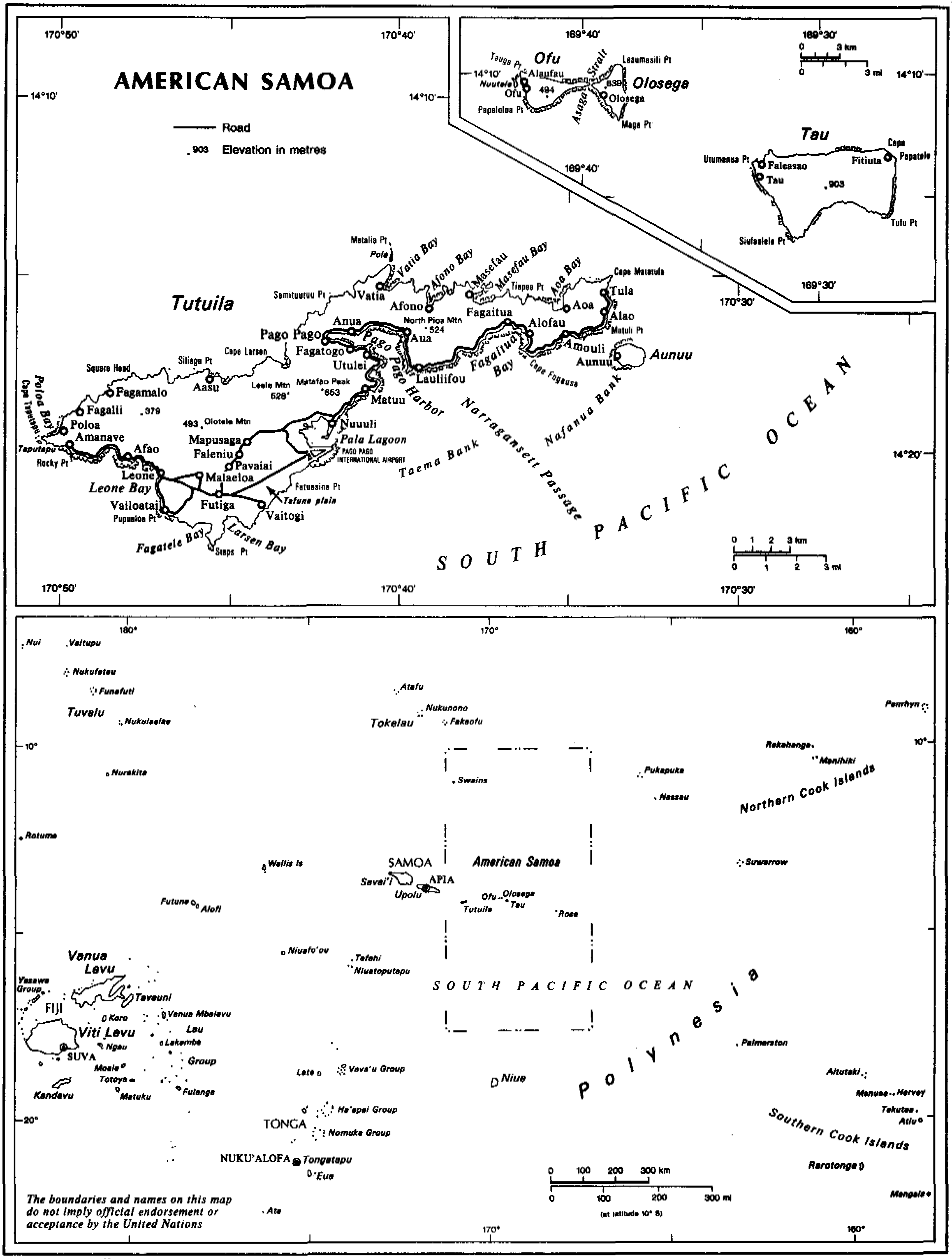
American Samoa lies at the margin of equatorial climatic influence. Two seasons occur, a wet season from November to the end of April and a dry one from May to the end of October. The intertropical convergence zone causes the wet season, which is dominated by weak and variable winds, and by high temperature, rainfall and humidity. During the dry season the south-east trade winds of the southern hemisphere prevail, the rainfall is moderate, and the temperature is slightly lower than in the wet season. Maximum temperature does not exceed 35° C and minimums are not less than 16° C. The average annual temperature is 27° C, the mean seasonal range is only 2° C and the mean daily range is 7° C. Average annual rainfall at Pago Pago harbour is 5,080 mm, while at the summit of Mt. Alava it is more than 6,350 mm. In spite of such high annual rainfall, droughts occasionally occur. Hurricanes may be experienced in the summer months but they are infrequent, averaging less than one occurrence every three years.

Drainage basins are small, short and steep. Streams respond quickly to rainfall but do not sustain significant flows when the showers cease. On Tutuila a few streams yield perennial flows of several litres per second, which originate as ground-water seepage. In droughts even these flows cease or are reduced to trickles. The valleys are not suitable for reservoir sites because of their steepness.

The five major islands consist of volcanic rocks of predominantly basaltic composition. Terrestrial sedimentary deposits of alluvium and talus are found as narrow wedges and terraces at the mouth of the main valleys. Marine biogenic calcareous deposits form a thin veneer along some sections of the coast.

Map 2. American Samoa

MAP 2



MAP NO. 2971 UNITED NATIONS
MARCH 1978

Tutuila was built by four volcanoes from Pliocene time to early Pleistocene. A fifth volcano, more recent but probably no younger than mid-Pleistocene, erupted after the initial period of erosion and created the Tafuna-Leone Plain by filling valleys and covering sediments. The volcanic formations consist of extrusive flows of aa and pahoehoe, among which pyroclastic materials settled. Dykes intrude the formations.

The small island of Aunu'u off the east coast of Tutuila is the remnant of a tuff cone. A single-shield volcano of thin basaltic lava flows resulted in Ta'u Island. Ofu and Olosega at one time were a single island of two coalesced shield volcanoes but are now separated by a narrow strait.

Seven geological volcanic formations have been assigned to Tutuila. The oldest (Pliocene?) is the Masefau dyke complex, which was succeeded by the Olomoana, Alofau, Pago and Taputopu volcanic series, all consisting predominantly of basaltic rocks. Trachytic rocks were then emplaced as dykes, plugs and crater fill. A long period of erosion ensued, followed by the extrusion of the basaltic Leone volcanics.

The geological stucture of the islands reflects, and is dominated by, volcanic processes. Rift zones, shields and calderas are principal features; tuff cones and other pyroclastic phenomena are secondary features. Deformation has not taken place, and significant faulting has not occurred.

Ground-water resources

Before the Second World War, little attention was given to organizing a water-supply system. Villages relied on perennial streams and springs and on dug wells. In this sense their basic water supply consisted of ground water. Not until 1943 was a deliberate attempt made to develop a ground-water supply. At that time the United States Navy constructed an infiltration gallery 100 m long in volcanic rock near Pago Pago. It yielded 12 l/sec of fresh water.

In 1960 a few wells were drilled, but not until 1973 was full-scale exploitation of the ground-water resources attempted. Although hydrogeological studies were initiated by the United States Geological Survey in 1962, the first comprehensive investigation of the aquifers was not started by that agency until 1973. Both the United States Geological Survey and the United States Army Corps of Engineers have made studies since 1973. Currently the government of American Samoa supports a well-drilling programme directed by a hydrogeologist. Investigatory and drilling efforts have been devoted almost entirely to the principal island, Tutuila.

The ground-water resources have been identified by classical methods of hydrogeological observations, measurements, and mapping in conjunction with the drilling of exploratory and producing wells. Geophysical methods of prospecting have not been employed; their applicability is severely limited by the small-scale complexities of ground-water occurrence.

All ground waters are classified as either high level of basal, depending on whether the aquifer is not in hydraulic continuity with sea water (high level) or occurs as a form of Ghyben-Herzberg lens (basal). High-level aquifers are often found between dykes, or perched on poorly permeable strata or in the caldera rock assemblage. These aquifers and their yields are small. Basal aquifers occur in lavas that are almost free of intrusive rocks and in sedimentary deposits near the sea coast. The largest continuous aquifers are basal.

The principal and only truly extensive aquifer occurs in the Tafuna-Leone Plain on the island of Tutuila. It is basal and the only aquifer that has undergone appreciable investigation, testing and development. Small high-level aquifers are common in the mountainous areas of the island.

On Aunu'u a thin basal lens underlies a narrow coastal plan, and inland very small high-level aquifers yield seepage. Similarly on Ta'u small basal and high-level aquifers are found, while on Ofu and Olosega the aquifers are chiefly basal, but small.

The Tafuna-Leone aquifer is composed of Holocene basaltic lavas and older terrestrial and marine sediments underlying them. Ground-water heads ascend to between 1.2 and 1.5 m above sea level at the aquifer's inland margin.

The aquifers of American Samoa are highly heterogeneous and exhibit a wide range in parameter values. Their characteristics are summarized in table 1 below.

Table 1. American Samoa: aquifer characteristics

Location	Ground-water type	Geological Age	Depth to water (m)	Depth of well (m)	Well yield (l/sec)	Specific yield (l/sec/m)	Trans-missivity (m^2/day)
Small alluvial aquifers, all islands	Basal	Recent	1-10	2-10	<2	<10	...
Tafuna-Leone, Tutuila	Basal	Holocene	18-60	28-73	3-21	6-39	230-4,070
Older volcanic rock, Tutuila	High level	Tertiary	20	25	10	1.1	...

Neither hydraulic conductivity nor coefficient of storage has been determined. It is evident from the above that a relatively slim hydrogeological data-base has been accumulated to date. Exploitation of ground water on Tutuila has proceeded without adequate arrangements for testing and data collection. At present data on ground-water are not being collected systematically.

Ground-water development

A centralized water-supply system is a recent innovation in American Samoa. Only within the past two decades did the government construct a central system to serve the main poplation centre of Tutila. Even so, village water systems continue to operate on the main island and on all of the smaller islands.

Responsibility for the central system is divided between two subdivisions of the Department of Public Works. The water system division is responsible for planning and design and is in charge of the pumping stations and distribution network. Operation and maintenance fall under the care of the water, sewer, and solid waste division. This separation of control has inhibited efficient organization. Water development, which in the past was guided by the United States Geological Survey and the United States Army Corps of Engineers, is at present handled by the local government, which contracts out for technical skills when they are needed.

In the past 20 years more than 60 wells have been drilled on Tutuila, largely without benefit of technical supervision. The first 20 were made with a percussion drill; no records were kept. During the next phase of drilling (1972-1975) a Failing model 1500 rotary rig was used by Water Resources International, Inc., of Honolulu, Hawaii. Results were variable and records of drilling are incomplete. Since then the United States Army Corps of Engineers has provided technical assistance to the Ground Water Development Corporation, an entity organized by the government. From 1975 to 1976, about 15 wells averaging 30 to 60 m deep were completed. Apparently the best drilling results are obtained by rotary drilling as long as heavy permanent muds are not employed. The typical well is fitted with a 200 mm casing and screened below the water table.

The central system derives practically all of its water from the Tafuna-Leone aquifer. An average of approximately 105 l/sec is extracted by 15 operating wells. The supply is pumped 18 km to the city of Pago Pago where it serves the needs of the government, industry and tourism. Agriculture is not a significant consumer of water because organized farming does not exist. The current supply is inadequate to meet demands, especially during the dry season, but more wells are being drilled to ameliorate this problem. A net gain in water is possible by improving the distribution system and eliminating leakage. Only about 25 per cent of the system is metred. The Government believes that the present per capita consumption of 1,140 l/day can be reduced to 570 l/day.

Village water systems supply the population not concentrated near Pago Pago. Except for areas where wells have been drilled or dug, the villages rely on ground water only in the sense that springs and perennial stream flow originate as ground-water seepage. About 40 independent village systems are in operation. On Aunu'u three shallow dug wells providing about 4 l/sec supply the inhabitants. On Ofu a dug well yielding 2 l/sec is used, and on Ta'u a drilled well that produces 7 l/sec and a dug well yielding about 0.5 l/sec constitute the village supply.

The chief ground-water problem is the insufficiency of producing wells to meet current and growing demands. Because ground water has only recently become the dominant source of water, effects such as sea-water intrusion, manifested by increasing salinity and declining head, have not yet set in. However, an organized programme of hydrological observations has not been put into operation so that the early stages of intrusion may be occurring without having been detected. Neither drainage nor subsidence is a problem in American Samoa.

Conclusions

Ground water developed by wells has replaced streams and springs as the principal source of supply and its use will continue to grow. Surface water is unreliable and cannot serve all of the expanding needs of the economy and population. The estimated low flow of streams on Tutuila is only 25 l/sec, far less than the 105 l/sec already being pumped from wells. Drainage basins are small and good reservoir sites non-existent. Apart from roof-cistern catchment, there is no natural water-supply alternative to ground water in the future of American Samoa.

The cost of producing ground water for the central system is not clearly established. Energy is expensive and, as is to be expected, the cost of pumping water is high. The cost at the well is of the order of $0.25/m^3$.

In 1977 the estimated population of American Samoa was 30,600, a substantial proportion of which relied on ground water from wells. Most economic growth will take place on Tutuila, where the anticipated population for the year 2000 will be 40,000 and the estimated demand for water will be 350 l/sec. Most of the supply will be obtained from the Tafuna-Leone aquifer. On the smaller islands, wells, both drilled and dug, will continue to provide much of the supply. Ground water will be the principal water source, but more studies and exploration are urgently needed if the aquifers are to be identified and correctly developed.

Selected references

At least 30 government publications deal with the water-supply problems of American Samoa; half of them are concerned with ground water. These publications have not been widely distributed outside the Territory. A reconnaissance geological map is available. Further geological and hydrological investigations are needed, however, before reliable hydrogeological maps can be prepared.

Principal ground-water studies with reasonable distribution are as follows:

Bentley, C. B. 1975. Ground-water resources of American Samoa with emphasis on the Tafuna-Leone Plain, Tutuila Island. Water Resources Inventory Report 29-75, United States Geological Survey.

Davis, D. A. 1963. Ground-water reconnaissance of American Samoa. Water Supply Paper 1608-C, United States Geological Survey.

Stearns, H. T. 1944. Geology of the Samoan Islands. Bulletin of the Geological Society of America, 55/1279-1332.

AUSTRALIA

Area: 7,687,000 km^2

Population: 16 million (United Nations estimate, 1977)

Conditions of ground-water occurrence

Physiography

Apart from an irregular belt of coastal lowlands, the continent of Australia is broadly divisible into three main physiographical regions: the Western Plateau, the Interior Lowlands and the Eastern Highlands (see map 3). The Western Plateau occupies about half the continent, extending from the coastal lowlands of Western Australia to the MacDonnell and Musgrave Ranges in the Northern Territory and South Australia. Eastwards, the Western Plateau passes gradually into the Interior Lowlands, a tract of country of variable width stretching from the Gulf of Carpentaria to the Southern Ocean, mostly with an altitude less than 245 m. Low topographical barriers separate the Interior Lowlands into a number of units, the most important being the Murray-Darling Basin containing Australia's largest river system. Lake Eyre Basin, an area of inland drainage, forms the lowest part of inland Australia at 10 m below sea level and is separated from the lowlands around the Gulf of Carpentaria by a low topographical divide. The structural depression in South Australia occupied by Spencer Gulf and Lake Torrens is isolated from the Murray-Darling Basin by the Mount Lofty, Flinders and Barrier Ranges.

The Eastern Highlands vary greatly in character along their course; they stretch from Cape York Peninsula in the north to the vicinity of Hamilton in Western Victoria. For the most part, they are uplifted and dissected peneplains presenting a steep face seawards and a gentle slope inland towards the Interior Lowlands. Within the Eastern Highlands there are only a few mountain areas above 1,000 m. The highland axis varies in altitude and bears little relation to the strike of the underlying rocks, particularly in Victoria, where the main ranges are aligned westwards across structural trends. Tasmania, a mountainous island, is a detached mass of the Eastern Highlands.

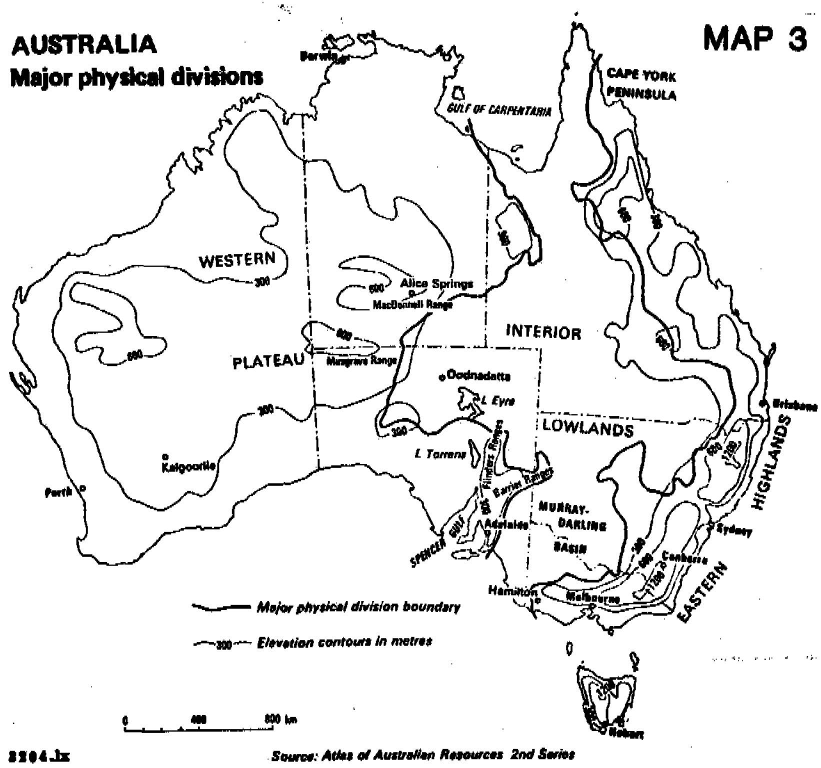
Climate

Rainfall

The main features of the distribution of rainfall are the clearly defined wet summer and dry winter of northern Australia; the heavy summer and light winter rain of the east coast of Queensland; the relatively uniform distribution through the year in south-east Australia; the marked wet winter and dry summer of the south-west of Western Australia and, to a lesser extent, of much of the remainder of southern Australia; and the large area of low, irregular rainfall extending from the north-west coast to the interior of the continent. High rainfall areas (2,400 mm/year) occur in Tasmania, the Snowy Mountains and parts of the north Queensland coast. Areas of good rainfall (800 mm/year) are restricted to the north, east, south-east and far south-west (see map 4) and constitute only 12 per cent of the total area of the continent (see table 2). Nearly 30 per cent of the total area receives less than 200 mm/year.

Map 3. Australia: major physical divisions

Map 4. Australia: median annual rainfall



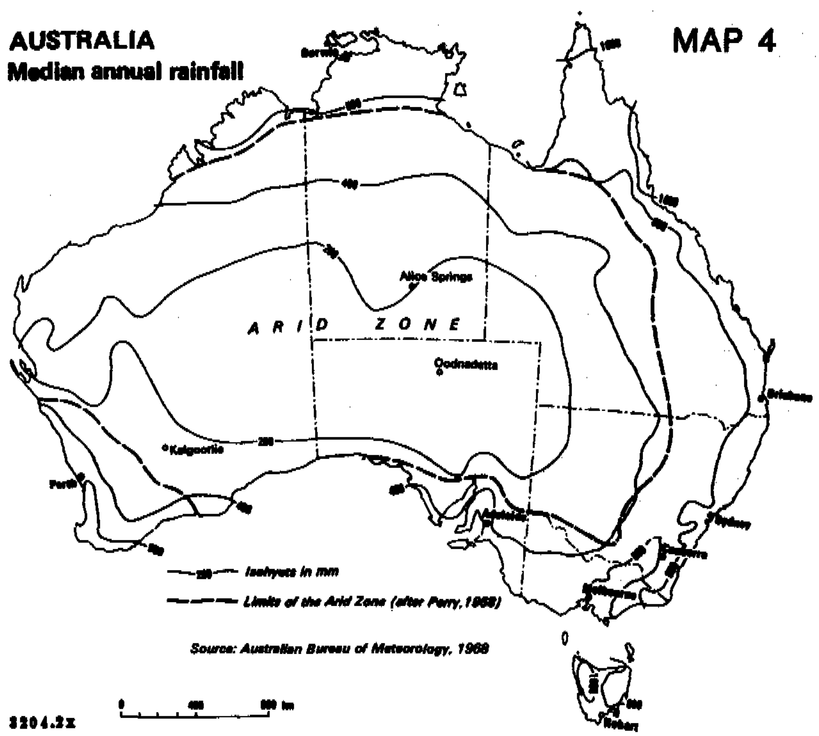


Table 2. Australia: median annual rainfall by area

Rainfall range (mm)	Area (10^3 km^2)	Area (percentage)
100	60	0.8
100-150	860	11.2
150-200	1,305	17.0
200-300	1,275	22.3
300-400	857	11.1
400-510	689	9.0
510-610	521	6.8
610-800	782	10.2
800-1,200	616	8.0
1,200-1,600	228	3.0
1,600-2,400	39	0.5
2,400	5	0.1
Total	7,687	100.0

In 1969, the Commonwealth Bureau of Meteorology prepared a map of Australia with 11 broad climatic zones based on the amount and seasonal distribution of rainfall. The isohyetal boundaries of the subdivisions were based on median rainfall, since it has a known frequency of occurrence, rather than on the more common mean rainfall. Seasonality boundaries were also based on median rainfall (see table 3).

The effectiveness of the rainfall over most of Australia is greatly affected by marked alternation of wet and dry seasons, unreliability from year to year, high temperatures and high potential evaporation. Irregularity of the rainfall leads to widespread droughts, and there is rarely a period when a portion of the continent is not suffering from a drought. The greater part of Australia's pastoral land lies within the region of low and unreliable rainfall.

Temperature

The temperature régime in Australia is essentially continental with the high temperature range of the inland area reaching almost to the coastline in some areas. Average annual air temperatures range from 28° C along the Kimberley coast in the extreme north of Western Australia to 4° C in the alpine areas of south-eastern Australia. July is the month with the lowest average temperature in all parts of the continent. The highest average temperature occurs in January or February in the south and December in the north, except in the extreme north and north-west where it occurs in November.

Table 3. Australia: classification of precipitation zones

Symbol	Description a/	Median annual precipitation (mm)	Altitude (m)	
LS	Low summer	38-63	No altitude limits	
MS	Medium summer	63-140		
HS	High summer	more than 140		
LU	Low uniform	25-50		
MU	Medium uniform	50-90		
HU	High uniform	More than 90		
LW	Low winter	25-50		
MW	Medium winter	50-90		
HW	High winter	More than 90		
AZ	Arid zone	Less than 25 in uniform and winter rainfall areas; less than 38 in summer rainfall areas		
A	Alpine	Any amount	New South Wales:	above 1,500
			Victoria:	above 1,300
			Tasmania:	above 1,000

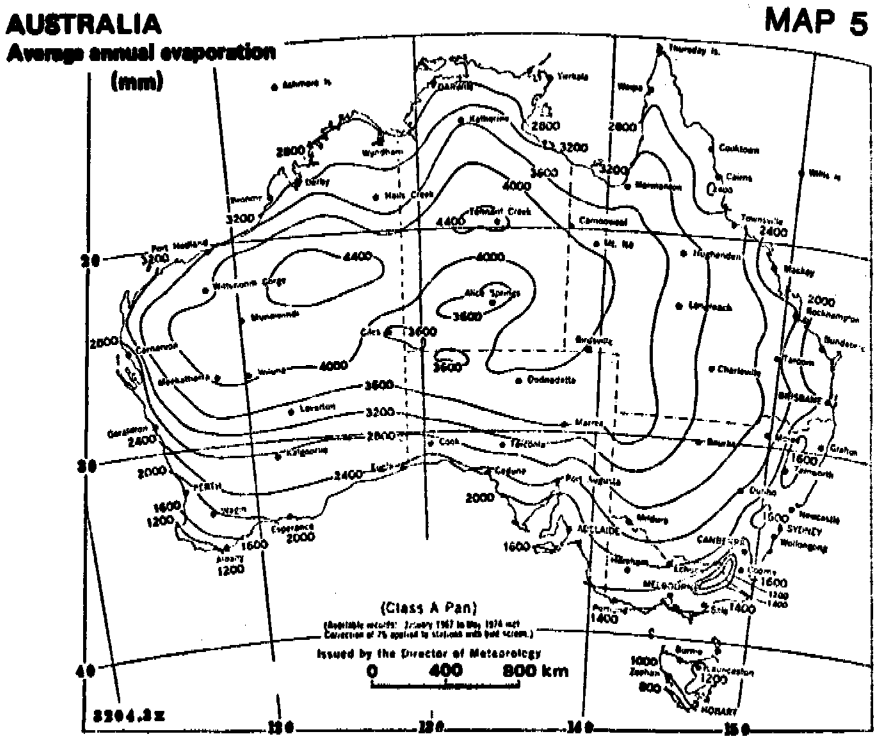
Source: Commonwealth Bureau of Meteorology.

a/ For definitions, see Australian Water Resources Council, Hydrological Series No. 2,1969.

Evaporation

Average annual Class A pan evaporation varies from 800 mm in south-west Tasmania to 4,500 mm in the dry interior of Western Australia with 75 per cent of the continent exceeding 2,500 mm (see map 5). In about 75 per cent of the continent rainfall does not exceed evaporation loss from free water surface in any month of the year. In the central and north-west parts of the continent the annual pan evaporation is 10 times greater than the rainfall.

Map. 5 Australia: average annual evaporation



Surface water

Much of Australia is without permanent river systems because of low and uncertain rainfall, low relief, high evapotranspiration and a lack of permanent snow fields from which melting snow can replenish rivers and streams in summer.

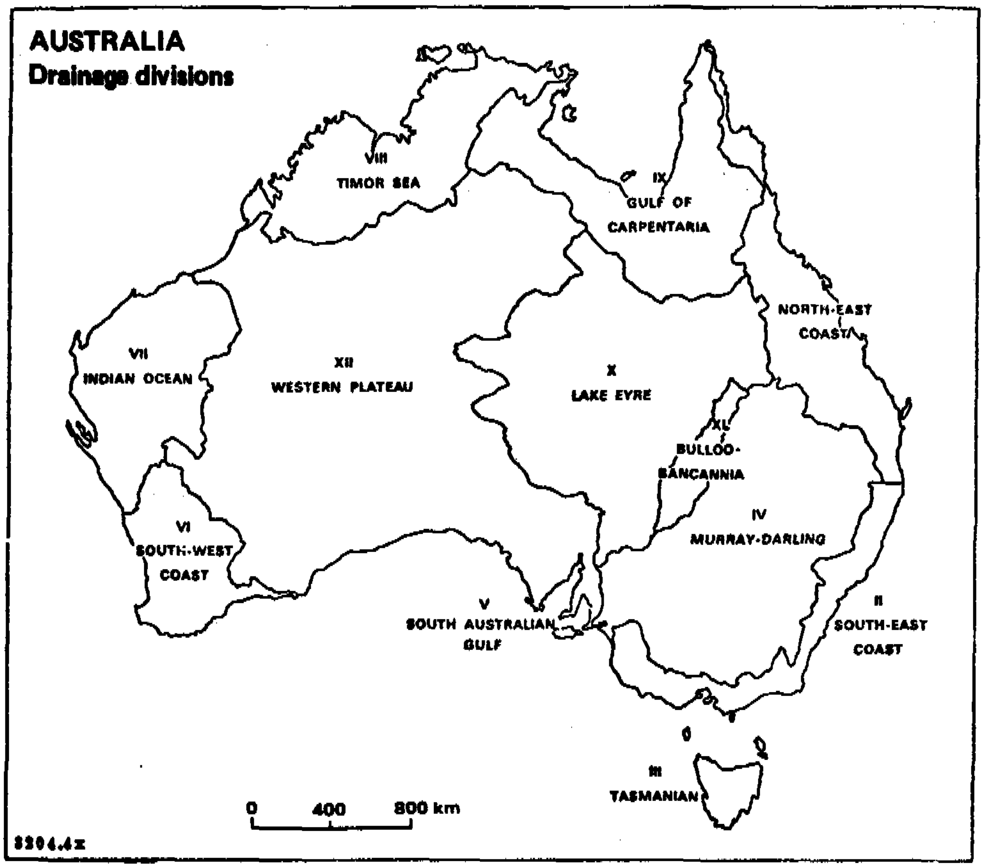
For the purpose of national assessment of surface-water resources the Australian Water Resources Council has delineated 242 primary river basins on the mainland of Australia and Tasmania. These are grouped into 12 drainage divisions, as shown in map 6. The mean annual discharge of the rivers in all divisions (see table 4) has been estimated to be about 3.45×10^{11} m^3, which is equivalent to a run-off of only 45 mm over the whole continent, including Tasmania, or about 10 per cent of mean annual precipitation. Of the whole of Australia, only an area of about 5×10^6 km^2 is regarded as contributing to streamflow. There is little flow from almost all of the Western Plateau drainage division and from some arid parts of other drainage divisions.

Table 4. Australia: mean annual discharge from drainage divisions

	Drainage divisions	Area (thousands of km^2)	Mean annual discharge (billions of m^3/year)
I	North-east coast	450	83.0
II	South-east coast	270	36.0
III	Tasmania	65	47.0
IV	Murray-Darling	1,100	24.0
V	South Australian Gulf	75	0.5
VI	South-west coast	140	7.2
VII	Indian Ocean	520	6.1
VIII	Timor Sea	540	74.0
IX	Gulf of Carpentaria	640	63.0
X	Lake Eyre	1,100	4.5
XI	Bulloo-Bacannia	100	0.4
XII	Western Plateau	2,700	...
	Total	7,700	350.0

Map 6. Australia: drainage divisions

MAP 6



Since precipitation over the continent varies considerably from year to year, annual streamflow is highly variable. Seasonal conditions are such that large rivers in the north of the continent carrying in excess of 30,000 m^3/sec in high flood may cease to flow altogether in the dry season. The highest recorded annual discharges in many rivers are as much as 300 times the lowest. Large variability in flow means that most streams must be regulated by surface storage for local or regional development. In many areas of Australia, however, evaporation is so great that storage costs are high in terms of yield and problems of salinity are apparent.

Geology

The main elements of the solid geology of Australia are shown in map 7. Most of the western and central part of the Australian continent consists of basement rocks of Precambrian age. Younger Palaeozoic rocks, mainly of geosynclinal origin, form a discontinuous belt several hundred kilometres wide on the eastern side of the continent from north Queensland to Tasmania. Both provinces are extensively covered by younger rocks in sedimentary basins of various ages. Mesozoic platform sediments extending from the Gulf of Carpentaria to central New South Wales form a broad zone between the Palaeozoic and Precambrian rocks. Cenozoic rocks occur mainly in southern Australia, and as residual basalt cappings over extensive areas of Palaeozoic rocks in eastern Australia.

Ground-water resources

Ground water is widespread throughout Australia and in half the country it assumes special significance because it is more abundant and more reliable than surface water, being much less susceptible to evaporation.

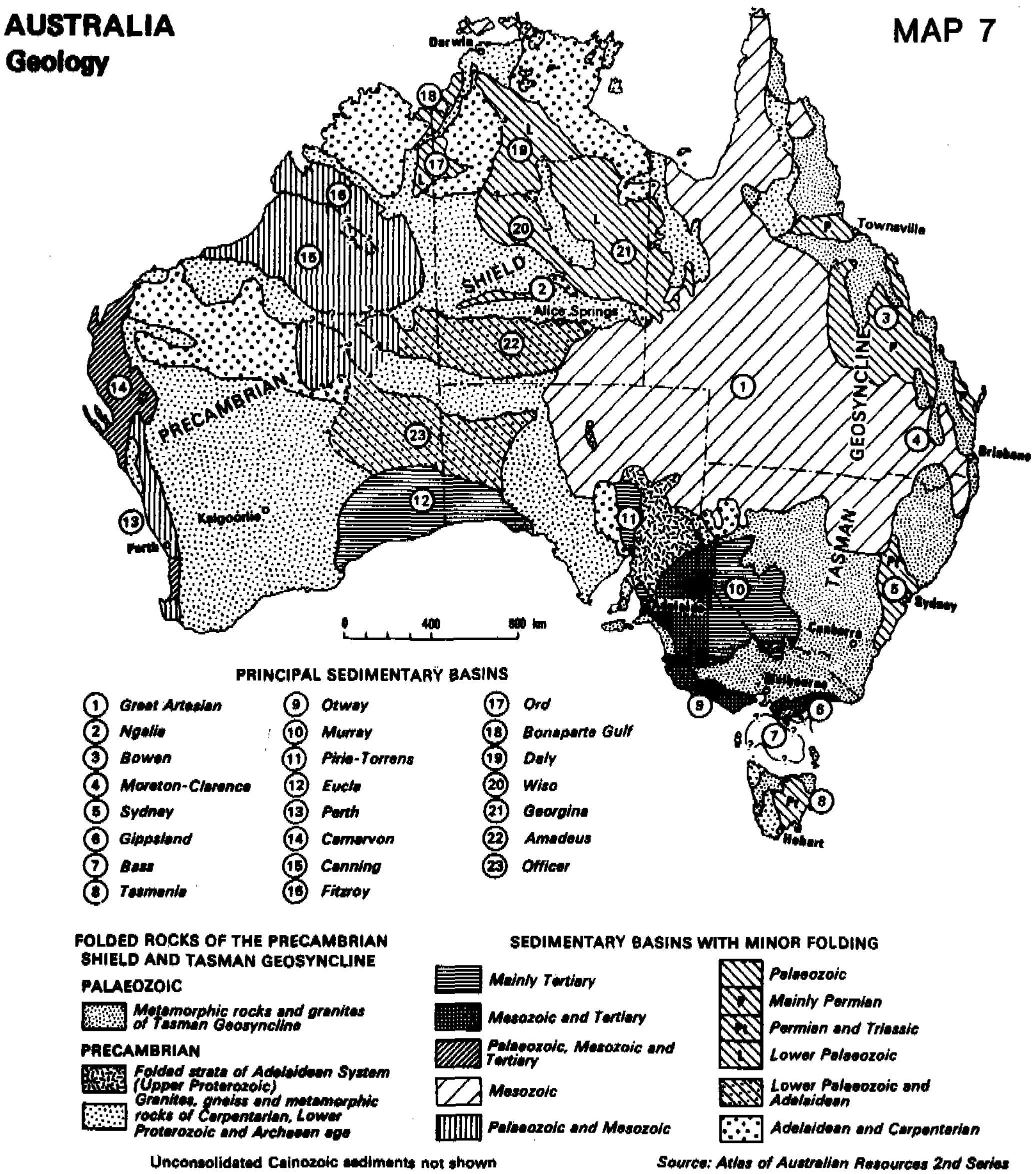
History

There is evidence that Aborigines had been using ground water extensively in Australia by the time European settlers arrived in the late eighteenth century. Aboriginal wells are known in many parts of the continent, and artifacts show that some of them were in use for long periods. European settlers chose their locations according to the availability of surface-water supplies and used ground water, from hand-sunk wells in alluvial aquifers, only in times of drought.

As settlement spread inland into grazing country inadequately furnished with surface water, the value of reliable supplies of underground water was realized and in 1857 the earliest official investigation of ground-water resources was reported. The next recorded advance was in 1871, when a bore was sunk 52 m and tapped artesian water near Perth in Western Australia.

In Queensland, under the impetus of the 1885 drought, bores were sunk at various places in the Great Artesian Basin and all flowed. Since then, some 30,000 bores have been drilled in the Great Artesian Basin, about one fifth of which are still flowing. The waters of the basin have been a major asset to the pastoral industry since the last decade of the nineteenth century. It is estimated that between 1870 and 1970 the average annual bore discharge was 600 x 10^6 m^3 of low salinity ground water.

Map. 7. Australia: geology



3204.5x

The first bores in the Murray Basin were drilled in 1886 in Victoria and in 1887 in South Australia. Exploration of the Eucla Basin in South Australia established the existence of an artesian aquifer under the Nullarbor Limestone and in 1903 a flowing supply was obtained. In the same year a bore drilled near Carnarvon, Western Australia, flowed at 2×10^3 m^3/day, proving the existence of an artesian basin in rocks of Permian age, the oldest artesian aquifer then known. Subsequently, artesian water was also obtained in the Canning Basin.

In later years a number of smaller sources of artesian water were discovered and exploited, especially in South Australia and New South Wales. All major artesian basins of the continent have probably been delineated, though aquifers in the Amadeus Basin could possibly yield a flowing supply.

During the 1940s, numerous bores were sited and drilled by the military for airfields, roads and army camps in the Northern Territory, Queensland and Western Australia. The need for dependable emergency supplies in 1942 led to the drilling of 16 reserve bores in the Botany Sands to supply Sydney. After the war, increased use of rotary drilling and geophysical techniques permitted ground-water resources to be explored and utilized more thoroughly.

In 1957 attention turned to the ground-water resources of inland drainage systems of New South Wales. The alluvium of the Lachlan Valley was found to possess substantial ground-water potential for irrigation in an area where, previously, shallow bores had produced supplies useful only for domestic and stock purposes. Development of other inland valleys in New South Wales soon followed.

Today the most intensive use of ground water is from unconsolidated sediments, particularly alluvial and aeolian deposits. However, major sedimentary basins underlie 60 per cent of the continent and one, the Great Artesian Basin, has sustained much of Australia's inland pastoral industry since the late nineteenth century.

Management

Federation in 1901 made virtually no change in the legal and administrative control of ground water in Australia. Under the Constitution the Australian Government has specific powers relating to water conservation and management in federal territories only. Assessment, conservation and development of water resources within states is the responsibility of the state governments. In each state and the Northern Territory, central and local water authorities have evolved to carry out these functions (see table 5). They are empowered to regulate the drilling of bores, the extraction and pollution of ground water, as well as other aspects of ground-water management. In most cases the use of these powers, such as the licensing of bores, is confined to those areas in which the controls have specifically been proclaimed to apply. Much of Australia still remains outside such declared areas.

The usual arrangement is that the government agency responsible for administering the use and development of surface water is also responsible for administering ground-water law. The decisions of these water authorities are subject to appeal before special tribunals, not the ordinary courts of law. Thus ground-water legislation and administration have developed by analogy with the principles earlier established in Australia for surface-water control, and extensive private litigation over rights to water, as occurred in the western states of the United States of America has not taken place.

Table 5. Australia: government agencies concerned with water resources, their functions and prospecting equipment

Government agency	Functions: Water resources as a whole	Functions: Exploration and assessment	Prospecting equipment
<u>Queensland</u>			
Irrigation and Water Supply Commission	x	x	SIE borehole logger; ABEM terrameter resistivity equipment
Queensland Geological Survey		x	Widco downhold logger; surface resistivity equipment; 24 channel SIE seismograph
<u>New South Wales</u>			
Water Resources Commission	x	x	Failing logmaster LMRD system; McPhar fluxgate magnetometer; refraction survey unit
Geological Survey, Department of Mines		x	Neltronic downhold logger; Austral 1500 downhold logger; seismic field system
Water Conservation and Irrigation Commission		x	...
<u>Victoria</u>			
State Rivers and Water Supply Commission	x	x	Surface resistivity tester
Geological Survey, Department of Mines		x	...
<u>South Australia</u>			
Engineering and Water Supply Department	x	x	...
Department of Mines		x	Neltronic downhole logger; Failing logmaster LMRD system; IP transmitter and receivers; electromagnetic unit; magnetometers; SIE seismic systems

Table 5 (continued)

Government agency	Functions: Water resources as a whole	Functions: Exploration and assessment	Prospecting equipment
<u>Western Australia</u>			
Public Works Department	x	x	Austral mini downhole logger; salinity and temperature logger
Geological Survey, Department of Mines		x	Widco downhole logger; GOI downhole loggers; surface resistivity units; magnetometer; SIE seismic system
<u>Tasmania</u>			
River and Water Supply Commission	x	x	...
Department of Mines		x	...
<u>Northern Territory</u>			
Mines and Water Resources Branch, Department of Northern Territory	x	x	SIE borehole logger; Failing logmaster LMRD system; gamma ray spectrometer; resistivity and other electrical equipment; magnetometers; SIE seismic system
<u>Australian Capital Territory</u>			
Department of Construction	x		...
Bureau of Mineral Resources, Department of National Development		x	...

The water authorities are also responsible for the assessment and, in part, the development of ground-water resources. In practice, each state's geological survey undertakes much of the work of investigation and assessment and commonly has a leading part in ground-water development, for instance, in providing advice to individuals, companies and public authorities on bore siting, analysing water quality and recommending safe rates of extraction to the water authority. In recent years, overuse and pollution of ground water have become important issues in some areas and, in these instances, also, the geological surveys have a significant advisory role.

The Australian Water Resources Council, which comprises the appropriate ministers of the Australian and state Governments, was established in 1962. The Council has helped to stimulate the review of legislation and the adoption of improved principles for the orderly management of water resources. It has also successfully recommended to the Australian Government the allocation of funds to the states for the expansion of ground-water investigations.

Exploration

In recent years important changes have been occurring in Australia in the methods used for the discovery and development of ground water. Cable-tool rigs for drilling bores have mostly been replaced by faster rotary drilling equipment. Exploration has become more systematic and has benefited from the increased rate of regional geological and geophysical investigations. Computers are being used to perform previously impracticable analyses of ground water data; for example, the Bureau of Mineral Resources, Geology and Geophysics (BMR) is currently carrying out a hydrogeological study of the Great Artesian Basin using a digital computer simulation model based on records of 4,700 flowing bores and 2,000 sub-artesian bores.

Since the early 1960s, BMR and the state geological surveys have carried out a great deal of regional geological mapping, mostly on a scale of 1:250,000, and much of this work has been done in the drier parts of the mainland. Geophysical investigations have also contributed to knowledge of the nature and distribution of rock types underground. In some areas, information has come as a by-product of stratigraphic drilling and drilling for oil and natural gas.

During the past 20 years, systematic exploration has shown that large amounts of ground water suitable for irrigation and urban use are available from the extensive alluvium of many seasonally fluctuating inland streams, such as the Lachlan and Namoi in New South Wales. Many of these aquifers are high yielding and recharge rapidly during periods of high river flow.

A tabulated summary of the prospecting methods utilized by the major state authorities is given in table 5.

Main aquifer groups

The assessment of ground-water resources in Australia may be divided according to the occurrence of ground-water in one of three main classes of aquifer: unconsolidated sediments, sedimentary basins and fractured rocks.

Unconsolidated sediments are mostly of Cenozoic age and lie within 150 m of the surface. They are poorly consolidated, usually uncemented and are of fluviatile, estuarine, lacustrine or aeolian origin. The characterisitics of unconsolidated aquifers are summarized in table 6.

The sedimentary basins, which underlie about 60 per cent of Australia, generally contain at least one major aquifer system. The aquifers are usually continuous, large in area and of considerable thickness. They dip gently, but in many areas reach great depths because of their extent. Hence bores may be costly to drill. Sedimentary basins have proved of great value to Australia, providing water to semi-arid and arid regions. In so far as they do not depend on local intakes they are independent of local rainfall and high evaporation, which characterize low rainfall areas in Australia. Aquifer characteristics of the sedimentary basins and ground-water yields are given in tables 7 and 8.

Fractured igneous, metamorphic or sedimentary rocks may provide appreciable supplies of ground water from fractures, joints, solution cavities and zones of weathering in an otherwise relatively impermeable rock unit. Water-bearing zones are commonly discontinuous and lithologically diverse. Depth to the water-bearing zone varies considerably but is generally less than 300 m and commonly less than 100 m. Recharge is usually local and seasonal fluctuations of water levels and yields are very common. The chemical quality of water from fractured rocks is usually good in areas of higher rainfall but generally poor in arid zones; it may also change rapidly over fairly short distances. Drilling is frequently slow because of the hardness of the rock. Ground-water yields, which are usually small, are governed by the type of fracturing, the degree of weathering, and local recharge conditions.

Fractured rocks are an important source of water for livestock in parts of the Eastern Uplands, particularly in south-eastern Australia, and in parts of the Western Plateau in South Australia, central Australia and Western Australia.

Although ground-water quality may be affected by land-use practices, it is largely determined by four factors: its origin, distance from areas of recharge, solubility of aquifer formations and extent of concentration of salts by evapotranspiration. Map 8 shows the average salinity of ground water in Australia. In many places, especially in north-eastern and central Australia, the quantity and salinity of ground water are unknown. Water of lowest salinity is generally found in the eastern half of Australia and the Great Artesian Basin where relatively high rainfall and surface run-off are available for recharge. Brackish and saline ground water is more prevalent in the arid western half of the continent. Ground-water supplies for urban use are often purified by aeration, chlorination, coagulation, sedimentation or filtration before use.

Table 6. Australia: aquifer characteristics of unconsolidated sediments

Geographical location	Aquifer type and depth	Number of bores	Total volume of water in storage (millions of m^3)	Storage coefficient	Trans-missivity (m^2/day)	Hydraulic conductivity (m/day)	Water salinity (mg of TDS/l)	Yield (millions of m^3/year)	Use
Queensland									
Fraser, Noreton, Bribie, North Stradbroke, South Stradbroke Islands	Unconsolidated dune sand (30-90 m)	...	3 700 (North Stradbroke Island)	...	...	6	Less than 100	Less than 1	...
Haughton River Valley	Holocene alluvial sands (9 m)	200	19 (estimated) 12 (extractable)	0.2-0.25	...	...	300-600	12-20	Sugar cane cultivation
Burdekin Delta	Alluvial sands and gravels (9-12 m, average)	190	2 000-2 500 (estimated) 680 (available)	0.16	3 000	289	...	200	Sugar cane cultivation
Lower Don River Valley	Medium to coarse sands (up to 40 m below surface)	...	(14 estimated)	0.20	3 000	Moderate to high	Less than 600	7	Agricultural, industrial and urban supplies
Pioneer River Valley	Fine to coarse sand and gravel	...	220 (estimated)	0.09-0.21	920 (average)	...	500-2 000	30	Sugar cane cultivation
Callide Valley	Sand and gravel (up to 9 m thick)	...	260 (estimated)	0.1	1 500	...	500-2 000	35	Cash and fodder crops
Don and Dee River Valley	Sand and gravel (3 m)	...	70 (estimated)	0.1	1 100	...	1 000-5 000	7	Cash and fodder crops, irrigation and urban supplies
Boyne River Valley	Quaternary alluvium	...	60 (estimated)	0.03-0.22	600-6 200	...	500-1 000	0.01-0.8	Irrigation of fodder crops
Lower Burnett River Valley (Bundaberg)	Sands and gravels of Tertiary Elliott formation	1 500	...	0.15	300-10 000	...	500	96	Sugar cane cultivation; sugar cane processing mills, Bundaberg Council
Lockyer Valley	Three aquifers, fine to coarse sand and gravel (0.3-6 m)	500	150 (estimated)	0.1	150-750	...	Less than 1 500	70	Crop irrigation
Bremer River Valley	Quaternary alluvium	...	...	...	3 000	...	500-14 000	2.2	Crop and pasture irrigation
Flinders River Valley	Quaternary alluvium, coarse sand and gravel (up to 12 m thick)	...	...	0.02	Up to 1 800	...	200-1 000	0.8	Stock and domestic supplies

Table 6 (continued)

Geographical location	Aquifer type and depth	Number of bores	Total volume of water in storage (millions of m^3)	Storage coefficient	Trans-missivity (m^2/day)	Hydraulic conductivity (m/day)	Water salinity (mg of TDS/l)	Yield (millions of m^3/year)	Use
Queensland (continued)									
Condamine River Valley	Five aquifers, Cenozoic sands and gravel (up to 9 m thick)	More than 300	3 000 (maximum)	0.05	150-3 000	...	Less than 1 000	15	Agriculture
Dumaresq River Valley	Holocene alluvium at depths up to 18 m; sand and gravel up to 12 m thick	...	...	0.1	Up to 1 500	...	Up to 2 000	40	Crop irrigation
New South Wales									
Hunter River Valley Denman/ Aberdeen area	8-12 m	More than 500	...	0.2-0.01	150-1 800	...	...	0.4-1.2	Irrigation
Tomago	Aeolian sands	...	...	...	...	...	Low salinity	35	Urban supplies
Botany	Aeolian sands	...	...	...	...	...	...	20	Industrial supplies
Namoi Valley Peel River	Alluvium (6-9 m deep in gravel)	...	...	0.2-0.01	149-1 500	...	200-800	0.4-0.8	Irrigation and stock supplies
Narrabri	45-105 m	...	...	0.2-0.01	149-1 500	...	200-800	2.5-10	Irrigation, urban and industrial supplies
Macquarie Valley	Alluvium (12-90 m)	...	...	0.2-0.01	6-900	...	...	0.3-5	Irrigation and town water supplies
Lachlan Valley	Pleistocene Cowra formation, sandy gravel and sands;	...	...	0.2-0.01	45-3 500	...	7 000	0.4-12	Stock and domestic water supplies
	Tertiary Lachlan formation, sandy gravel (75-120 m)	...	...	0.2-0.01	45-3 000	...	800-900	35	Stock and domestic water supplies
Murrumbidgee Valley	Alluvium (18-180 m)	...	...	0.2-0.01	45-1 500	...	150-1 500	35	Domestic and irrigation; augment town water supplies

Table 6 (continued)

Geographical location	Aquifer type and depth	Number of bores	Total volume of water in storage (millions of m^3)	Storage coefficient	Trans-missivity (m^2/day)	Hydraulic conductivity (m/day)	Water salinity (mg of TDS/l)	Yield (millions of m^3/year)	Use
<u>Victoria</u>									
Gippsland Basin	Basdale beds of deltaic origin overlying lower Pliocene calcareous sand dunes - Jemmy's Point formation (100-150 m)	...	...	...	1 200	...	500-1 500	Up to 33	Stock and domestic supplies
<u>South Australia</u>									
Adelaide Plains Basin	Sand and gravel in alluvium	600	...	...	40-1 600	4-1 400	1 200	5	Irrigation and domestic supplies
Lincoln Basin	Quaternary aeolianite over-lying sand and lignitic clay	...	...	...	2 300-8 000	...	600	2	Town and farm water supplies
<u>Western Australia</u>									
Perth Coastal Basin	Unconsolidated terrestrial sands (more than 60 m thick)	...	...	0.01-0.16	500	...	300	26	Domestic water supply, Perth and Bunbury
<u>Northern Territory</u>									
Cabbage Gum Basin	Unconsolidated sand, clay and gravel (up to 20 m thick)	...	...	0.0002-0.0003	15-370	...	360	0.2	Water supply, Tennant Creek
Kelly Well Basin	Silicified sandstone, uncon-solidated sand and gravel (17-34 m below surface)	...	620	0.002	750	...	Less than 1 000	13	Water supply, Tennant Creek
Alice Springs Town Basin	Unconsolidated fluviatile gravel and sands, silts and clay of Quaternary age	...	1.6	0.07	450	...	250-3 000	...	...

Table 7. Australia: aquifer characteristics of sedimentary basins

Sedimentary basins	Area of aquifer (km^2)	Range of common depth to aquifer (m)	Range of common thickness of aquifer (m)	Estimated number of bores, 1974	Range of common bore yields (m^3/day)	Range of common total dissolved solids (mg/l)
Laura Basin	22 000	250-350	50-150	10	...	1 000-3 000
Bowen Basin	93 700	30-600	15-300	900	20-1 000	200-20 000
Maryborough Basin	9 000	50-150	50-150	300	0.1-0.3	1 000-3 000
Moreton-Clarence Basin	82 400	10-85	0.5-55	2 100	10-1 300	140-15 000
Great Artesian Basin	1 611 000	20-1 500	0.3-1 500	22 770	0.4-5 200	100-14 000
Sydney Basin	30 300	25-80	0.1-15	610	10-2 000	300-6 000
Gippsland Basin	7 800	30-600	30-150	650	50-1 500	500-1 500
Western Port Basin	940	40-200	30-45	400	8-800	1 500-4 000
Port Phillip Basin	2 150	50-90	6-40	250	170-800	500-1 000
Otway Basin	24 070	5-1 000	25-300	51 700	8-10 000	400-10 000
Tasmanian Basin	9 280	10	30	120	2	700
Murray Basin	279 600	20-300	1-110	18 200	0.3-2 700	300-30 000
St. Vincent Basin	4 000	5-150	10-120	7 500	100-2 500	700-25 000
Willochra & Walloway Basins	1 700	10-100	5-70	200	50-1 600	1 000-7 000
Pirie-Torrens Basin	10 000	5-80	10-150	850	150-1 500	1 000-30 000
Eyre Basins	750	3-25	5-45	40	500-4 000	500-2 000
Eucla Basin	181 500	30-150	50-150	130	5-250	1 000-25 000
Officer Basin	274 500	10-180	5-120	90	0.1-100	500-25 000
Perth Basin	58 900	5-300	500-1 000	35 000	20-4 000	300-5 000
Carnarvon Basin	128 000	10-600	6-30	800	20-4 000	900-12 000
Canning Basin	468 500	20-600	100-500	1 000	20-6 000	200-14 000
Bonaparte Gulf Basin	10 500	10-80	5-100	130	40-700	200-7 000
Ord Basin	19 500	10-150	5-50	120	10-900	100-8 000
Victoria Basin	44 000	5-120	5-100	420	40-300	50-1 500
Daly Georgina Basin	289 400	35-200	10-100	1 600	100-400	250-6 000
Arnhem-McArthur Province	200 000	1-120	5-100	1 000	40-4 300	50-15 000
Wiso Basin	140 000	10-80	5-50	100	40-400	500-5 000
Ngalia Basin	15 000	30-50	50-200	40	40-1 000	500-5 000
Amadeus Basin	120 000	50-500	30-300	500	40-5 000	500-10 000

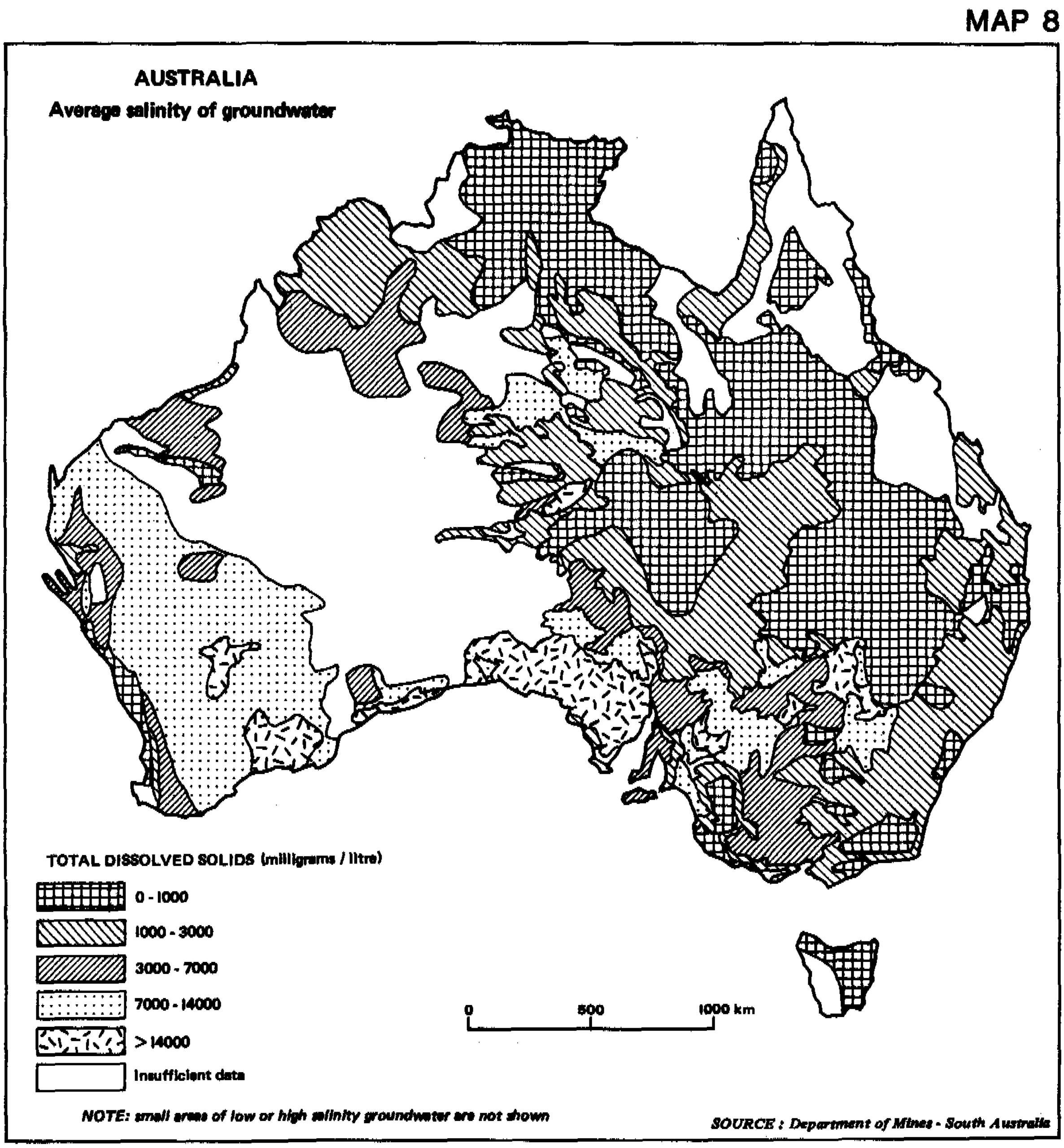
Table 8. Australia: ground-water yields of sedimentary basins

Sedimentary basins	Abstraction during 1974 (m^3x10^6)	Estimated annual recharge (m^3x10^6)	Estimated possible annual yield (m^3x10^6) — From recharge: 1 000 mg/l	1 000-3 000 mg/l	3 000-7 000 mg/l	7 000-14 000 mg/l	14 000 mg/l	Total: 1 000 mg/l	1 000-3 000 mg/l	3 000-7 000 mg/l	7 000-14 000 mg/l	14 000 mg/l	Reliability of estimate a/
Laura Basin	...	22	0	22	0	0	0	0	24.5	0	0	0	(iii)
Bowen Basin	8	2 160	454	1 089	272	182	163	500	1 200	300	200	180	(ii)
Maryborough Basin	0.4	1.5	0	1.5	0	0	0	0	1.7	0	0	0	(iii)
Moreton-Clarence Basin	4.1	50.2	48.6	1.1	0.2	0.3	0	55	1.3	0.26	0.4	0	(ii)
Great Artesian Basin	526	410	217	187	5.6	0.6	0	872	900	56	1.6	0	(i)
Sydney Basin	3.3	166	106	54	4.4	2.2	0.2	230	180	15	21	4.8	(ii)
Gippsland Basin	18	404	191	213	0	0	0	276	261	0	0	0	(ii)
Western Port Basin	4.5	7.6	1.5	6.1	0	0	0	50	18	15	0	10	(ii)
Port Phillip Basin	1.2	29.4	21	8.4	0	0	0	74	24	59	0	0	(ii)
Otway Basin	223	922	654	152		116		1 540	714		373		(ii)
Tasmanian Basin	4.3	1 179	1 054	104	19	0	0	1 061	116	20	0	0	(ii)
Murray Basin	124	451	220	121		110		1 030	1 300		2 650		(ii)
St. Vincent Basin	30	16	8	8	0	0	0	9.5	15	0	0	0	(i)
Willochra and Walloway Basins	0.3	0.6	0	0.6	0	0	0	0	10	0	0	0	(ii)
Pirie-Torrens Basin	10	8	0	1	3	3	1	0	2	20	8	5	(ii)
Eyre Basins	4.9	14	14	0	0	0	0	20	2	0	0	0	(ii)
Eucla Basin	0.01	50	0.01	...	...	...	50	0.01	0.1	1	10	5 400	(iii)
Officer Basin	0.001	50	...	...	...	...	...	...	...	...	...	...	(iii)
Perth Basin	130	1 200	1 060	120	20	1	0.5	1 800	400	140	50	5	(ii)
Carnarvon Basin	20	50	2	6	16	16	...	2	10	35	20	...	(iii)
Canning Basin	10	1 200	1 000	200	...	...	...	10 000	10 000	...	...	...	(iii)
Bonaparte Gulf Basin	2	810	810	0	0	0	0	810	0	0	0	0	(iii)
Ord Basin	0.3	650	...	...	...	...	...	...	...	...	...	...	(iii)
Victoria Basin b/	2	4 000			4 000					4 000			(iii)
Daly Georgina Basin	13.1	3 375			3 375					3 410			(iii)
Arnhem-McArthur b/ Province	5	20 000			20 000					20 000			(iii)
Wiso Basin	0.5	60		60		0	0		300		0	0	(iii)
Ngalia Basin	0.3	10		10		0	0		150		0	0	(iii)
Amadeus Basin	5	80		80		0	0		500		0	0	(iii)

a/ Reliability of estimate: (i) derived from reasonable investigation information; (ii) derived from limited investigation information; (iii) derived without investigation information.

b/ Yields from storage negligible in comparison with yields from recharge.

(Map 8: Australia: average salinity of ground water)



3204.6x

Ground-water development

The magnitude of the task of assessing the water resources of the continent led to the formation in 1962 of the Australian Water Resources Council by the Australian and state Governments. The Council has as its primary objectives the provision of a comprehensive continuing assessment of Australia's water resources and the extension of measurement and research so as to provide a sound basis for the planning of future development. The Council is supported by a number of technical committees and panels of experts, including the Technical Committee on Underground Water.

Ground water is an important substitute for surface water in many parts of Australia. It is the main source of water for more than half the continent, where reliable surface water supplies are not readily available. It is also the source of supply of a number of smaller areas needing large amounts of water for industrial or irrigation purposes.

Reliable data are not available on the number of bores, wells and springs used for widely scattered pastoral and domestic water supplies and the amount of water withdrawn from these sources cannot be estimated with any accuracy. Certainly hundreds of thousands of watering points have been developed for these purposes and new supplies are still being developed. Excluding the Great Artesian basin, which is considered separately below, it is possible that withdrawals for scattered rural and domestic supplies are about 730 x 10^6 m^3/year (200,000 bores with an average discharge of 10 m^3/day). The withdrawal points are scattered throughout most of the settled parts of Australia except the western half of Tasmania and other areas with permanent streamflow, where surface waters meet all requirements. There is some concentration towards the more densely settled areas, even though the relative importance of ground water is greater in the arid areas.

In recent decades there has been a marked increase in the withdrawal of ground water to meet irrigation, industrial and urban water-supply requirements. Areas of ground-water use resulting from intensive development are quite small, although by 1970 they accounted for 40 per cent of ground-water withdrawals in Australia. Table 9 shows the more important areas of concentrated use of ground water in Australia.

The Great Artesian Basin underlies 22 per cent of the continent and since the 1880s, more than 20,000 boreholes have produced water from its sandstone aquifers. Of these, about 4,500 flowed when originally constructed; the remainder were sub-artesian. Two thousand nine hundred of the artesian bores were still flowing in 1975. Ground water from the Great Artesian Basin has the inestimable advantage of being mostly fresh in those areas where surface water, if it is found at all, is brackish or saline.

Withdrawals from the basin are mainly for pastoral purposes and are widely spread. The greater part of the discharge from the flowing bores is lost by non-beneficial transpiration and evaporation associated with distribution of water by open bore drains. The requirements for stock and domestic purposes are no more concentrated than those of other pastoral areas, and measures are being taken, when and where practicable, to increase the efficiency of water use. Recent discharge from the basin is about 540 x 10^6 m^3/year (Queensland, 330 x 10^6 m^3/year; New South Wales, 130 x 10^6 m^3/year; and South Australia, 75 x 10^6 m^3/year).

Table 9. Australia: important areas of intensive use of ground water

Area	Quantity (millions of m^3/year)	Use
Burdekin Delta (Queensland)	320	Irrigation of sugar cane
Namoi Valley (New South Wales)	108	Irrigation of small crops
Condamine Valley (Queensland)	100	Irrigation of grain crops
South-eastern South Australia	98	Irrigation; town and industrial supplies
Bundaberg (Queensland)	94	Irrigation of sugar cane; industrial and domestic supplies
Lockyer Valley (Queensland)	70	Irrigation of small crops and fodder
Perth (Western Australia)	66	Irrigation of market gardens, domestic gardens, and urban supply
Hunter Valley (New South Wales	53	Irrigation of small crops
Callide Valley (Queensland)	35	Irrigation of fodder and grain crops
Tomago Sands (New South Wales)	31	Urban and industrial supplies
Pioneer Valley (Queensland)	31	Irrigation of sugar cane and domestic supply
North Adelaide Plains (South Australia)	21	Irrigation of market gardens
Botany Sands (New South Wales)	20	Industrial supply

The distribution of ground-water development by state is summarized in table 10. Scattered rural use is estimated to be in the range of 500-1,000 x 10^6 m^3/year.

Table 10. Australia: ground-water withdrawals by state

(Millions of cubic metres per year)

State	Intensive use (urban supplies and irrigation)	Great Artesian Basin
Queensland	710	330
New South Wales	230	130
South Australia	170	75
Western Australia	50	-
Victoria	85	-
Northern Territory	...	1
Tasmania	-	-
Total	1,245	536

Future trends in ground-water development are difficult to predict. In a number of basins, including the Great Artesian Basin, the Burdekin Delta, the Bundaberg area and the North Adelaide Plains, development has reached or exceeded the level that can be sustained by natural recharge. Artificial recharge has been of value in the Burdekin Delta, but in the other areas mentioned some reduction in the level of withdrawals seems likely. In many other basins present withdrawals are less than, and in some cases only a small fraction of, the available resources, although generally the resources of the less developed areas cannot be assessed for lack of data. In addition to an overall increase in ground-water use, it is likely that in future development greater attention will be directed to the management of surface- and ground-water resources as interrelated parts of a total water resource.

Experiments with artificial fracturing of rocks are in progress to increase the yields of ground water from the extensive basalts of central and western Victoria, which are important sources of water.

More attention is at present being given to the integrated management of Australia's water resources. For example, the potential of conjunctive use - the complementary development of surface- and ground-water resources - is being examined. In the drier regions of Australia, with high evaporation and variable streamflow, it is often not possible to build economic storage facilities that will provide water reliably throughout the dry season. However, where ground-water supplies can be tapped to make up this surface-water deficiency, smaller storage facilities may be quite adequate. Such developments are being considered as a means of water supply to the new mining towns of the north-west. In the Burdekin Delta, ground-water aquifers are being artificially recharged during the summer wet season, enabling water to be stored at low cost with negligible evaporation.

The concept of a river basin as a water resource unit has been developed in the valley of the Hunter River, New South Wales, which contains industry and towns heavily dependent on local water supplies. In the early days, surface reservoirs supplied water to the Hunter Valley, but in 1920 the Tomago Sands were investigated as a source of water supply for Newcastle and in 1939 the first supplies reached the city. Since 1970 approximately 9 x 10^6 m^3/year has been extracted from the Tomago Sands, about 15 per cent of the total amount of water supplied by the Hunter District Water Board.

Problems associated with ground-water development in Australia

Burdekin Delta

Concentrated use of ground-water close to tidal estuaries and near the coast has caused salt-water intrusion into the aquifer and water quality has deteriorated in bores close to the tidal estuaries. A programme of water sampling every two months has been initiated on 190 bores in the delta. Tidal dams have been constructed on estuaries to prevent excess surface water escaping to the sea and to hold back tidal flow. They have succeeded in raising the water-table near the coast, thereby reducing the ingress of sea water.

Condamine River Valley

Ground water has been used to a considerable extent in the Condamine Plains between Tummaville and Dalby and over-develoment has caused a serious decline in water levels in many bores.

Bundaberg: Lower Burnett River

During the period 1953-1963 the quality of water in the zones tapped for irrigation remained stable, but since then significant increases in conductance have been detected in bores up to 8 km from the coast and some bores have beem abandoned. Salt-water intrusion has developed from overdraught conditions. Trials have shown that artificial recharge by spreading or injection is not feasible. Consequently a large surface storage facility is being constructed on the Kolan River to provide a surface-water supply to some farms at present using ground water, thus enabling ground-water withdrawal to be restricted.

Murray Basin: Victoria

Channelled irrigation schemes to the Riverine Plain have disturbed the natural hydrological balance of shallow aquifers. Infiltration of irrigation water has raised water-tables and increased the pressure in deeper confined aquifers. This effect has been most pronounced in the Kerang-Cohuna district, where the water-table has risen progressively with each irrigation season and is above the surface in places. Other associated problems are waterlogging, increased ground-water salinity and salinization of the soil.

Northern Adelaide Plains

Water levels in this part of the Adelaide Plains have fallen progressively for more than 12 years owing to an increasing demand for irrigation water. Total aquifer recharge has been calculated at 5 x 10^6 m^3/year and total pumping estimated at 4 x 10^7 m^3/year. Excessive use of ground water for market gardening is creating a problem in water-resources management. With a reduction of pressure head in the aquifers there is a possibility that salinity will increase owing to influx of adjacent and overlying saline ground water.

Perth Basin

The limited supply of surface water and its increasing salinity could lead to restrictions in the growth of the City of Perth. Hence greater use must be made of ground water, especially from the upper unconfined aquifer, for both agricultural and domestic supplies. However, in many areas this water has a high iron content, resulting in substantial staining of facilities as well as deposition in pumping equipment and pipes. Studies have been initiated to determine the nature and causes of the high iron content in relation to the hydrogeochemistry of the ground water in the Perth area.

Confined aquifers have been tapped to supply the Perth metropolitan area, but the formation is poorly consolidated and has been known to collapse and crush casing and screens to depths of 600 to 750 m. Furthermore, the geological structure is complex and block faulting, tilting and absence of parts of the sedimentary sequence makes prediction of salinity and depth of usable supplies difficult.

Other areas in which there are problems associated with ground-water development include the Darling Ranges, Western Australia; the Mount Gambier-Padthaway area, South Australia; the Western Port Basin, Melbourne, Victoria; the Namoi River Valley, New South Wales; and Botany Basin, Sydney.

In many arid and semi-arid pastoral areas which are dependent on ground water from deep bores in sedimentary basins, the water is hot and highly corrosive, so that corrosion of bore-casings and bore-head control equipment becomes a problem. Experiments are in progress, notably in South Australia, with plastic corrosion-resistant equipment.

Selected references

General

Australia, Department of National Development (for the Australian Water Resources Council). 1975. Groundwater Resources of Australia. Australian Government Publishing Service, Canberra.

Australia, Department of National Development (for the Australian Water Resources Council). 1969. Quality Aspects of Farm Water Supplies, Canberra.

Australia, Department of National Resources (for the Australian Water Resources Council). 1975. Review of Australia's Water Resources. Australian Government Publishing Service, Canberra.

Australia, Department of National Resources. 1962. Atlas of Australian Resources. Second series. Map-sheets with booklets containing commentaries, especially climate, rainfall (2nd ed.), Surface Water Resources, Groundwater, Water Use. Canberra. (Published until 1972 by the former Department of National Development; and until 1975 by the former Department of Minerals and Energy.)

Australian Academy of Science. 1964. Water Resources Use and Management. Melbourne University Press, Melbourne.

Australian Bureau of Statistics. 1970-. Official Yearbook of Australia. Australian Government Publishing Service, Canberra.

Dunk, W. P., M. D. Gange and S. J. Hutchinson. 1967. Water in Australia. Cheshire, Melbourne.

Hart, B. J. 1974. A compilation of Australian Water Quality Criteria. Australian Water Resources Council, Technical Paper No. 7. Australian Government Publishing Service, Canberra.

Slatyer, R. O., and R. A. Perry, eds. 1969. Arid Lands of Australia. Australian National University Press, Canberra.

Queensland

Geological Survey of Queensland and Irrigation and Water Supply Commission. 1973. Groundwater Resources of Queensland.

New South Wales

Water Conservation and Irrigation Commission. 1971. Water Resources of New South Wales. Government Printer, Sydney.

Victoria

Meacham, I. 1974. "Surface Water Resources of Victoria". Victoria's Resources, vol. 15, No. 4, pp. 2-5.

Lawrence, C. R. 1976. "Underground Water Resources in Victoria". Geology of Victoria. Geological Society of Australia.

Mines Department and State Rivers and Water Supply Commission. 1974. "Development and Use of Victoria's Groundwater Resources". Victoria's Resources, vol. 15, No. 4, pp. 6-9.

Tasmania

Rivers and Water Supply Commission. 1966 et seq. Tasmanian Water Resources Survey. A series of reports.

South Australia

Department of Mines. 1971. Underground Water Resources of South Australia. 4 maps, scale 1:5,000,000.

Western Australia

Bestow, T. T. 1969. The Assessment and Utilisation of the Underground Water Resources of Western Australia. Australian Institute of Engineers, Perth Division.

COOK ISLANDS

(Self-governing State in free association with New Zealand)

Area: 236 km^2

Population: 18,000

Conditions of ground-water occurrence

Geography and physiography

There are 15 islands in the Cook group, scattered over an area of some 2.2 million km^2 in the south-west Pacific between Penrhyn, situated at latitude 9° S, and Mangaia, at latitude 22° S near the Tropic of Capricorn, and between longitudes 156° W and 167° W (see map 9).

In the Southern Group, Rarotonga (67.08 km^2), the capital and largest of the Cook Islands, Mangaia (51.80 km^2), Atiu (26.94 km^2), Mitiaro (22.27 km^2), Mauke (18.39 km^2) and Aitutaki (18.13 km^2) are elevated and volcanic in origin. Together they support 88 per cent of the total population of the Cook Islands.

Manuae (6.22 km^2) and Takutea (0.29 km^2) in the Southern Group and the islands of the Northern Group, comprising Penrhyn (9.84 km^2), Manihiki (5.44 km^2), Rakahanga (4.14 km^2), Palmerston (2.07 km^2), Pukapuka (1.29 km^2) and Suwarrow (1.52 km^2), are low-lying coral atolls, while Nassau (1.29 km^2) is a sand cay on a coral reef foundation. The total population of some 2,000 on these northern islands live mainly on a diet of fish and coconuts.

Climate

All the islands of the Cook group lie within the hurricane zone. A meteorological service with headquarters in Fiji covers the islands and gives advance warning of the intensity and path of tropical storms. The wet season, when the climate is warm to hot and humid, extends from December to March. On Rarotonga, from data recorded over the past 40 years, mean annual temperature and rainfall are 23.6° C and 2,134 mm, respectively. The remainder of the islands in the Southern Group receive an average annual rainfall ranging between 1,515 mm and 2,000 mm.

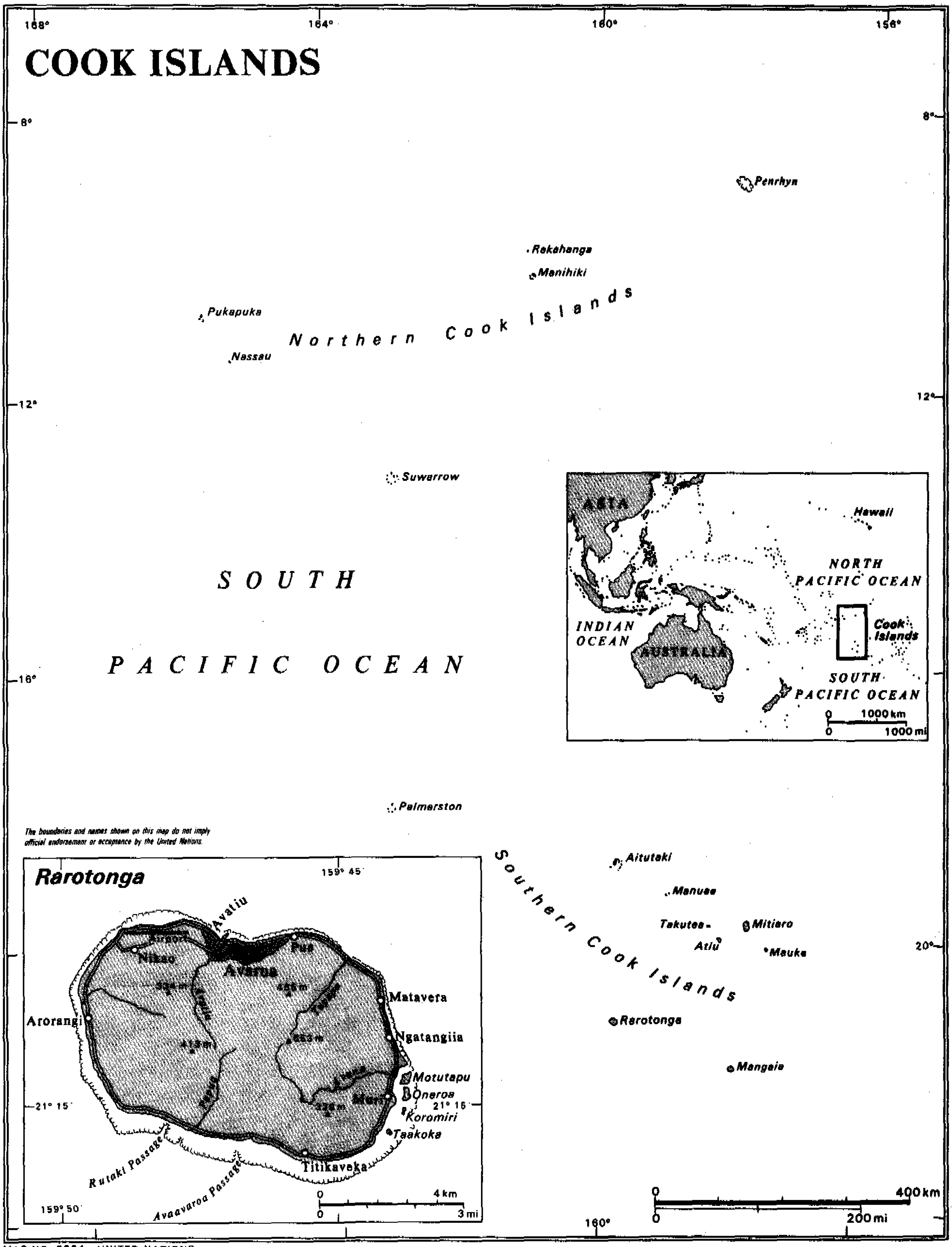
Geology

The Cook Islands include both volcanic land-forms of early Tertiary to Pleistocene age, rising to more than 650 m above sea level on Rarotonga, and coral atolls and cays of Oligocene to Holocene age rising to only a few metres above sea level.

The Northern Group, widely scattered over an area of some 30,000 km^2 of ocean, represent the limestone-topped summits of volcanoes rising 4,500 m to 6,700 m above the sea floor. Each of the six atolls in the group consists of a continuous coral reef surrounding a lagoon containing small islets (motus) rising 3-5 m above sea level. The rock of which the reefs and islands are composed is

Map 9. Cook Islands

MAP 9



MAP NO. 3224 UNITED NATIONS
JANUARY 1983

wholly coral reef limestone and derivative boulders, cobbles, pebbles and sand, overlying a cemented foundation of reef rock.

Penrhyn atoll is the largest and most northerly of the Cook Islands and encompasses a lagoon some 280 km^2 in area and up to 65 m deep. The surrounding reef, segments of which collapsed during the Pleistocene, is broken by three passages. These permit the entry of ships and were possibly drainage channels during times of low sea level. The remaining atolls in the Northern Group are Rakahanga, which is completely surrounded by a reef on which islets are built, rising to 3 m above sea level; Manihiki, a reef-studded lagoon surrounded by islets rising to 5 m above sea level; Pukapuka, broadly triangular in shape with islets at each extremity and probably a shrunken remnant of a formerly much larger structure reduced by the collapse of its foundation which slid into the sea; Palmerston, a more or less circular atoll, the four islet groups of which are equidistant around the perimeter and probably much reduced in size by hurricane seas; and Suwarrow, uninhabited and with only a few small islets on the atoll rim.

The Southern Group of eight separate islands includes a high mountainous island, Rarotonga; four raised coral islands with volcanic cores, Mangaia, Mauke, Mitiaro and Atiu; one atoll, Manuae; one near atoll with a volcanic core, Aitutaki; and a sand cay on a coral foundation, Takutea.

Rarotonga, rising more than 650 m above sea level, is more or less circular with a high volcanic interior of scoria, ash, basaltic flows and dykes of Late Pliocene to Early Pleistocene age, surrounded by a narrow coastal plain of volcanic alluvium, gravel, swamp, and beach deposits underlain by coral.

Each of the islands of Mangaia, Atiu, Mitiaro and Mauke, comprises a core of basaltic volcanics surrounded by a fringe of raised coral limestone (makatea) between 1/2 km and 2 km wide and up to 60 m high. The volcanic cores are normally extremely weathered, eroded and flat topped, and date back probably to the mid-Eocene. The makatea limestone surrounding these islands is craggy surfaced, rugged and bluff forming, commonly with a discontinuous swampy depression separating it from the volcanic interior.

Aitutaki, a volcanic island rising to 124 m above sea level, is situated on a "near atoll" comprising some 15 islets in a lagoon about 40 km in circumference. The igneous rocks are mainly basaltic pyroclastics of lapilli, tuffs and agglomerate, basaltic scoria, breccia and cinders, underlain by solid, thick flows of nepheline basalt. There is no makatea or raised reef on Aitutaki, but eustatic fluctuations of sea level have left benches veneered with alluvium at various levels between 12 m and 76 m above sea level and beach deposits at 1 m and 2.5 m.

The remaining islands in the Southern Group are Manuae and Atiu, both coral sand islets on an atoll within a closed lagoon, and Takutea, an uninhabited sand islet surrounded by a coral reef a short distance offshore.

Ground-water resources

Historical

On the volcanic islands water supplies were originally obtained from permanent inland streams or fresh water springs near the coast. On the atolls, supplies were obtained from holes dug to the water table and from seeps. Subsequently, rain water tanks, initially constructed of sand and cement and later of galvanized iron and steel, were installed for community purposes. These community facilities, usually of a capacity of 45 m^3, still exist in many villages, but the installation of individual household tanks in houses that increasingly reflect European design, has resulted in many families having their own supplies.

Regional distribution of aquifers

In recent years, the gallery system of water supply has been introduced on Rarotonga and on Aitutaki, four such systems having been constructed in the high interior on Rarotonga at Avana, Avatiu, Takuvaine and Papua, and one on Aitutaki at Vaitekea. Although the installation, consisting essentially of a porous pipeline buried below the water-table along an intake area, is initially labour intensive, it is maintenance free once commissioned. On Rarotonga, water from each of the galleries flows by gravity via storage reservoirs to a ring main which services virtually every domestic, industrial, and commercial facility on the island.

On the islands of Aitutaki, Atiu and Mauke, drillholes in the volcanics supplement community water supplies. Their yield is not great (less than 0.22 l/sec) but might be increased with future improved design. The depth of the hole is determined by the height of the drill collar above sea level, since overpumping, and consequent potential lowering of the water level to below sea level, could result in sea-water contamination.

A drilling project sponsored jointly by the Governments of New Zealand and the Cook Islands is currently (1979) being undertaken on the outer islands of the Southern Group. It entails drilling eight holes in the volcanics on Mangaia, Atiu, Mauke and Aitutaki, and one hole in the makatea on Mauke. In the volcanics the water is probably perched, with some leakage penetrating to underlying rocks. In the makatea the hole will penetrate to the dome-shaped fresh-water lens known to float on salt water.

Although in the Southern Group the quality of water is variable, it generally receives little or no treatment. Community supplies from roof catchments and drillholes are stored in covered tanks, and galleries are sited in areas away from taro plots and swamps. Pools in the makatea have so far been utilized solely for irrigation and washing purposes.

The pH averages 6.9 in water from drillholes and 7.2 in undisturbed surface samples from pools within the makatea. As expected, chloride and pH, increase with depth as a result of the lens mixing with underlying sea water.

In the Northern Group, roof water stored in tanks is the main source of domestic supply. Additional supplies could be obtained from the fresh-water lens but the pumping facility and abstraction rates will need careful design and management to maintain acceptable quality.

Selected references

Overseas Territories, and Cook Islands and Niue. New Zealand Official Yearbook, 1978, 83rd Annual Edition, Section 36. Wellington, Government Printer.

Waterhouse, B. C. 1974. Report on Rarotonga Infiltration Galleries. New Zealand Geological Survey Report, Otara. 16 pp.

____________. The hydrogeology of the Southern Cook Islands, Niue and Tonga. Pacific Island Water Resources, W. R. Dale, ed. (Wellington, New Zealand, Department of Scientific and Industrial Research, 1981), pp. 57-74.

____________, D. R. Petty and K. Browne. 1978. Cook Islands; Outer Islands Water Supply (Southern Group). New Zealand Geological Survey Report, Otara. 16 pp.

Wood, B. L. and R. F. Hay. 1970. Geology of the Cook Islands. New Zealand Geological Survey Bulletin, n.s. 82. 103 pp.

EASTER ISLAND

(Chile)

Area: 179 km^2

Population: 1,600

General

Easter Island is considered to be the most solitary island in the world. It is located at a distance of about 3,700 km from Chile and about 1,700 km east of Pitcairn island and French Polynesia. It is a volcanic island, triangular shaped (see map 10). The inhabitants are of Polynesian origin. The climate is of the sub-tropical type, warm and humid with an average temperature of 20° C (18° C in August, the coldest month, and 24° C in February, the warmest month). Yearly rainfall is in the range of 1,000-1,400 mm; highest rainfall values are observed in May. The northern part of the island is more humid than the southern part. Evaporation is relatively high (1,200 to 1,500 mm) due partly to the great number of windy days (78 per cent).

Geology

Easter Island is the highest part of a volcanic, mostly submarine, ridge. It has developed from three main volcanic centres: Maunga Terevaka, Rano-Kau and Poike, and many additional "parasitic" centres.

Poike may have been a separate island at one time; it is a volcano with simple lava stratification and a small crater at its summit.

The crater of Rano-Kau is certainly a caldera. From its size and steep slopes, Rano-Kau was probably higher at one time before collapsing. Maunga Terevaka does not have a recognizable crater, although it might have had one in the past; it shows small eruptive areas at the top. On Poike, three secondary eruption centres may be seen; they are trachyte cupolas.

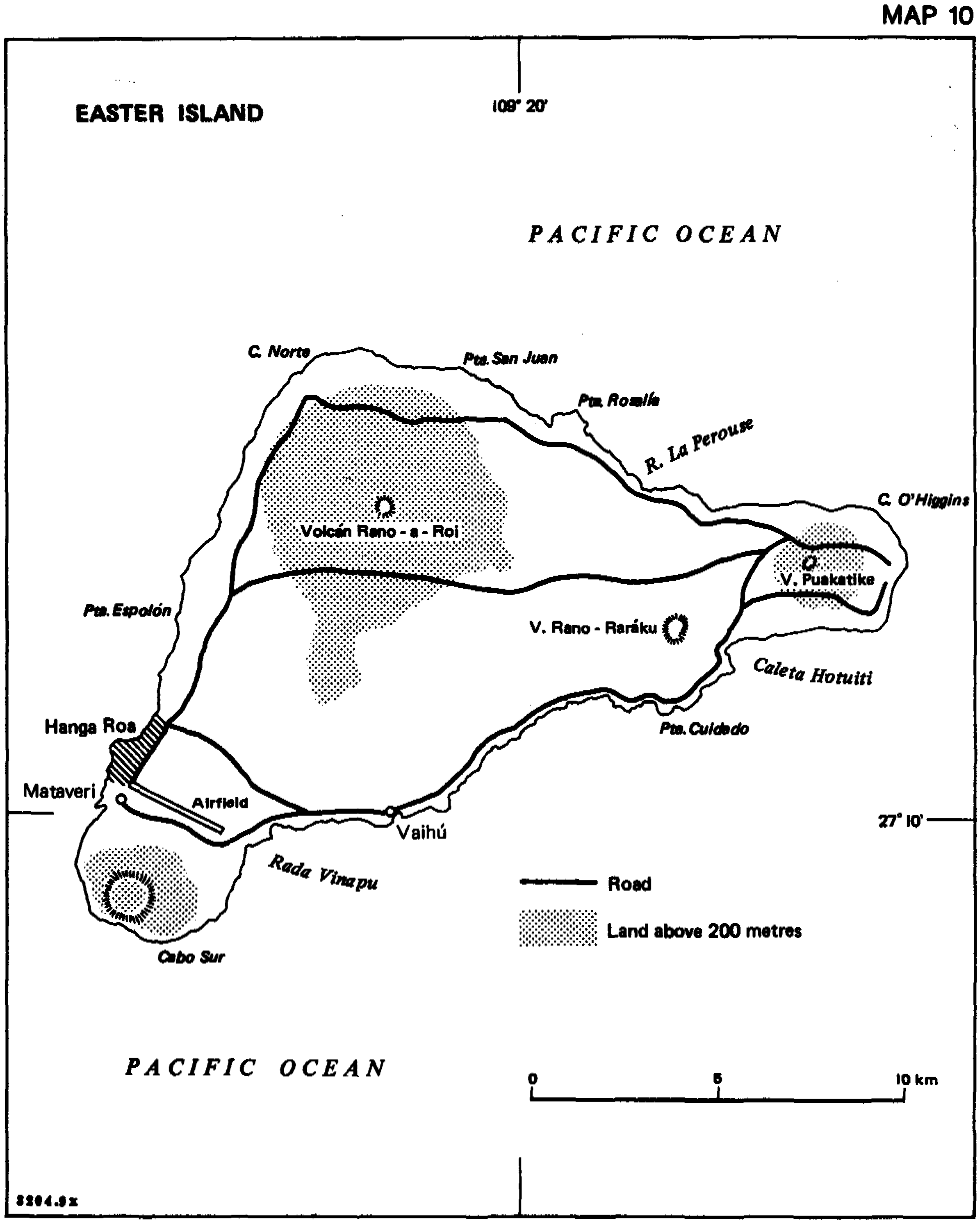
On Rano-Kau to the north east in the lower part of the mountain, a secondary crater can be seen, on top of which a small trachyte outcrop is visible, with associated obsidian.

The parasitic centres of Terevaka are mainly cinder cones, some of which have produced lava flows. Others are made of basaltic volcanic tuffs, well stratified, with inclusion of dense basaltic lava, as in the case of Rano-Raraku.

Orito hill may have originated from a lava cone and basaltic ashes in which a trachytic cupola developed and an outflow of obsidian.

Easter Island lavas belong to a series which includes basalts, trachytes and rhyolites - mainly alkaline - and which is characteristic of high seas oceanic islands.

Map 10. Easter Island



In Easter Island many volcanic features are fairly recent. For example, it clearly appears that Terevaka and its calderas experienced appreciable volcanic activity after such activities had ceased in Poike and Rano-Kau. On the other hand, the ancient eruption activities of the three volcanic centres may have occurred contemporaneously, while a number of the parasitic cones of Terevaka, together with some lava flow, may have developed several thousands or several tens of thousands of years later.

The most recent activity took place in the northern area (Los Escoriales). It resulted in three small cones and a discharge of basaltic lava (with olivine) in the Rohio area. This lava field seems to be fairly recent, as shown by the rare vegetation and the soils. It is estimated that its age is of the order of 2,000 to 3,000 years.

Most of the soils have a volcanic origin as a result of a relatively recent laterization and weathering of lavas and ashes. They contain a fair amount of rocky and argillaceous elements and show an advanced process of lixiviation of bases. Most of them lack potassium, phosphorous and nitrogen. They are less than 50 cm thick and have a poor water retention capacity. The deepest soils occur in the lower third of the volcanic slopes or in areas where surficial deposits tend to accumulate, especially in the vicinity of the coastline. In certain areas close to the bedrock, a clayey layer has developed which does not allow much infiltration of water. Erosion marks are abundant and landslides are frequently observed, specially on the steepest slopes.

Water resources

No surface streams occur on the islands. Ground water cannot be widely used owing to its saline content, and extraction is not easy since the depth to water is great.

Three surface-water sources are found in the craters of Rano-Aroi, Rano-Raraku and Rano-Kau, where small lakes have developed; water infiltrates and seeps through rocks to the surface, emerging in the form of small springs, especially near the coastline. Fresh-water occurrences are quite rare and their yield does not exceed at best 1 l/min; they are of great importance on account of their location and their chemical quality. They are found at some distance from the sea. Brackish water sources are utilized for watering livestock and, at times, as drinking water by the population. Fresh water occurs mainly at the following locations:

Vai Inu Inu, in Rano-Kau cliff;

Punapau, close to Hanga-Roa;

Roiko, a group of underground caves near the leper hospital;

Puna Marugo, near Vai-Matá;

Vai Utu, in the cliff located under Ahu-Vai-Matá;

Vai Tara-Kai, near Anakena;

Ana o Keke, behind Poike;

Roi, between Hanga Tetenga and Anakahanga.

Brackish water is to be found mainly at:

Mataveri o Tai, below Rano-Kau

Te-hai, near Hanga-Roa;

Hanga-Kao-Kao, near Ahu Akapu;

Hanga-Kuakena, near Hanga o Teo;

Te-ava-Renga, between Hanga o Teo and Anakena;

Te-Puna-Rere-Takatea, east of Anakena;

Mauku-Roa, east of La Perouse;

Several ancient wells between Ovahi and Makatua.

Most wells are fitted with windmills and are utilized for watering cattle and occasionally for the drinking water supply of the community.

Rain water may accumulate in depressions of rock areas, providing additional water. The best known of the natural ponds are:

Vai-Atare, in Rano-Kau plain;

Vai a Ripa, in Vaitea;

Vai a Are, near La Perouse.

In order to increase the availability of water supply, tubewells have been drilled since 1964. Out of a total of 26 wells drilled, 15 proved productive (however, 3 of these 15 wells contain highly saline water).

The wells of Mataveri o Tai and Terehai are utilized for the supply of Hanga-Roa town; their yield is adequate to cover present needs. Coastal brackish springs are utilized for the watering of cattle in Vaihu, Hanga Tetenga, Akahanga, Maukuroa and Puna-tere-takatea. Water originating from Rano-Raraku and Rano-Aroi volcanoes are also utilized, as well as ground water from deep wells recently drilled, Hanga (No. 11), Rano-Raraku (No. 24), Poike (No. 19), Orahe (No. 14), Vaitea (No. 23), and La Perouse (No. 15). In some wells no pumps or engines were installed. In many of them fluctuations in water level appear to be related to tide movements, which precludes their utilization. Table 11 shows ground-water yields.

A rough estimate of the availability of water resources on Easter Island is presented below:

(a) Rainfall (1.2 m/year; area 179 x $10^6 m^2$): 258 x $10^6 m^3$/year or $8.2 m^3$/sec;

(b) Water resources potential after evapotranspiration: 15 per cent of the above value or $1.2 m^3$/sec;

(c) Water resources that could be developed for irrigation: about 200 l/sec.

Table 11. Easter Island: Ground-water yields

	Depth of well (m)	Depth to water (m)	Yields l/sec.	Water quality
Mataveri o Tai ravine	27.5	22.6	5.5	Good
Mataveri	20.9		Dry	
Bajo Coquimbo	23.8		Dry	
Rano-Aroi ravine	15.0		Dry	
Vaitea	24.0		Dry	
Mataveri o Tai 2 ravine	35.7	30.2	7.6	...
Rano-Raraku 1	13.0		Dry	
Rano-Raraku 2	7.0		Dry	
Rano-Aroi 2 ravine	31.0	24.1	10	Good
Rano-Aroi 3 ravine	44.5	33.8	50	Good
Hanga-Roa Alto	18.7		Dry	
Anakena	26.6	19.7	20	Saline
Ovahe	17.4	17.8	15	Saline
Hanga-Hanu	25.0	23.8	15	Good
Vaihú	28.0	26.5	20	Good
Sanitorium	21.1	19.8	10	Saline
Hanga To Tea	34.0	31.7	15	Good
Oroina	34.0	31.6	20	Good
Teca-Oi 1	14.0		Dry	
Teca-Oi 2	64.0	60.3	15.3	Good
Hota-Sti 1	14.2		Dry	
Marunga-Oroa	102.0	94.2	30	Good
Hota-Sti	45.1	41.6	50	Good
Mataveri o Tai 3 ravine	48.0	42.3	30	Good
Sanitorium	68.1	62.3	30	Good

Note: The total volume of good quality water extracted is 291 l/sec.

Area: 18,274 km2

Population: 596,000 (United Nations estimate, 1977); 73 per cent in Viti Levu; 17 per cent in Vanua Levu

General

Physiography

Fiji is composed of more than 300 islands, most of which are situated between latitudes of 16° S and 20° S and longitudes 177° E and 178° W (see map 11). The total land mass is 18,274 km^2. The two largest islands, Viti Levu and Vanua Levu, have areas of 6,418 and 3,419 km^2, respectively; the next two largest islands are Kandavu and Taveuni. Situated adjacent to these four islands are three main groups of small islands, the Moala-Lomaiviti group, the Mamanutha-Yasawa group and the Lau group. Isolated from all these islands is Rotuma, which is situated 418 km north of Viti Levu.

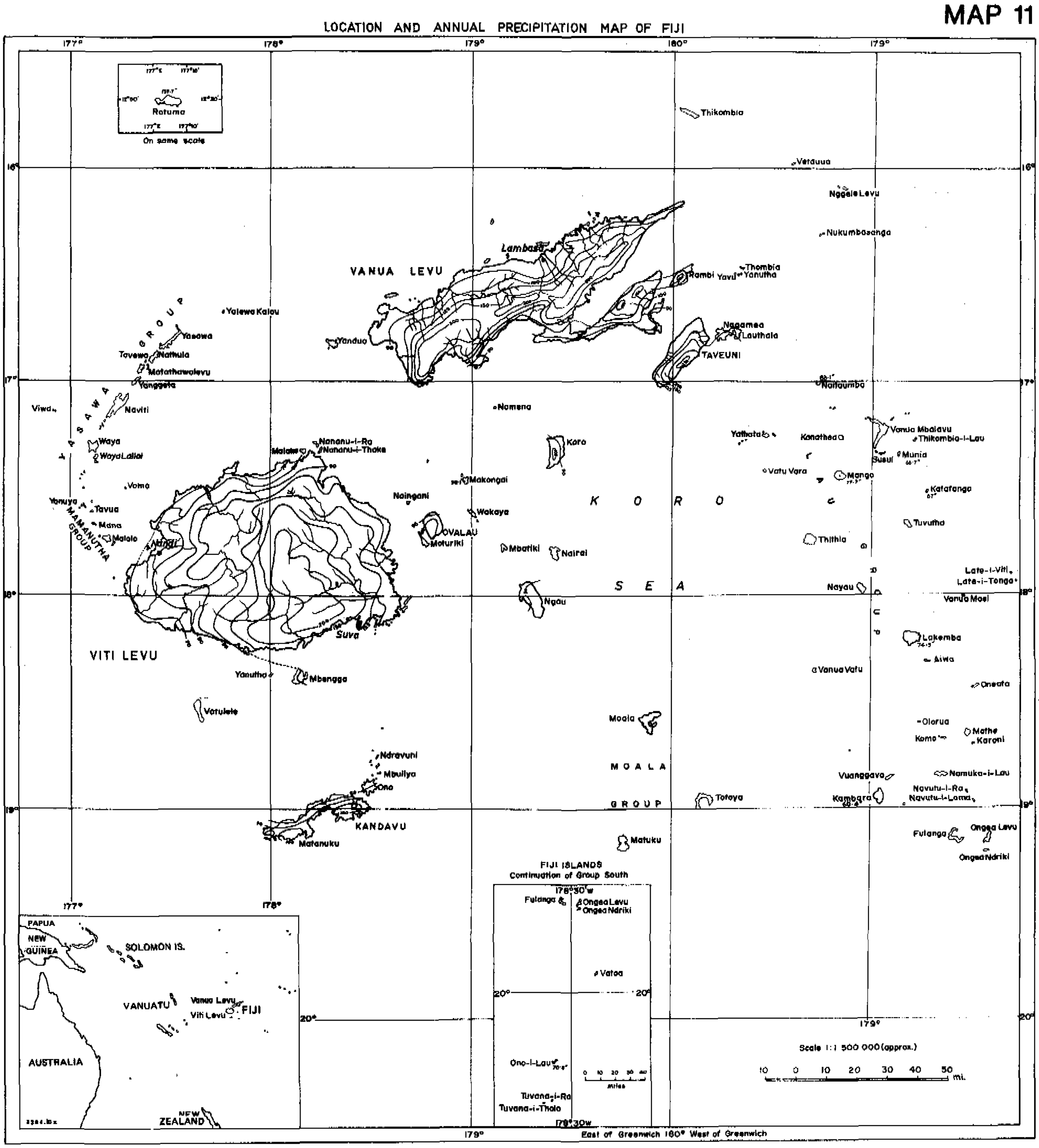
Except for a few islands underlain by limestone, all the islands in Fiji are mountainous. The highest mountains are to be found on the two largest islands. Viti Levu has a central plateau with elevations greater than 1,000 m, but most of the land is composed of steep slopes with elevations ranging between 150 and 1,000 m. The lowlands, where the majority of the population has settled, occur below 150 m and consist of generally flatter land forming the coastal fringe and several large deltas. Most of Vanua Levu consists of generally flat-topped mountains cut by deep, narrow, immature valleys. The height of the land on both these islands has a profound effect upon the climate.

Climate

Fiji has a tropical oceanic climate; the yearly temperature maxima and minima are normally about 32° C and 16° C and the cool season extends from May to October. The dominant winds are the south-east trades which control the pattern of rainfall. Because they are saturated with moisture, any high land mass which lies in their path receives much of the precipitation. The mountains of Viti Levu and Vanua Levu create wet climatic zones on their windward sides and dry climatic zones on their leeward sides. A third climatic zone, between these two extremes, occurs in the intervening mountainous region. Little climatic differentiation occurs on the smaller islands having low relief.

The south-eastern halves of Viti Levu and Vanua Levu, which generally receive between 300 and 500 mm of rain a year, support lush jungle vegetation. The north-western parts of these islands are in the rain shadow of the mountains. They receive less rainfall, generally 180 to 300 mm a year, and have a prolonged dry season, usually of three months' duration. The only parts of Fiji where the mean annual rainfall is less than 180 mm are in the extreme west of Vanua Levu, around the coastal fringes of western Viti Levu and in parts of the Yasawa and Lau islands. The wettest month is usually March and the driest month is almost always July. The annual rainfall between 1965 and 1969 was very low, causing extreme drought conditions and considerable hardship over a large part of Fiji.

Map 11. Fiji: location and annual precipitation



When the monthly rainfall is less than 60 mm in the tropics, it is near the point at which evapotranspiration accounts for most of the water loss from the soil and run-off and percolation become practically zero. In the wet zone, the rainfall is never less than 60 mm, thus there is a surplus of moisture in the soil and plenty of recharge is available for any aquifers. On the dry sides of Viti Levu and Vanua Levu, however, rainfall is less than 60 mm for three months each year. The average soil moisture deficit is about 75 mm from August to November and the average surplus of water is about 300 mm from January to April.

Surface water

Surface water is used to supply all the large communities and most of the villages. Nearly all the villages are situated on the tributaries of main rivers, which usually remain clear after heavy rains, whereas the larger rivers often become turbid with suspended silt. Surface water can be readily polluted by village and cattle effluent. Pollution, a problem requiring costly treatment to overcome, is a particular disadvantage of surface-water supplies that does not arise with ground-water supplies. To date, ground-water supplies have been developed only to a small extent.

During periods of drought, when the small creeks dry up completely, more reliance is placed on ground water. During the drought years of the late 1960s the Government had either to truck water to isolated communities or to ship it to distant islands, at great expense. Thus it is desirable to supplement surface-water supplies with ground water. The Government has a programme within the Department of Public Works involving the drilling of production wells for villages and schools, so that these places will become self-sufficient in water during dry periods.

With the recent tourist boom in the drier and sunnier parts of Fiji, the demand for water has increased sharply, so that a heavier burden is being placed on surface-water resources. More information is therefore required concerning the availability of ground water.

Geology

Geological subdivisions

The geology of Fiji is very complex. Three hundred islands have been grouped into four geological types, each of which has similar geological characteristics (see table 12).

Table 12. Fiji: geological subdivisions

Type 1	Type 2	Type 3	Type 4
Large islands in which the lavas are mainly submarine	Small islands in which the lavas are either submarine or subaerial	Islands with significant amounts of pahoehoe lavas and cinder cones	Small islands with large amounts of limestone
Viti Levu	Moala-Lomaiviti group	Taveuni	Lau group
Vanua Levu	Mamanutha-Yasawa group	Rotuma	Viwa
Kandavu	Mbengga		Vatulele

Type 1 islands

Viti Levu, Vanua Levu and Kandavu are the three largest islands in Fiji. They are composed of many volcanic centres and intervening basins, in which volcaniclastic sediments and flows were deposited. Flows are dominantly intermediate and basaltic, of submarine origin. The sediments are invariably fine-grained tuffs, siltstones and minor sandstones which have received little reworking and often exhibit rapid facies change. Plutonic stocks are known to intrude these rocks in Viti Levu and Vanua Levu. The rocks range in age from late Tertiary tc Pliocene.

(a) Viti Levu

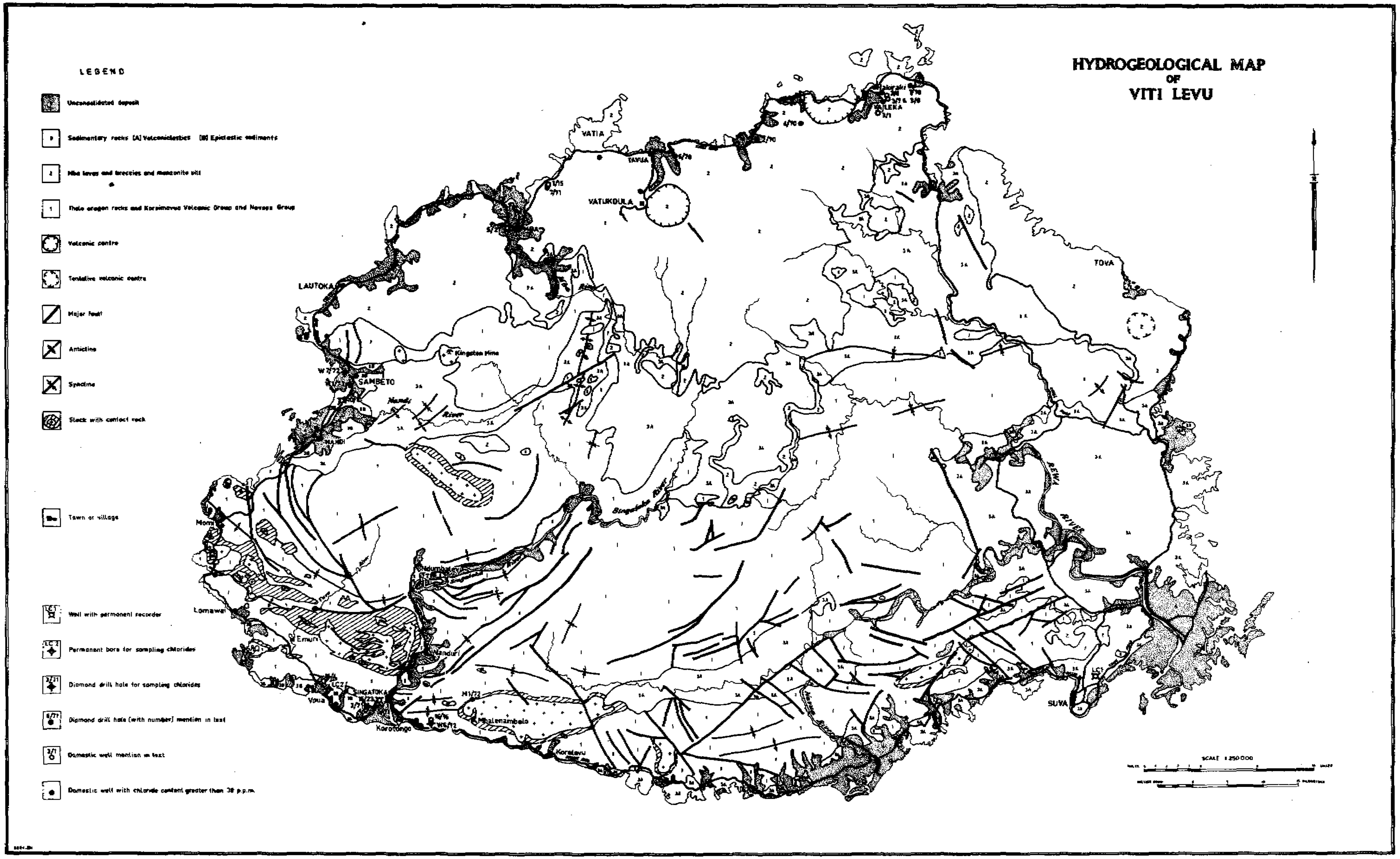
A thick sequence of flows and volcaniclastic rocks ranging from basalt to dacite extends across the southern part of Viti Levu. This sequence was intruded by two gabbro stocks of Eocene age. Starting in early Miocene time, epiclastic strata including limestone lenses were deposited. Major orogeny, involving folding and faulting occurred in the early and middle Upper Miocene. Although the rocks include many geological groups, they have all been classed together in the present report as Tholo orogen rocks (see map 12).

Widespread sedimentation took place during the latter part of the Upper Miocene. Andesite was erupted and provided detritus for the sedimentary basins. Sedimentation continued into the Pliocene.

In northern Viti Levu basaltic volcanoes produced an estimated 3,000 m of lava, essentially marine, during Pliocene time. The rocks of this volcanic pile, excluding its associated sediments, are referred to in the present report as the Mba flows and breccias.

Over most of the bedrock is a thin veneer of unconsolidated material composed of weathered bedrock. Alluvial deposits occur in river valleys as sand and gravel bars and as modern deltas at the mouths of large rivers.

MAP 12



Map 12. Fiji: hydrogeological map of Viti Levu

(b) Vanua Levu

About 10 main centres of volcanic eruption have been recognized on Vanua Levu, which form the main highlands. Mainly Miocene submarine flows and volcaniclastics underlie the island (see map 13).

There are four distinct volcanic groups: the Natewa and Undu Groups, both of Upper Miocene to Lower Pliocene age; the Nararo Group, probably of the Lower Pliocene age; and the Mbua Group of Pliocene age. The Natewa Volcanic Group consists mainly of basic andesites and volcaniclastics which extend from Yandua island in the west through central Vanua Levu to Rambi island in the east. The Undu Volcanic Group comprises mainly dacite and rhyolite volcanics, and assorted sediments which occur in the north-eastern part of the island. The Nararo Group is composed of light grey acid andesites occurring as volcanic plugs and bedded breccias. The Mbua volcanics are dominantly massive, subaerial flow basalts which originated from a shield volcano in the south-western part of the island. Some small areas around the shield volcano has aa flows and brecciation. Most of the flows, however, have columnar jointing and are not brecciated at the top or bottom.

Faulting has cut the island into a series of blocks. Uplift has produced some raised beach deposits on the southern side. Recent weathering has produced a weathered rock mantle of up to 12 m in thickness. Alluvial deposits occurring near the mouths of most rivers and creeks appear to be dominantly clayey mud.

(c) Kandavu

Kandavu and its associated islands have not been mapped geologically, but some reconnaissance work has been done. Kandavu is known to be made up of the products of eight main volcanic centres, which are composed predominantly of andesites.

Type 2 islands

(a) Moala-Lomaiviti group

The smaller islands are the eroded remains of single basaltic volcanoes, whereas the larger islands are the remains of the coalescing of two or more volcanic piles.

The islands of Ovalau, Moturiki, Naingani, Wakaya and Vatu-i-Thake are composed dominantly of submarine volcanic deposits, mainly pillow lavas. The other islands consist of dominantly radially dipping, subaerial lavas and interbedded volcaniclastics cut by swarms of basaltic dykes. This volcanism probably started in Late Miocene time and continued throughout much of the Pliocene. Aa lava flows are the predominant rock type in all these islands except Mbatiki where volcaniclastic rocks predominate.

(b) Mamanutha-Yasawa group

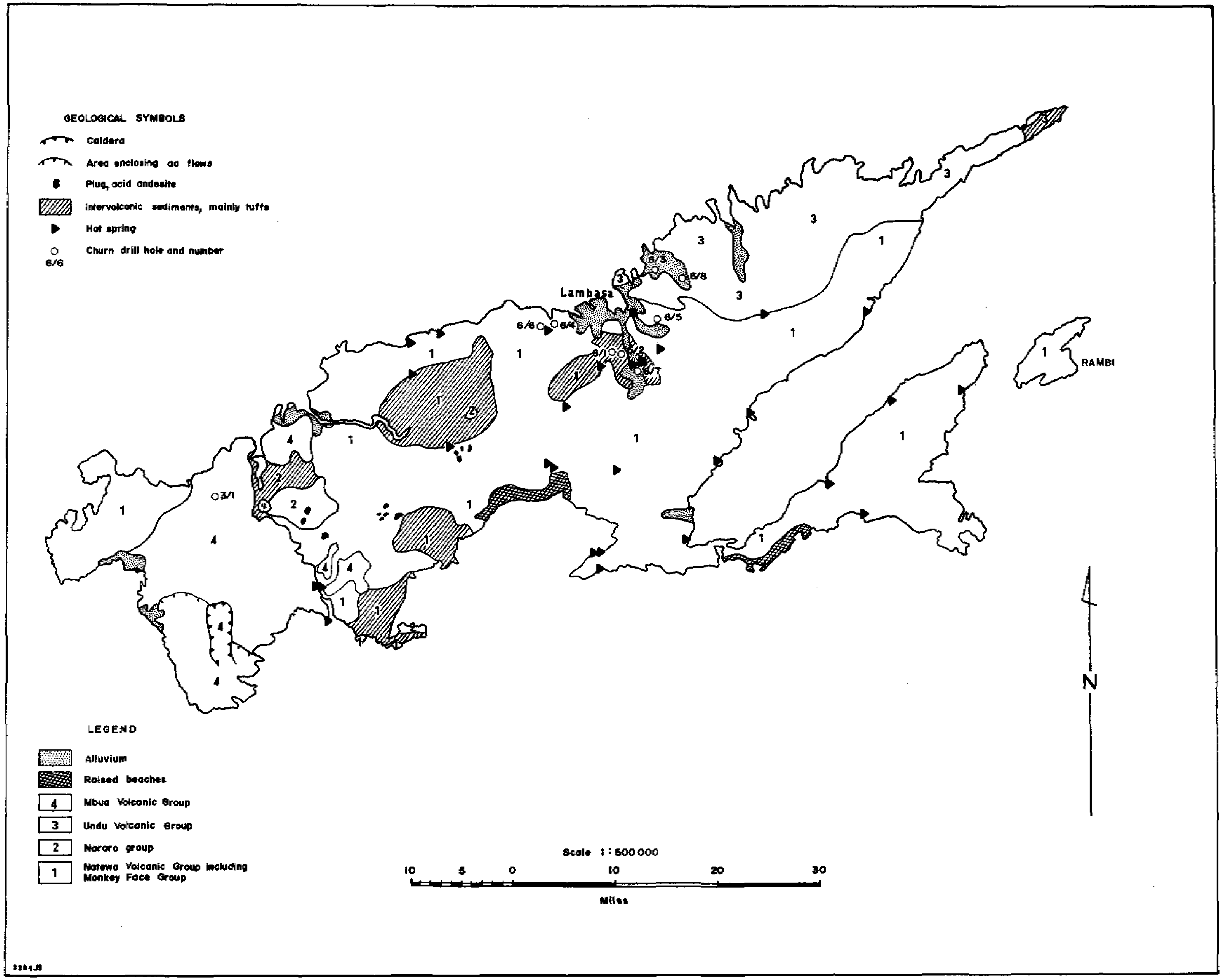
Geologically, all of these islands, except Viwa, are composed largely of submarine basalt of Miocene age. Coral sand has been deposited in low areas around the coast.

(c) Mbengga

Mbengga is situated about eight miles south of Navua, Viti Levu; it is a single-shield volcano composed of subaerial basaltic rocks.

SIMPLIFIED GEOLOGICAL MAP OF VANUA LEVU

MAP 13



Map 13. Fiji: simplified geological map of Vanua Levu

Type 3 islands

Taveuni and probably Rotuma are Pleistocene in age and are two of the youngest islands in the Fiji group.

(a) Taveuni

A series of volcanic centres forms a mountainous ridge about 1,000 m in height, which occurs along the central axis of the island. Taveuni is underlain by rocks that are wholly basaltic in origin; the dominant rock type is undifferentiated alkalic olivine basalt. Aa flows with well preserved levees are dominant throughout the central part of the island; subaerial flows of pahoehoe with lava tunnels and vesicular flow tops occur in southern Taveuni.

(b) Rotuma

Rotuma is very similar geologically to Taveuni. It has a central backbone of highlands, composed of two lines of volcanic cones oriented in an east to west direction. The youthfulness of the topography and the numerous well preserved cones suggest that the island is very young, either of Pleistocene or Recent time. The cones are composed mainly of cinders and blocks of lava. Basaltic lavas slope away from the cones and underlie most of the island. The flows are hard pahoehoe having vesicular flow tops; they are distinct from one another and probably have an average thickness of about 6 m. Jointing is prominent throughout the basalt, and lava tubes can be seen along the coast.

Relatively large areas of coral sand flats occur in the north-east and south-east corners of the island. Considerable amounts of beach rock composed of coarse grains of reef limestone occur around the coast (see map 14).

Type 4 islands

(a) Lau group

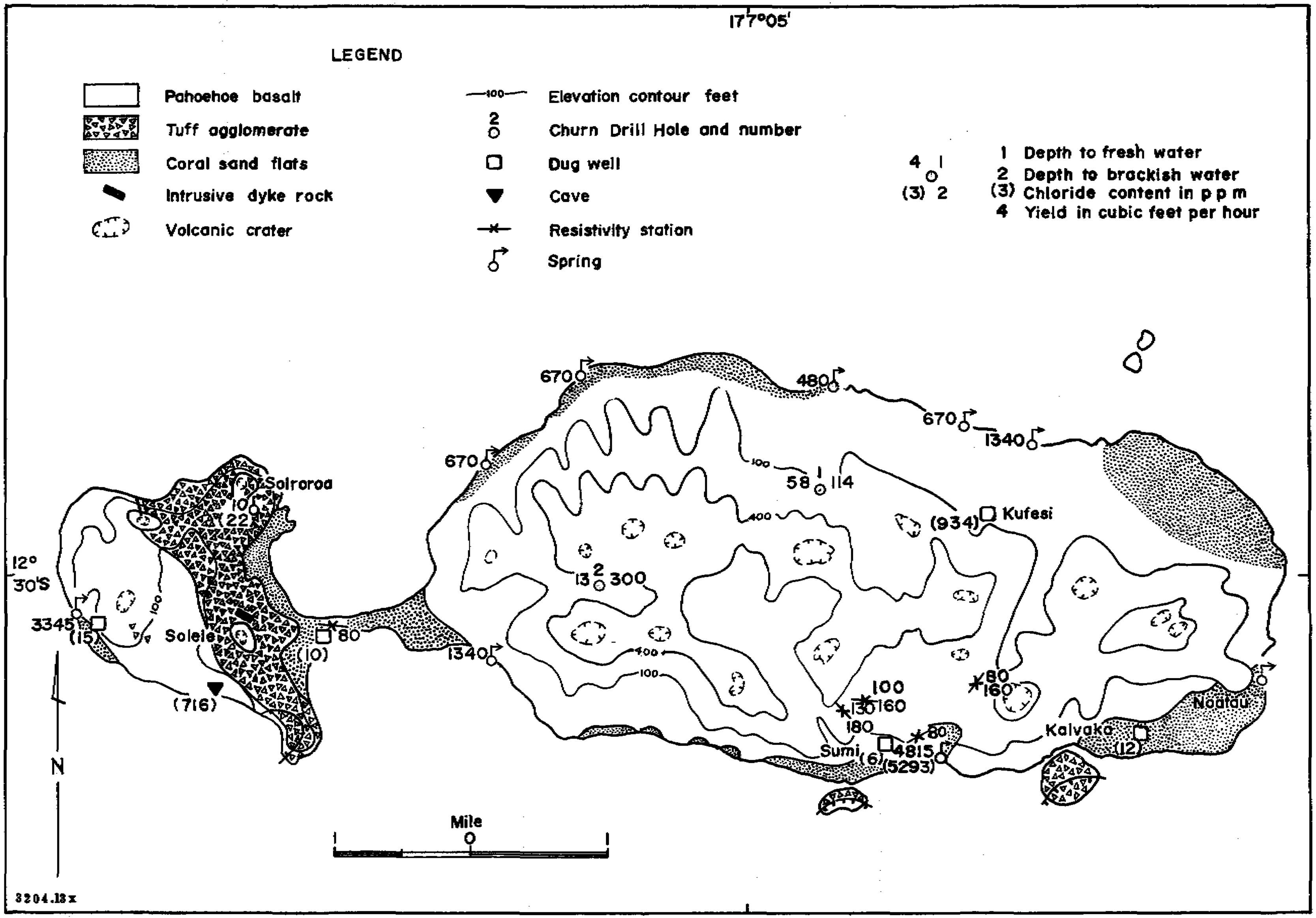
There are two main rock types: volcanics, composed of andesite, basalt, dacite and associated volcanic breccias; and limestone, most of which is composed of foraminiferal detritus. These two main rock types control the physiography and drainage of the islands. Some of the islands which are underlain completely or in part by volcanic rocks have rounded hills and gentle slopes, and others have rugged topography. Small streams occur and develop a dendritic drainage pattern. The islands composed of limestone are often forested and have cliffs around the shore line. No streams have developed on this rock; all the precipitation sinks into the ground and reaches the sea through an intricate system of subterranean caverns and fractures.

The islands of Kanathea, Mothe and Munia are composed solely of volcanic rocks and the islands of Namuka, Ongea, Vanua Vatu, Fulanga, Vatu Vara and Marambo are composed solely of limestone. The remaining islands contain both volcanics and limestone.

(b) Viwa

Viwa is a small island situated west of the Yasawas which consists wholly of uplifted coral-algal reef, probably Pleistocene in age.

Hydrogeological map of Rotuma. MAP 14



Map 14. Fiji: hydrogeological map of Rotuma

(c) Vatulele

The island of Vatulele is situated south of Viti Levu, and consists of uplifted and tilted limestone, with a small area of basaltic rocks. Repeated uplift has tilted the island so that it slopes from west to east. An escarpment up to 30 m has been formed along the western side. The limestone is dense and white, and is composed mainly of reef detritus and broken fossil fragments. Sinkholes have developed extensively along the entire length of the island and two large caves have developed in the north-west. The east coast is covered with brown coral sand, and further inland the soil varies from brown to reddish-brown clay.

Ground water

Hydrogeological history

Most of the water supply, both rural and urban comes from surface-water sources. The main areas where ground water has been investigated are in western Viti Levu and Vanua Levu.

Before 1971, well records for all bores were written by staff of the Geological Survey. These reports were concerned with requests for ground water information in various villages and islands. In 1968, the hydrogeology of southern Taveuni was studied and the basaltic rocks were found to be very permeable; in the same year, water problems on some of the Lau and Moala Islands were investigated (Rodda, 1968); and, in 1969, the hydrogeology of Namuka-i-Lau, Vatoa and Ono-i-Lau Islands was assessed. There are also reports on hydrogeological problems and the selection of borehole sites at Vatulele, Rotuma, Mango, Mana, Vanua Levu and Viti Levu (Gill, 1970-1972). All that work served as a basis for the United Nations Development Programme project entitled "Survey of Ground-water Resources in Fiji" (Carr, 1974).

Since 1974 several projects have been carried out, including Naduri; Nacocolevu (Ratuyawa and Simpson, 1980); Lautoka (Coulson, 1977); Rewa (Australian Groundwater Consultants, 1978) and Nadi (Gale, 1980). Work is at present being carried out at various settlements in Vanua Levu for the purpose of developing a rural water supply.

Prospection

Resistivity is the main tool of prospection and investigation. Other methods used are aerial photography for the location of lineaments, detailed geological studies and, occasionally, other geophysical methods.

Resistivity was used in determining thickness and likely lithology in the Rewa River gravel investigations; it was also used to a great extent in the Nadi investigation, where location of saline contamination was determined. In consolidated sediments surrounding the Nadi Basin, faults/fractures were located on aerial photographs and detailed geology and geophysical traverses were carried out in the areas of interest.

Main Aquifers

The most permeable materials that contain fresh water are pahoehoe lavas found in southern Taveuni and Rotuma.

In Viti Levu the unconsolidated sands and gravel deposits found along the Rewa, Singatoka and Nadi rivers have proved to be very permeable but water quality is unacceptable.

The Meigunyah aquifer, composed of semi-consolidated muds, sands and occasional gravel, has proved to have moderate permeability. The aquifer, in the form of a small basin (61 km^2 in area) on the western coast of Viti Levu, reaches depths in excess of 180 m.

Apart from these aquifers the majority of rocks throughout Fiji are not very permeable, so that ground water is not a large resource. Water is found in small quantities in localized areas of subaerial lavas, fault structure and contact rocks adjacent to stocks that have been only lightly metamorphosed.

Results of ground-water investigations

Apart from the detailed investigations mentioned above, the aquifers have only been classified on the limited data available (Carr, 1974), as shown in the hydrogeological map of Viti Levu (see map 12).

A limited investigation was carried out in Lautoka area (Coulson, 1977), which was followed by a more detailed investigation in 1979. Neither of these investigations discovered any major aquifer, but located individual sites of varying productivity. Location of ground water in these areas has not reached a stage at which aquifers can be delineated since most of the water is found in localized structures.

The Rewa River investigation of the river gravels showed very high transmissivities suitable for an induced recharge scheme but had to be abandoned due to the excessively high iron content of the water which precipitated out in contact with air and increased with time during an extended pumping test. The cause of the high iron content is still under investigation.

The Naduri ground-water investigation was carried out in an area of recent alluvium deposited by the Singatoka River. The sediments were found to have a high clay content resulting in low transmissivity values.

The Nadi project mainly investigated the ground-water resources of the Meigunyah beds, involving recharge studies, extensive drilling and well testing, modelling of the aquifer and study of the saline-intrusion problem. It was concluded that approximately 35 l/sec could be abstracted from the aquifer without causing a major drop in water levels and saline incursion. River gravels were also investigated in this area and were found to be of high permeability but abstraction would be restricted by the minimum flow required in the river and manganese and iron would have to be removed from the water.

The Nacocolevu Project was undertaken to determine the aquifer properties of alluvium along the Singatoka River which again had high permeability but manganese and iron were a problem and chloride becomes excessive if boreholes were sunk too deep.

The results of the investigations are shown in table 13.

Table 13. Fiji: results of ground-water investigations

Geological age and thickness of aquifer	Geographical location	Depth of wells (m)	Specific capacity (l/sec/m of draw-down)	Hydrogeological parameters		
				Hydraulic conductivity (m/day)	Trans-missivity (m^2 day)	Coefficient of storage
Recent (5 m)	Nacocolevu	8	7	Not determined owing to fluctuations and boundary conditions		
Recent	Rewa	...	...	...	...	...
Pleisto-cene (60 m)	Nadi	60	0.7	2.0	100	10^{-4} to 10^{-3}
Recent (13 m)	Nadi River	20	14	360	5,000	...
...	Rotuma	...	...	...	...	...
5-8 m	Southern Taveuni	80-150	...	30-100	200-800	10^{-5} to 10^{-4}

Water quality

Ground waters found in Fiji are dominantly of the calcium bicarbonate and sodium bicarbonate type and nearly all fall within the recommended limits. When boreholes have been drilled too close to the sea, however, the ground water has a high chloride content. There is the further problem of the high manganese and iron content of the ground water in river gravels. This problem does not appear to clear up with time, since analyses of waters indicate that the manganese and iron ions are in equilibrium with the ground water.

Water quality was found to deteriorate at depth in the Meigunyah beds near the contact with the underlying formations. This is not recent saline intrusion but continual and weak flushing by meteoric water of the deep residing saline water.

Thermal springs occur at 15 localities on Viti Levu and 25 localities on Vanua Levu and a few others on smaller islands. All thermal spring waters are heated meteoric water.

Further work required

No aquifer has yet been found that will provide ground water in sufficient quantities for urban supplies of suitable quality. The main use of ground water will therefore be to supply settlements where no surface supply is available. Steelements are usually of low population and are spread over a large area, so that a few boreholes for each settlement would provide sufficient water to meet demands. In this connection, work is being carried out by the Mineral Resources Department in Vanua Levu. This type of water supply also needs investigating on the smaller islands which are either limestone or volcanic. However, alternative methods (e.g., ground water from boreholes, wells or trenches, surface-water supplies and roof catchments) should be compared to find the optimum method of supply.

For large areas of the main islands there is no knowledge of ground-water resources, since only a few boreholes have been drilled and no resource investigation has been carried out.

Ground-water development

The Water and Sewerage Sector of the Public Works Department is responsible for the provision of a water supply. In 1980, it was estimated that 84 per cent of urban households have piped water and 74 per cent of the rural population have reasonable access to a clean water supply. Most of the water comes from surface sources. When ground-water sources are required the hydrogeology section of the Mineral Resources Department is requested to carry out an investigation. The Department keeps records of hydrogeological data and collects relevant data when available. Limited investigative drilling is carried out by the Department's drilling section. Hydrological studies are undertaken by the Hydraulic Section of the Public Works Department.

In the Mineral Resources Department, the Principal Geologist (Hydrogeology/Mapping) is in charge of the hydrogeology section. At present, the section has two hydrogeologist posts and four technical officer/assistant positions.

Hydrogeologists and technical officers have attended training courses in the United States of America and Japan and all technical officers and technical assistants have attended a short course in earth sciences at the University of the South Pacific. Beyond this, training is provided by hydrogeologists on the job.

Hydrogeological equipment includes water-level recorders and dippers, depth samplers, pressure transducers, borehole flow-metres, weir tank and field chemistry kits. The Mineral Resources Department has a chemistry section where a full analysis of water samples can be made including identification of some trace elements.

Drilling

The Mineral Resources Department (drilling section) has three churn (percussion) rigs, one Universal rig (air hammer, auger, rock bit and diamond drill) and three diamond drill rigs with ancillary equipment, compressors, pumps, etc. Borehole test pumps owned by the Public Works Department are available. The drilling record of the Mineral Resources Department for the years 1975-1979 is shown below.

	1975	1976	1977	1978	1979
Hydrogeological	301	1,418	412	1,758	1,499
Other	143	365	455	37	51
	444	1,774	867	1,795	1,550

The drilling section operates under a superintendent who has in his charge two drillers (higher grade), one technical officer II (drilling), five senior technical assistants (drilling) and one technical assistant (drilling). In addition, a drill crew of two or three members is assigned to each rig. The drillers, technical officers and some of the senior technical assistants have had overseas training, in the form of secondment to a drilling company for several months.

In the private sector, one major contractor (Nagan Engineering) has carried out drilling of private wells with two or three rigs. The company also carries out drilling contracts for the Public Works Department when the capacity of the Mineral Resources Department is insufficient. The Emperor Drilling Company has also carried out work for the Government, but little work in the private sector. Except when these contractors are working for the Government, lack of adequate legislation does not permit accurate records of drilling to be kept.

Utilization of ground water

At present, ground water is only used to a very limited extent for water supply. At Mba (Viti Levu), there are six boreholes pumping into the town reticulation scheme and one borehole at Tagitagi. At Nadi two boreholes pump approximately 600 m^3/day into the reticulation scheme which is mainly supplied from two river intakes.

At Singatoka there is one borehole and at Korotongo there are two boreholes pumping into town the supply.

A borehole also provides water at Naselesele on Taveuni.

Private boreholes are used by several companies (e.g., Shell Vuda), schools and private individuals.

Rotuma has had boreholes drilled, which are to be put into production in the near future, as are the boreholes at Nacocolevu near Singatoka.

The use of borehole supplies is likely to increase in the future, the main area of interest being settlement supplies in Vanua Levu.

Ground-water problems

In Viti Levu the majority of boreholes for water supply are situated near the coast owing to the distribution of population. This has led to saline-intrusion problems at Tagitagi, Singatoka and Korotongo and appears to be causing the movement of saline water towards the borehole at Waimalika (Nadi).

Large potential sources of ground water from induced recharge into river gravels have had to be abandoned subsequent to investigation, owing to the high concentrations of manganese and iron in the water. To date a policy of removal of suspended solids from river water has been followed in preference to removal of the manganese and iron by precipitation and filtration.

Selected references

Published

Rahiman, A. The hydrogeology of Fiji. Pacific Island Water Resources. W. R. Dale, ed. (Wellington, New Zealand, Department of Scientific and Industrial Research, 1981), pp. 87-90.

Unpublished reports

Australian Groundwater Consultants. 1978. Navuso Project.

Carr, P. 1974. Survey of groundwater resources in Fiji.

Coulson, F. 1977. Groundwater exploration in the Lautoka region.

Gale, I. 1980. Nadi Groundwater Project.

Gill, S. A. 1970. Pump test results at Nangingi, Vanua Levu. Fiji Geological Survey file BS. 1, vol. 2, p. 75.

__________ 1970. Pump test results on borehole at Nakama near Labasa. Fiji Geological Survey file BS. 1, vol. 2, p. 27.

__________ 1970. Occurrence of groundwater on Vatulele. Fiji Geological Survey file BS. 1, vol. 2, p. 33.

__________ 1971. Rotuma water supply. Fiji Geological Survey file BS. 1, vol. 2, p. 123.

__________ 1971. Selection of borehole sites for Mango estate water supply. Fiji Geological Survey file BS. 1, vol. 2, p. 130.

__________ 1972. Water supply from Mana Island, Mamanutha Group. Fiji Geological Survey file BS 1, vol. 3, p. 74.

__________ 1972. Resistivity work at the airport - Sambeto area, Nandi. Fiji Geological Survey file BS. 1, vol. 4, p. 7.

__________ 1972. Mango water supply. Fiji Geological Survey file BS. 1, vol. 4, p. 13.

Rodda, P. 1968. Water Supply in the Lau and Moala Groups. Fiji Geological Survey note PR1.

Simpson, A., and S. Ratuyawa. 1980. Report on Matovo (Cocolevu) borehole site investigation. Mineral Resources Department file BP/18.

FRENCH POLYNESIA

(French Overseas Territory)

Area: 4,000 km^2

Population: 140,000

General

French Polynesia comprises 130 islands belonging to five archipelagos (see map 15):

The Society Islands (population, 117,700) which include:

Windward Islands: Tahiti and Moorea;

Leeward Islands, 200 km west of Tahiti;

The Marquesas Islands (population, 5,500), 1,500 km north-east of Tahiti;

The Tuamotu Archipelago (population, 9,000), some 80 coralline atolls, 1,000 to 1,500 km east of Tahiti;

The Gambier Islands, 10 islets, 1,700 km south-east of Tahiti; and

The Austral Islands (population, 5,000), 600 km south of Tahiti.

Tahiti is the largest and most populated island. It covers an area of 1,000 km^2 and has a population of 95,000 which is about 70 per cent of the total population of the Territory. Central French Polynesia alone is scattered over some 4 million km^2 of ocean waters.

The weather is of the tropical oceanic type, a cooling effect being exerted by a secondary branch of the Humboldt stream.

At Papeete, the capital, located in Tahiti, the average temperature is 26.5° C. The average daily increase is 10° C (the maximum temperature recorded was 36° C).

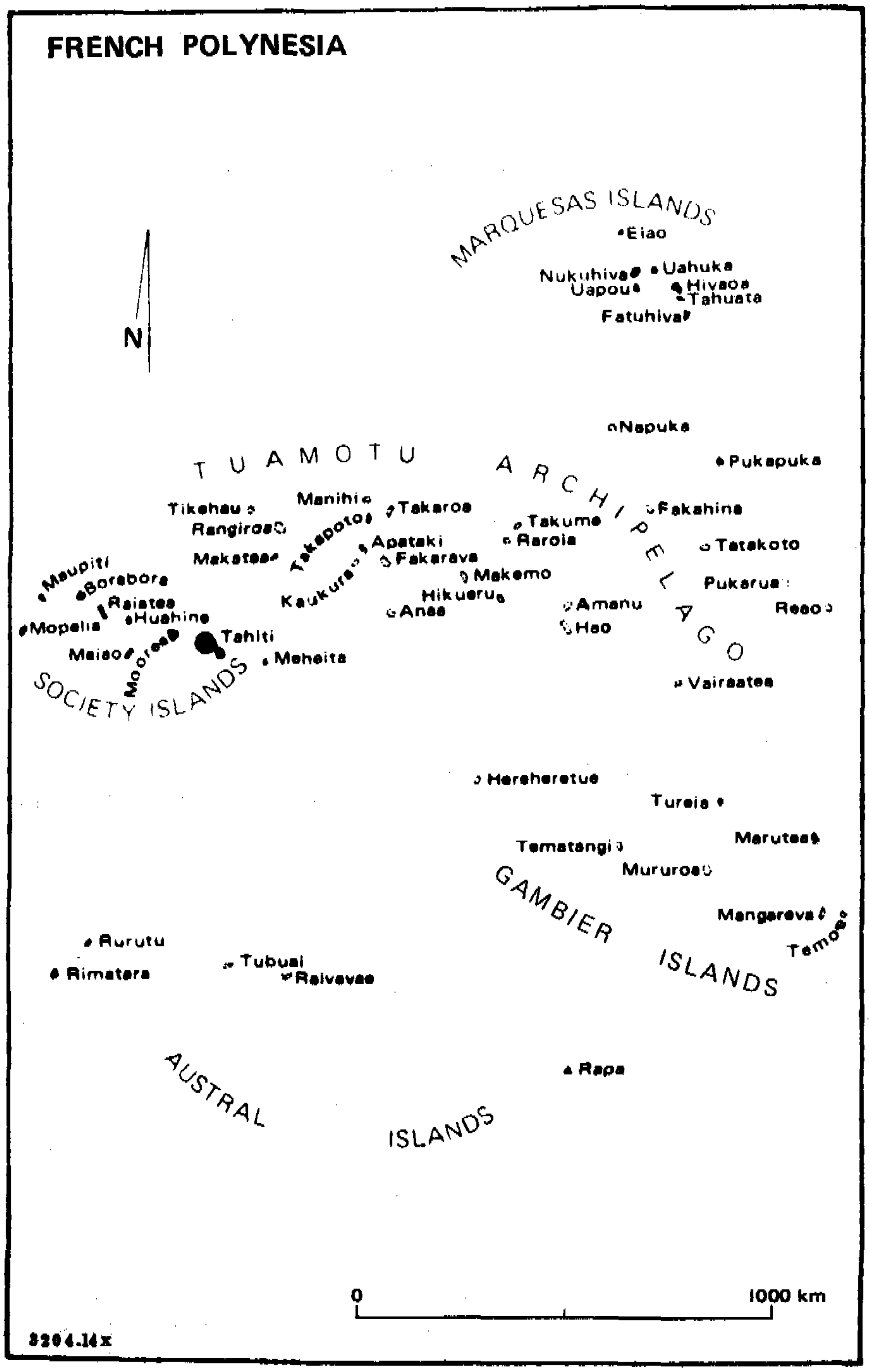
Rainfall is abundant; it is quite unevenly distributed throughout the year, the variations depending on the movement of the southern Pacific subtropical high pressure belts. During the hot season (austral summer), that is, from 1 October to 31 March, rainfall is abundant; from 1 April to 30 September, the dry season, rainfall is notably less.

Rainfall also varies according to location. In Tahiti it increases from the western coastal plain (2 m/year) to the eastern coastal plain (3 m/year). The mountainous central area receives 9-10 m/year. Yearly rainfall averages 1.1 m in the Marquesas, 2 m in the Austral Islands, 1.5 m in western Tuamotu and 1 m in eastern Tuamotu.

The Marquesas have a rain season in the middle of austral winter. In the Austral Islands, especially Rapa, no significant seasonal rainfall variations are observed.

Map 15. French Polynesia

MAP 15



Geology

All five archipelagos are volcanic in origin; they are distributed along lines oriented west-north-west/east-south-east or east-west, corresponding to submarine mountain ridges.

Volcanic activity began during the Tertiary age. The most recent manifestations occurred some 2,000 to 3,000 years ago. At present volcanic activity is limited to quakes, the epicentres of which are located south-east of the Society Islands and in the Austral Islands.

Geological evolution is summarized below, from north to south.

Marquesas Islands

The Marquesas are a group of 10 islands located upon a network of orthogonal faults oriented 83° N and 179° N. Volcanism began with a piling up a basalt flows beginning with oceanites and ending with andesites. Then an explosive phase occurred during which pyroclastic breccias were thrown out and an important network of dykes, trachytic lavas or phonolites appeared. The explosive phase was followed by movement of collapsing and subsidence. Marine erosion was facilitated by the absence of coralline formations related to the existence of cold streams and, as a result, the islands were reduced to their highest central areas.

Tuamotu Archipelago

The coralline atolls which make up the Tuamotu Archipelago are scattered over a line 1,000 km long, with an elevation not exceeding 2 m above ocean level. Some islands (e.g., Makatea and Niau) have been raised a few metres higher. The atolls are located on the top of ancient volcanoes, as may be seen from the results of deep boreholes drilled in Mururoa atoll. During the glaciation periods of the Quaternary, the development of madreporic formations ceased.

Visible geological formations are related to the development and destruction of coralline structures and rocks such as reefs, sands, limestones and "beach rocks".

Society Islands

The archipelago comprises volcanic islands. Tahiti, the largest and one of the most recent islands of French Polynesia, belongs to this group. The main geological feature is the Hawaiian type of basalt volcanism. The volcanic activity has been moving from the north-west to the south-east, the youngest and easternmost volcano being Meheita. Tahiti, where no volcanic activity has taken place for 1.4 million years, is characterized by "young" morphological features. The core of the island comprises two volcanic cones gently sloped and deeply cut by erosion. The calderas filled with late intrusion of granular crystalline rocks are drained by means of two important valleys oriented north-west.

The coastal plain which developed during the last marine regression is a narrow strip of land a few tens to a few hundreds of metres in width; it broadens in the vicinity of the mouths of main rivers.

Similar overall structural features are encountered in the other islands of the archipelago, with variations according to the importance of the erosion and/or subsidence phenomena.

The volcanic Hawaiian structure has been formed by the piling up of gently sloping (6° to 10°) basalt flows alternating with cinder horizons. Three phases of activity have been identified:

(a) A major phase, which produced main outcrops consisting of a thick piling up of basaltic lavas of the oceanite type, cut by a network of dykes;

(b) An intermediary phase, which produced lava containing more alkaline elements (trachyandesites; the phonolitic domes of the Leeward Islands);

(c) A terminal phase, which produced very fluid basaltic lavas, similar to those of the initial phase.

Also to be mentioned, mainly for Tahiti, are valley-filling formations which include breccia or strictly lavic types of rocks.

The Society Islands are surrounded by a lagoon protected by a well developed barrier reef. Volcanic tectonics have deeply marked all the islands in the form of dense networks of faults oriented north-east/south-west and east-north-east/north-south-west.

Gambier Islands

This group of 10 volcanic islands is located at the intersection of the Tuamotu and Society alignments. It is surrounded by a 80 km long circular reef. All the islands have been formed by a piling up of slightly sloping basaltic flows and cinder beds which constitute a single collapsed eruptive unit, only a few points of which emerge. All rock formations are basalts with a dense network of dykes.

Austral Islands

These seven islands are oriented along a 1,500 km alignment from Rapa-Bass in the south east to Maria island in the north west. (The Cook archipelago is a north-west extension of the Austral Islands.) It is the most ancient archipelago of French Polynesia. The initial phase included submarine and aerial basalt formations (aubaramites, oceanites). By the end, explosive phenomena occurred to which are related dykes, flows, and trachyphonolitic thrusts (Tubuai island). Further movements, up to 100 m, have at times resulted in the raising of ancient reefs (Rurutu island). In many places they were accompanied by renewed activity which produced breccias and lavas.

Ground water

Ground-water investigation and development differ broadly according to the type of island which is considered: high islands (emerged volcanic masses) and low islands (atolls).

High islands

Ground-water conditions have been studied in some detail in Tahiti. By and large they can be considered typical, as far as high islands are concerned, although significant variations can be observed in aquifers from one island to another.

Basalt aquifers

The mass of volcanic rocks which constitute the high rise islands include a network of fractures and permeable horizons (mostly scoria) which are at the origin of the infiltation of precipitation and the subsequent circulation of ground water. Some obstacles to the flow of ground water can be found, however, such as impervious compact rock horizons, ancient argillaceous weathered areas and basaltic lava dykes. The search for exploitable aquifers requires that detailed prospection should be undertaken, due to the great lithological variations encountered from one area to another. A systematic approach has been tentatively developed and several types of aquifers have been defined; (all of them, however, are fissure aquifers).

Perched aquifers

These aquifers discharge through springs, the yield of which varies widely. A regulating effect, however, is exerted by the important condensating effect of vegetation. Large-scale exploitation of these aquifers is not permitted except in areas of extreme water shortage.

Perialluvial aquifers

Most of the alluvium can be considered impervious, compared with the embanking surrounding basaltic rocks. These rocks have been drilled, and yields up to 10 and 100 l/sec have been obtained, depending on the importance of the valleys and local conditions.

Dyke aquifers

This type of aquifer is intensely tapped in Hawaii. In the Society Islands the network of vertical dykes, dense in the vicinity of the caldera but less so at the periphery of the volcano, is likely to constitute a natural underground reservoir having separate compartments. Ideally the network should be dense enough to prevent the outflow of ground water downstream, but not too dense, since the various compartments should be of reasonable size. Fissured or fractured rocks constitute ground-water reservoirs. The occurrence of recrystallization is, in general a sign of water unproductivity (Huahine and Bora Bora Islands).

A detailed study which was carried out in Fantana Valley permitted the identification of important dyke aquifers and the studying of their recharge through horizontal boreholes. Ground-water extraction was optimized up to a yield of 140 l/sec, which corresponds to the natural recharge of the aquifer system. Small perched aquifers were recognized and exploited through horizontal boreholes yielding a few litres per second or some tens of litres per second (Moorea and Maupiti islands). Tapped water proved to be of an excellent quality. However, it has to be noted that ideal conditions for the existence of dyke aquifers exist only in large volcanoes, of which Tahiti is the unique example in French Polynesia.

Weathered mantle aquifers

Chemical alteration of basalts under oceanic tropical climates resulted in a thick silty layer in which, in many cases, the initial structure of the rock can be identified.

The silty layers always hold a high water content so that they constitute at times a true aquifer which can be exploited by means of drainage ditches. Yields, which rarely exceed a few litres per second, are utilized for the supply of small communities (e.g., in the Marquesas).

Coastal aquifers

Coastal plains may theoretically contain fresh-water bodies floating on top of salt water. Coastal sediments are mainly constituted of silty or clayey material or coralline debris with poor hydrogeological characteristics in most cases. In low alluvial valleys overall conditions are similar.

In Tahiti, in conditions similar to those observed in Oahu (Hawaii), a confined coastal aquifer has been identified under impermeable volcanic or sedimentary formations called caprock which provide good protection to the aquifer.

A systematic study of the extension of these formations was undertaken in Tahiti and their exploitability was determined in the north-west, where three test pumping stations have yielded up to 277 l/sec. In addition, unconfined coastal aquifers have been identified mainly in areas where caprock does not occur. In general, they are connected to submarine springs. To date little has been done to develop these aquifers owing to their vulnerability to sea-water contamination.

Atolls and low islands

The conditions of occurrence of ground water in atolls are by and large those described in the classical scheme of Ghyben-Herzberg which shows an asymetrical fresh-water lens floating on oceanic salt water. However, this oversimplified picture, under real conditions, is greatly modified owing to the dynamics of the fresh-water/salt-water complex and to local geological characteristics, especially the occurrence of beach rock.

The Polynesians have for many years known the possibilities offered by fresh or brackish atoll aquifers and have exploited them by means of shallow wells. Waters, however, have a high calcium and hydrogen sulphur content, which originates from the decomposition of coralline organic matter. Rain water collected from tin roofs and stored in cisterns is generally preferred. As a result of more elaborate studies on Rangiroa and Manihi atolls, it has become possible to define better the ways and means of optimizing exploitation of fresh-water aquifers in the atolls, through:

(a) Determination of the thickness of the fresh-water lenses;

(b) Knowledge of the evolution of the fresh-water/salt-water interface under the influence of pumping, so as to determine the safe yield and avoid raising the interface.

One of the main conclusions of the hydrogeological reconnaissance was to acknowledge the relationship existing between the occurrence of beach rock and the occurrence of a fresh-water lens. The evolution of the lens was checked through resistivity measurements made in piezometres surrounding the test borehole. The optimal safe yield could be determined as well as the optimal duration of the pumping periods.

In the exceptional case of raised atolls, a true karstic network could be identified in the mass of coralline limestone, and the exploitation of some ground-water outflows could be undertaken (e.g., on the atoll of Niau).

Hydrogeological investigations

Systematic hydrogeological investigations have been undertaken since 1966, inspired by those carried out in Hawaii since the late nineteenth century.

Hydrogeological conditions in Oahu and Tahiti were found to have much in common when the geological map of Tahiti was completed.

In 1964 a local ground-water investigation was made in Bora Bora by the Bureau de Recherches Géologiques et Minières (BRGM).

A first three-year hydrogeological study was entrusted to the Laboratoire des Travaux publics de Polynésie française by the Service de l'Equipement covering Tahiti and some other islands. Four drilling rigs were used and air photographs on a scale of 1:40,000 were available. The study resulted in the identification of three types of exploitable aquifers: dyke aquifers, perialluvial aquifers and coastal aquifers. An inventory of springs and wells was made and hydrogeological characteristics of aquifers were determined.

In addition to the study, which was of a general nature, systematic investigations were carried out in some areas of Tahiti and some of the outer islands where water needs are important, as follows:

(a) Sector of Faa-Punaavia (Tahiti), where seven boreholes were drilled and the exploitability of confined aquifers under caprock conditions was ascertained. The eight pumping stations which were built in the area deliver at present some 40,000 m^3 of water a day to the densely populated north-western coastal area of Tahiti, where no surface-water resources are available for use;

(b) Zone of Papeete (Tahiti), where dyke aquifers were studied. These aquifers currently produce some 12,000 m^3/day of good quality water for the supply of the capital;

(c) Islands of Raiatea, Huahine, Tahaa, Bora Bora, Maupiti, Mangareva where extensive investigations were carried out.

Since 1972 the management of the piping systems for the supply of water has been the responsibility of the newly created communes. The communes of Tahiti have set up a Syndicat central de l'Hydraulique, entrusted with the exploitation of new sources of water and the construction of new water works, mainly for tapping the flow of the numerous perennial rivers.

In the other islands, hydrogeological investigations were developed on a local basis as a result of specific requests - rather than systematically - under the sponsorship of the Service de l'Equipement with the assistance of the Laboratoire des Travaux publics.

As far as high islands are concerned ground water is either considered as a complement to surface water or as the unique or most economical source of water to serve local needs related to hotels, schools or health centres. The results achieved are shown below.

Bora Bora (Leeward Islands)

An aquifer was discovered in the weathered basaltic mantle ("mamu") in Tiipoto and in Vaitape village; it has been exploited through a battery of 10 wells yielding an average of some 1,200 m^3/day. As a result, there has been a noticeable improvement in the water-supply conditions on the island, where tourist development appears to be quite promising. Further investigations have been concentrated on a coralline islet close to the main island through a low-yield pumping system tapping water from drainage trenches, which is piped under the sea to the island of Bora Bora. Investigations in Faanui and Anui villages have not proved successful.

Tahaa (Leeward Islands)

The water-supply system of Vaitoare village was improved through the exploitation of an artesian well (4 l/sec), and investigations were conducted in Tapuamu Valley.

Moorea (Windward Islands)

The northern part of the island, where prospects for tourist development are promising, lacks surface water. Ground-water exploration resulted in (a) the identification in Temae of a perched aquifer (in dykes) at some 60 m above sea level, with a yield in the range of 15 l/sec; and (b) the development of small yields (1 l/sec) in trachytic lavas located in the coastal plain.

Maupiti (Leeward Islands)

A perched aquifer at an elevation of 25 m was identified in basaltic lavas compartmented by a relatively dense series of dykes. Yielding 3 l/sec, it is utilized for increasing the water supply of the islands during the dry season.

Huahine (Leeward Islands)

Ground-water exploration has shown that hydrothermal kaolin deposits have filled basalt fractures in most areas thus rendering them impermeable. Open fractures, however, have been found close to Fare village. A yield of 13 l/sec has been developed to serve the needs of the population located in the northern part of the island.

Raiatea (Leeward Islands)

West of the town of Uturoa artesian aquifers were identified at the bottom of an ancient trachytic horizon. Three boreholes deliver 200 m^3/hour, which satisfies the needs of the town (2,500 inhabitants).

Tubuai (Austral Islands)

Reconnaissance boreholes were drilled in Mataura sector. They proved largely negative, since both the basaltic bedrock and its cover show little permeability.

Maiao (Windward Islands)

An aquifer was identified in unweathered basalts underlying clayey deposits. During the dry season it supplies some 0.15 l/sec to local communities.

Manareva (Gambier Islands)

A well which was dug in the coastal aquifer close to Rikitea village and which was delivering 3 l/sec was contaminated as a result of overpumping. Further investigations focused on the availability of surface water in the northern part of the island.

Marquesas Islands

To date ground-water investigations have been quite limited, involving Nuku-Hiva (drilling in Taihoae) and Tahuata.

In the low islands the studies have dealt with the potential offered by the fresh water (Ghyben-Herzberg) lenses, especially for the water supply of small communities (hotels, hospitals etc.), as a complement to meteoric waters. Reconnaissance studies were carried out in the atolls of Rangiroa, Tupai, Tetiaroa, Niau and Manihi. The exploitation of this type of aquifer in the best possible conditions permits the extraction of 2-5 m^3/day per well through 12-hour pumping. The radius of influence of the wells is 80-100 m. The terrain is extremely vulnerable to pollution. In Niau atoll a karstic or fracture aquifer has been identified in coralline limestone.

Water-quality considerations with respect to Tahiti

Ground water has in general a low mineral content (150-400 ppm). There is a marked difference between basalt waters and waters from coastal deposits which include significant amounts of carbonated rocks. The latter waters contain a significant amount of calcium and magnesium bicarbonate.

Coralline waters are in most cases highly mineralized, with a significant amount of hydrogen sulphur, alkaline constituent.

Inland, close to the central caldera, mineral springs yielding gaseous water of the chalybeate sulphur type occur.

Conclusions

In French Polynesia, ground-water exploration and development are still in the early stages. Large-scale efforts were concentrated on Tahiti island where there are important water needs to be satisfied. Although surface water is abundant in Tahiti, its development may prove costlier than that of ground water, but the situation may change as a result of the rising costs of energy. More attention may be given in the future to the development of gravity schemes. An effort is also being made in the field of renewable energy with respect to the operation of pumping installations (e.g., windmills, solar cells and hydropower).

On most islands, however, surface water cannot meet the increasing needs resulting from population growth. Furthermore, since water is so cheap, there is a tendency to waste it: per capita consumption of 1,500 l/day and more has been observed, whereas normal needs are assessed at 350 l/day. Ground water is likely to play an essential role in the development of high islands. In some cases (in respect of hotels, for example), desalination of sea water may prove to be the only solution.

The Government is at present particularly concerned with improving water-distribution systems in order to reduce waste, remodelling the distribution networks, preparing an inventory of water points and intensifying ground-water studies.

Selected references

Unpublished reports from the open files of the Service de l'Equipement, Tahiti

Becker, M., and J. Guillen. Laboratoire des Travaux Publics de Polynésie française: Rapports sectoriels sur les recherches hydrogéologiques effectuées depuis 1970 en Polynésie.

Deneufbourg, G. Notes géologiques sur les îles de Maupiti, Raiatea, Tahaa, Huahine, Tahiti, Bora-Bora, 1961-1964. Bureau de Recherches Géologiques et Minières, Orléans, France.

_____________. Cartes dégologiques et notices de Tahiti, Huahine, Raiatea, Tahaa, Bora-Bora. Bureau de Recherches Géologiques et Minières, Orléans, France. 1965.

Espirat, J. J. Rapport sur une mission d'hydrogéologie dans l'île de Bora-Bora. Bureau de Recherches Géologiques et Minières, Orléans, France. 1964.

Mink, J. F. Les ressources en eau de Faa, Tahiti. 1971.

Petit, P. Etudes hydrogéologiques en Polynésie française. Centre d'Etudes du Bâtiment et de Travaux Publics. 1969.

Villot, R. Rapport sur la mise en exploitation des stations de pompage dans les archipels, 1978-1980.

GUAM

(Territory administered by the United States of America)

Area: 549 km^2

Population: 104,000 (United Nations estimate, 1977)

Guam, the southernmost of the Mariana Islands, lies at latitude 13°30' N and longitude 144°45' E. It is a single small elongated island, about 48 km long, with an area of 549 km^2 (see map 16).

Conditions of ground-water occurrence

The island is divided into nearly equal physiographical halves, the northern 260 km^2 composed of a limestone plateau that gently rises northwards, between elevations of 60 and 185 m and the southern half composed predominantly of a dissected volcanic terrain on portions of which isolated terraces of limestone rest. The maximum elevation of 407 m is a limestone-covered volcanic ridge in the southern half of the island.

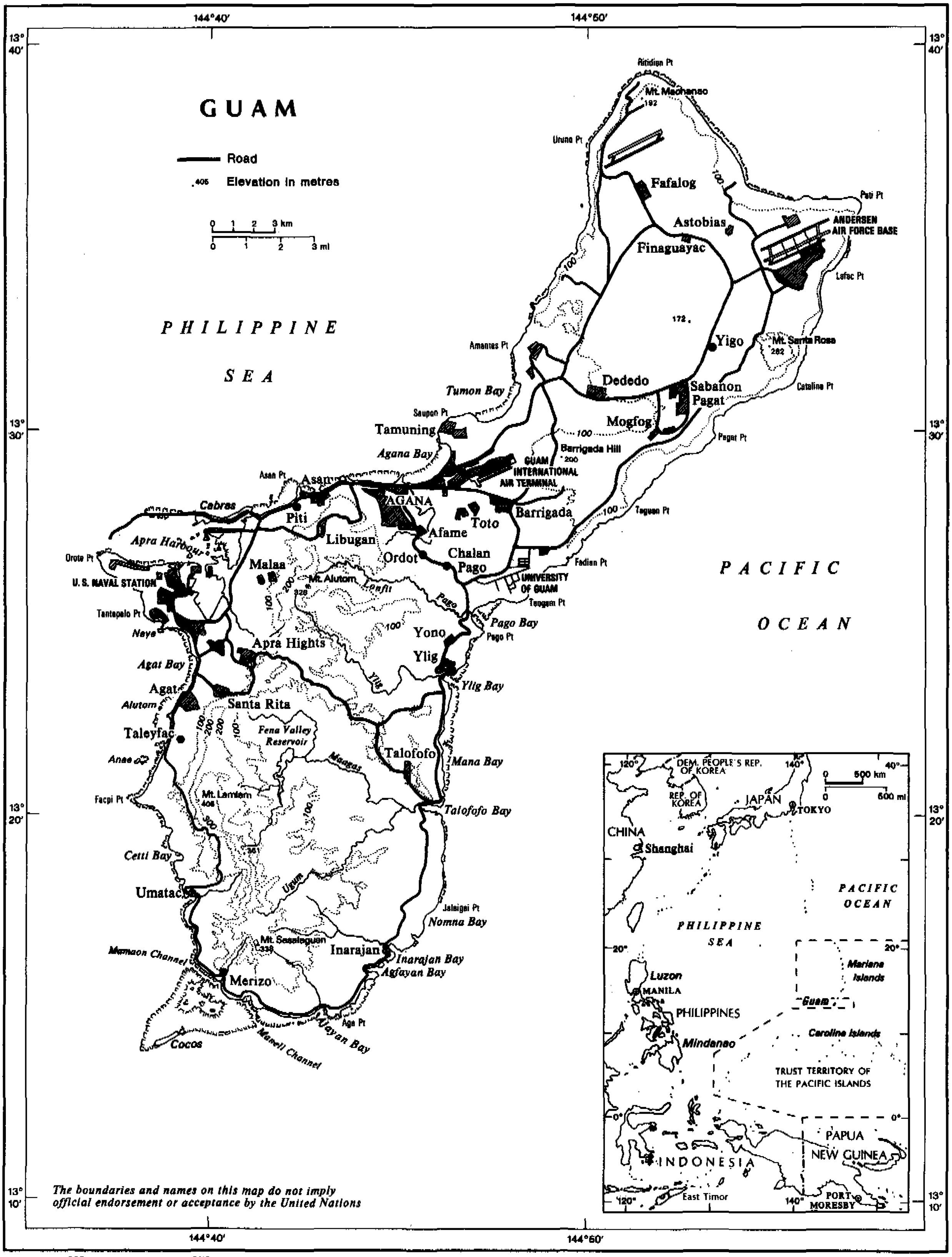
The limestones are remnants of emerged coral reef associations. They cover the entire northern half except for two small areas of volcanic rock exposures, totalling less then 5 km^2. The limestones form a muted karstic terrain in which the general form of the old coral reefs, such as the lagoonal and fore reef facies, stand out. The rock is so permeable that a normal surface drainage net has not evolved. Much of the northern coast is flanked by nearly vertical limestone cliffs up to 185 m high. Along portions of the coast a narrow shelf between the sea and the cliffs has formed.

The volcanic terrain of the south offers a rolling to sharply dissected landscape. A mountainous ridge lies a few kilometres inland from the west coast so that most drainage is eastwards. Except where raised limestone terraces occur along the island's margin, the volcanic hills plunge directly into the sea, forming a coastline of rugged sea cliffs. Along the limestone sectors a shelf with marine sediments is typical.

The climate is, on the whole, warm and humid, but during the first several months of the year when trade winds are dominant both temperature and humidity are moderated to yield pleasant conditions. Average annual temperature is 27.2° C, the coolest month (January) having an average of 26.7° C and the warmest (June) an average of 27.8° C. The daily range is less than 5.5° C. Relative humidity is always greater than 65 per cent and often reaches 100 per cent at night. January to May is the dry season, while July to November, when the trade winds are frequently interrupted, is the wet season. Even during the dry season significant rain falls but not in sufficient volume to sustain vigorous plant growth. Tangible droughts occur occasionally. In the wet season tropical storms, sometimes typhoons, bring abundant moisture. The annual average precipitation ranges from 2,150 mm at the coast of central Guam to about 2,800 mm on the higher lands. Storms yielding as much as 500 mm of rainfall in 24 hours have been experienced.

[Map 16. Guam]

MAP 16



MAP NO. 2974 REV. 1 UNITED NATIONS
DECEMBER 1982

In only one portion of the northern half of the island, near the contact with the volcanic rocks of the south, does a definable stream flow during heavy rainfall. The volcanic surface of the south, on the other hand, is drained by at least 40 streams. In this terrain about 55 per cent of the rainfall flows overland to the sea. The larger streams are perennial, although their low flows in the dry season are quite small. A large dam and reservoir impounds about 8.7 million m^3 and yields an average of 0.650 m^3/sec.

The entire island was initially formed by volcanic processes characteristic of the andesite volcano province of the western Pacific. The earlier rocks, the Alutom formation, consist of thick sequences of water-laid volcanic tuffaceous shales, sandstone and conglomerate in which lava flows, breccia and fragments of limestone are mingled. The formation is the result of Eocene-Oligocene volcanism. It underlies the limestone of northern Guam and accounts for about half of southern Guam. A second andesitic volcanic series, the Umatac formation of Miocene age, composes the southernmost quarter of the island. It consists of lavas, tuffaceous shale and sandstone, volcanic conglomerate and lenses of limestone. Both volcanic formations are very poorly permeable.

Volcanism ceased after emplacement of the Umatac formation. Marine limestones were laid down from late Miocene into Recent time, the principal accumulations taking place in the Pliocene-Pleistocene periods. Numerous distinct limestone series have been identified, but only the Alifan, Barrigada and Mariana formations are important in the occurrence and development of ground water. The Alifan formation is a fossil coral reef initiated in late Miocene time whose main exposure covers the highest ridge in southern Guam. The Barrigada limestone, a bank type of foraminiferal deposit predominantly of Pliocene age, may underlie much of northern Guam. However, the Mariana limestone, a classic and complete reef association of Pliocene-Pleistocene time, is the most widely exposed formation in northern Guam.

The Alutom formation is significantly deformed by faulting and tight folding. The Umatac is more gently folded. The limestones are undeformed, although in some places they are displaced by normal faulting. Structures of the limestone formations are predominantly original forms associated with reef building. The island has been emerging since the early Tertiary.

Ground-water resources

Precolonial Guam relied on rain catchments, streams, springs and dug wells for its water supply. The most thriving communities existed near the largest springs and perennial streams. The Spanish exploited two large limestone ground-water springs to support the main settlement of Agana. The United States carried on this policy until the Second World War. Upon reoccupying the island in 1944, the American military forces drilled many wells in northern Guam to supply their camps. Drilling was haphazard and the wells poorly designed. Improper techniques of exploitation resulted in sea-water intrusion. As a consequence, the reliability of the ground-water resource was doubted until 1964, when the civil government successfully initiated an extensive ground-water development programme.

The first drilled well was constructed in 1937, at which time also the first hydrogeological investigation was made. After the war, the United States Geological Survey carried out major geological and hydrological studies and has continued programmes of observation and evaluation. A summary of previous and ongoing studies was included in a major report (Mink, 1976) on Guam's ground water. At present, ground-water studies are being conducted by the United States Geological Survey, the Water Resources Center of the University of Guam, and by the government of Guam. A major effort to define the sustainable yield of the limestone aquifers of northern Guam was organized by the government of Guam in 1979 and will be completed by 1983.

From the first hydrogeological investigation in 1937 until 1980 the techniques of investigation consisted almost entirely of traditional geological mapping, the collection of hydrological data and aquifer testing by pumping. Under way is the employment of geophysical techniques to establish the subsurface boundaries of the northern aquifers. Seismic refraction, gravity, and magnetic surveys are planned. An extensive programme of exploratory drilling is also being considered.

Practically all of the exploitable ground water occurs in the limestone aquifers of the north. In the south the limestone sectors provide small aquifers but the volcanics are too impermeable to be considered exploitable at the present time. The aquifers of the north account for more than 95 per cent of the ground-water supply and about 75 per cent of the total water supply. They will become even more important in the future.

The northern limestone plateau, although composed of at least two different formations, is treated as a single general aquifer because the limestones are transitional and similar in hydrogeological properties. More differentiation exists among facies in the Mariana limestone than between that formation and the presumptively older Barrigada formation. Two principal facies occur, a nonargillaceous lagoon and fore reef facies constituting 80 per cent of the area, and an argillaceous lagoon facies near the volcanic contact across the middle of the island. The nonargillaceous sector exhibits an extremely high regional transmissivity, of the order of 30,000 m^2/day, while that of the argillaceous facies may be only a quarter as large. Local hydraulic conductivity measured at well sites is often much lower than regional hydraulic conductivity because of the extreme heterogeneity of the aquifers.

The Mariana-Barrigada aquifer is very productive. The ground water occurs either as a basal lens (Ghyben-Herzberg) or as parabasal water, which is continuous with the basal lens but is not underlain by sea water because it rests directly on the impermeable volcanic basement. The basal condition is most widespread but is subject to sea-water intrusion; parabasal ground water is less voluminous but is extremely important because it cannot be salinized. In some areas small limestone aquifers not contiguous with basal or parabasal aquifers rest on volcanic strata above sea level and yield water through high-level springs. They are important locally but volumetrically contribute only a fraction of the water yielded by basal-parabasal aquifers. In the south a few wells have been drilled into volcanic rock. These wells are considered successful if they produce as little as 1 l/sec at very high drawdown.

Although ground-water investigations have been nearly continuous during the past 20 years, aquifer parameters are not accurately defined. A summary of known aquifer properties and of well behaviour is given in table 14.

Table 14. Guam: summary of aquifer characteristics

Aquifer name and location	Ground-water type	Depth of well (m)	Capacity of well (l/sec)	Specific yield (l/sec/m)	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)
Mariana-Barridaga argillaceous facies, northern Guam	Basal and parabasal	<120	6-120	1-75	Local: 30 Regional: 300	3,000 30,000
Mariana-Barrigada nonargillaceous facies, northern Guam	Basal	<150	6-120	2-75	Local: 60 Regional: 600	12,000 120,000
Alutom volcanics, southern Guam	High level	<120	0-3	0-0.2	0.01-0.80	2-160

A good model of either aquifer characteristics or aquifer behaviour has yet to be made, chiefly because the aquifers are so variable over short distances. The subsurface boundaries of the limestone of the north are poorly defined, but the use of geophysical techniques supplemented with exploratory drilling will help diminish the uncertainty.

Ground-water development

The government of Guam, through its Public Utilities Agency, accounts for 90 per cent of all ground water pumped on the island. The remainder is produced mainly by the United States Armed Forces to supplement the yield of the dam-reservoir in south Guam. The government of Guam operates more than 60 wells and is drilling additional ones; the United States Armed Forces pump from eight wells and an infiltration gallery; and private developers pump from several wells. Except for a few small capacity wells in the south, all pumpage is from the aquifer of the north.

The Public Utilities Agency maintains an engineering staff but depends on the Environmental Protection Agency of Guam for hydrogeological assistance. This agency in turn has agreements with the United States Geological Survey, the University of Guam, and private contractors to perform hydrogeological studies. Ten years ago essentially no hydrogeological skills were resident on Guam; today a modest level of competence exists and is being enhanced.

Practically all well drilling has been accomplished with rotary rigs using drilling muds and, more recently, foaming materials. Until about 1970 a single company performed all the drilling; since then, however, two firms have been competing. The firms and their skilled help are resident in Guam. Wells, usually less than 120 m deep, are being drilled at the rate of about five per year. More wells could easily be drilled with the equipment available.

Total water production averages about 1.30 m^3/sec, of which ground water accounts for 0.95 m^3/sec. All of the civilian population except for some villages in the south of the island is served by a central system. The villages in the south of the island are served by a central system. The villages not yet on this system obtain their supply from springs, streams and diversions from the United States Navy system. The central system is supplied almost entirely from the northern aquifers. Its customers include all industry, except for an oil refinery that has its own well, agriculture and tourism. Agriculture is not yet a significant consumer of ground water but its needs may dramatically increase in the future.

The total population of the island is expected to reach 200,000 by the turn of the century. Ground-water production is expected to increase to about 2.0 m^3/sec, provided that the aquifers can sustain such a yield. Current studies are directed towards ascertaining whether the ground-water resources of the north will be adequate. If not, expensive surface-water impoundments in the south will have to be constructed.

At present overdraught is not a problem, although certain wells are improperly located or designed and consequently have suffered rises in salinity. Heads apparently have not declined. Neither subsidence nor drainage is a problem on Guam.

Because of the high surface and subsurface permeability of the major aquifers, pollution generated by land development always poses a threat. Dry wells and catchment basins are employed to capture local runoff from built-up areas to allow it to percolate into the limestones. Close monitoring of the effects of this artificial recharge is practised.

Conclusions

Ground water is vital to the maintenance of a viable economy on Guam. Its use will markedly increase in the next several decades because population, industry, tourism and agriculture are vigorously expanding. The limestone aquifers of the north have been declared a "principal aquifer" by the United States Environmental Protection Agency because of their importance to the island's economic and social welfare.

Although surface water from southern Guam is an alternative to ground water, the cost of pumped ground water is so much less than the expected cost of stream water impounded in reservoirs that it remains the premium water resource of the island. At present, water is pumped in the north at a cost of \$0.05/m^3 at the well; the cheapest surface water at the point of diversion would cost \$0.10/m^3. To this would have to be added the cost of transmission to the north where 75 per cent of the people live.

Past hydrogeological investigations concluded that the sustainable yield of northern Guam is approximately 2.21 m^3/sec. Not quite half of this amount is being used at present. If the sustainable yield is indeed greater than 2.0 m^3/sec, demand projection will be satisfied to beyond the turn of the century. In the long run, ground water in the south will also have to be exploited.

Selected references

The first discussion of the ground-water resources of Guam was made by H. T. Stearns in 1937 for the United States Navy. He was with the United States Geological Survey at the time, and that agency has conducted the largest proportion of studies since then. Numerous consulting reports have been written but their distribution is limited to Guam. In all, about 50 to 100 titles deal with ground water on Guam.

A hydrogeological map was drawn for the entire island by the United States Geological Survey (Ward, Hoffard, and Davis, 1965) and sectoral hydrogeological maps by J. F. Mink (1976). Comprehensive geological maps for the island have been composed by the United States Geological Survey (Tracey and others, 1964).

Primary regional titles

Johnson, E. G., and A. L. Williams. 1973. Bibliography Relative to Development of Water Resources: Territory of Guam. Micronesian Area Research Center, University of Guam.

Mink, J. F. 1976. Groundwater Resources of Guam: Occurrence and Development. Technical Report 1, Water Resources Research Center, Univeristy of Guam.

Tracey, J. I., and others. 1964. General geology of Guam. Professional Paper 403-A, United States Geological Survey.

Ward, P. E., S. H. Hoffard and D. A. Davis. 1965. Hydrology of Guam. Professional Paper 403-H, United States Geological Survey.

HAWAII

(United States of America)

Area: 16,700 km^2

Population: 900,000 (United Nations estimate, 1978)

Conditions of ground-water occurrence

General

The Hawaiian archipelago is the fiftieth state of the United States of America and consists of a chain of islands, reefs, shoals and atolls, extending a distance of 2,451 km between longitudes 154°40' W to 178°75' W and latitudes 18°54' N to 28°15' N from the north-west (Kure atoll) to the south-east (Hawaii island) (see map 17). The inhabited islands lie at the south-eastern end of the archipelago. The more populated islands are Oahu (1,573.9 km^2), Hawaii (10,458.4 km^2), Maui (1,887.6 km^2), Kauai (1,433.0 km^2), Molokai (676.2 km^2) and Lanai (361.3 km^2). The most populated island is Oahu, which accounts for 82 per cent of the state's population. The present paper is limited to a description of the major islands.

The major islands are basaltic shield volcanoes starting at the oldest, Kure island, which rose about 25 million years ago. The centres of eruption were focused in a hot spot on the Pacific tectonic plate which is moving north-westwards. The older islands shifted gradually to the north-west until today only the volcanoes on Hawaii island at the south-eastern end are still active. The magma generation centre is apparently located in the vicinity of Hawaii island.

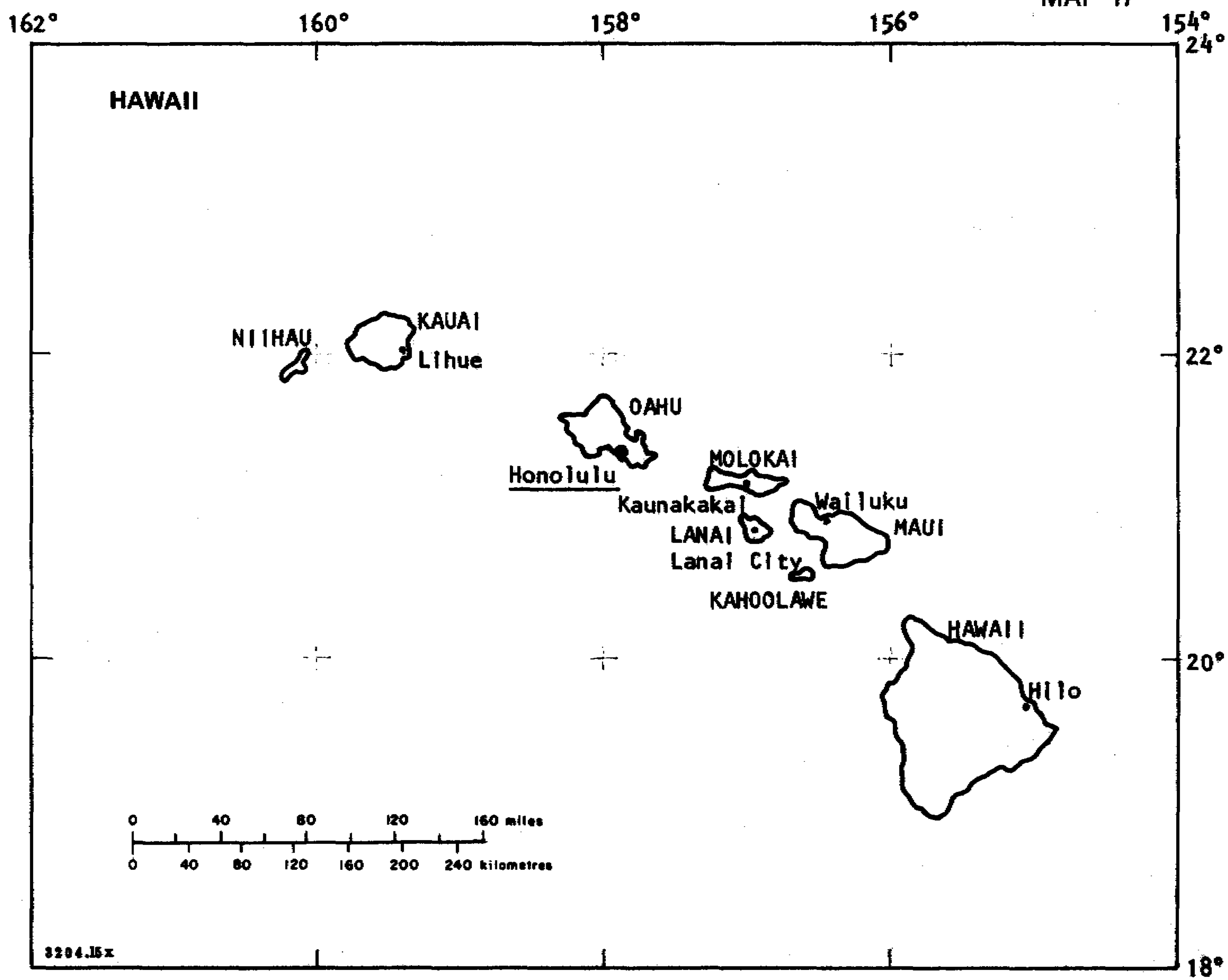
The islands rise high above sea level from the ocean floor which is as much as about 5,500 m below the present sea level. The top of Mauna Kea, the highest mountain on Hawaii island, rises 4,205 m above sea level. Even the least populated island, Niihau, has mountains 390 m above sea level.

Land-forms in Hawaii are diverse, consisting of caldera complexes, volcanic shields, deeply dissected uplands, cliffs and valleys, plateaux, coastal plains and cliffs, and sandy beaches. These forms are the result of construction by volcanoes, their erosion, the deposition of sediments and the construction of coastal platforms by marine organisms. The islands are almost wholly volcanic. Substantial deposits of sedimentary rocks form only limited platforms around the margins of the islands.

Climate

Hawaii's climate is tropical and features a mild and equable temperature the year round, moderate humidities, persistence of north-easterly trade winds, remarkable differences in rainfall within short distances and infrequent severe storms. The average temperature at sea level ranges from 23°-24° C in March to 26°-27° C in September. Temperatures decrease approximately 6.5° C per 1,000 m. The diurnal temperature ranges as much as 7° C for the windward coast and 11° C for the leeward coast and higher elevations. In most of Hawaii, there are only two seasons: summer, between May and October when the weather is warmer and drier and

MAP 17



Map 17. Hawaii

the trade winds most persistent and winter, between October and April when the weather is cooler and the trade winds are often interrupted by occasional widespread cyclonic storms. The Pacific high or anti-cyclone, which lies north-east of Hawaii and generates the trade wind, shifts seasonally to produce the climatic differences between the summer and winter seasons.

The mean annual rainfall for the state is about 1,842 mm but the spatial and temporal distributions are profound among islands and within each island, mainly as a result of orographic effects on the atmospheric circulation. Island by island, the mean annual rainfall in millimetres amounts to 1,582 for Oahu, 1,856 for Hawaii, 2,064 for Maui, 2,343 for Kauai, 1,154 for Molokai, and 715 for Lanai. On each major island, there are locations receiving more than 7,600 mm and less than 500 mm in a distance 12 km or less apart. The rainfall distribution pattern parallels closely the topographical contours for elevations below about 1,500 m; amounts are greatest over upper slopes and crests and least in the leeward lowlands. However, on the high mountains, the belt of maximum rainfall lies at only 60-914 m mainly as a result of atmospheric inversion operating during normal trade-wind weather in Hawaii. Above the belt, the rainfall drops off rapidly and sharply with further ground elevation. Hawaii's heaviest and most extensive rains are brought by winter storms. The lowland leeward areas receive their rainfall mainly from a few winter storms and only a small portion from trade-wind showers. Convective showers are not uncommon and can be intense but brief and localized. The windward coasts and slopes tend to be cloudier, cooler and more humid than the leeward areas.

Pan evaporation correlates inadequately with air temperature alone in Hawaii but the annual pan evaporation correlates fairly with mean annual wind movement which reflects advected heat and evaporation opportunity. Further, in Hawaii, the relationship between annual pan evaporation and annual rainfall has been useful in relating evapotranspiration to terrain. On an average day, the pan evaporation can be as high as 7 mm for a dry, leeward or windy station but as low as 1.5 mm at a high rainfall mountain station. Evapotranspiration is severely restricted by cloud cover in high rainfall areas.

Geology

The islands began to grow in Pliocene time from the ocean floor by numerous submarine volcanic eruptions until each island eventually emerged as a shield volcano rising several thousand metres above sea level. Calderas were formed and filled with ponded lava. All the islands have isostatically subsided, the older ones at least 365 m. The initial mountain-building phase was followed by a very long period of volcanic quiescence. During this period, profound marine and stream erosion partly destroyed the shield and carved out the deep valleys and jagged ridges and sea cliffs. The great erosion was followed by a period of deep submergence, drowning the valleys and developing fringing reefs and sedimentary coastal plains. The fluctuating seas of the Pleistocene were as much as 91 m lower and at least 30 m higher than at present. Post-erosional eruptions on some islands sent lava flows down the valleys and created cones such as Diamond Head within the past 150,000 years. Kilauea and Mauna Loa volcanoes on Hawaii island are still active.

The hydrogeology of each of the islands has common and similar features but also bears distinct variations. Each of the major islands consists of at least one to as many as five volcanic domes, the bulk of which are composed of thousands of generally thin-bedded, 6 m or less, highly vesicular basaltic extrusive lava flows. The structural features generally associated with these flows, such as an abundance of clinker sections, voids between flow surfaces, and shrinkage joints and fractures, make these rocks highly porous and permeable. In the rift zones lava remaining in the fissures that supplied the flows was quickly chilled by the surrounding rock to form dense, narrow, vertical sheets of rock, called dykes, with low permeability. The rock assemblage of highly permeable basaltic lava flows on the flanks of the volcanic shields makes up the principal aquifer in the Hawaiian islands. Smaller aquifers bounded by dykes occur in the rift zones.

The lava ponded in calderas at or near the summit of the volcanoes and in other places is thick and much less permeable than that extruded on the flanks. Ponded lava flows are poor aquifers. Fine particles of glassy volcanic ash formed in the air during the more explosive eruptions, have been altered and in many areas covered subsequently by permeable lava flows, creating aquicludes between the permeable flows. They act as important perching units for ground water. During the last stage of the initial mountain-building phase, massive andesite lava flows capped some flanks and summits. They are not important aquifers because of their low permeability. Localized post-erosional volcanic eruptions produced trachytes, which are limited and are not important aquifers.

Most sedimentary deposits, both terrestrial and marine, occur in the coastal plains of older parts of the islands, although there are isolated deposits of alluvium and talus in the lower and middle reaches of stream valleys. Terrestrial sediments consist of talus, older and younger alluvium, and clay. Marine sediments consist of coral reef deposits and sand derived from coral and other marine organisms. The sediments range from nearly impermeable clay to highly permeable beach sand and coralline deposits.

Caprock, as the coastal sedimentary column is locally known, is a poorly permeable combination of terrestrial and marine sediments and weathered basalt that constitute the most important confining aquitards overlying the basal basaltic aquifers in coastal plains and valleys. Sediment of low-permeability, including buried soils, acts as a perching member when it occurs at high elevations.

Surface water

The geomorphology reflects geological age and rainfall in different parts of the Hawaiian islands. The great permeability of basalt permits high infiltration and recharge, delaying erosion and stream development in spite of high rainfall. On many parts of the youngest island of Hawaii there are no distinctive drainage features developed in the barren lava land. Kauai, the oldest major island and the wettest, exhibits pronounced geomorphic development of drainage basins. The drainage basin parameters are characterized by small size (10-100 km^2), steep slopes, short stream courses and little channel storage.

The streams respond quickly to rainfall but many are only weakly perennial or even nonperennial. A base flow is sustained in high rainfall mountainous areas where there is daily orographic rain producing constant overland flow and interflow and where there are high-level springs discharging perched and dyked impounded ground water. Streams that pass dry lowland and coastal plains tend to lose water by infiltration. Some streams, before reaching the ocean, may gain water at low elevation as a result of channels intersecting ground water. There are only two streams with average discharge reaching 6.6 to 8.1 m^3/sec. Most other streams are at least one order of magnitude less.

Flood flow in Hawaii is devastatingly flashy, requiring only a very short time to peak (usually less than an hour) and producing steep triangular hydrographs. There are few natural lakes and few sites suitable for surface reservoirs in Hawaii.

Ground-water resources

Historical

The discovery of artesian ground water by the successful drilling of James Campbell's Pioneer Well on Oahu Island in 1879 marked the beginning of geological and geohydrological investigations in Hawaii. The discovery also opened for exploitation the largest and most dependable source of water supply on Oahu.

Hawaii has contributed much of the ground-water knowledge and development technology needed not only in Hawaii but also in other Pacific insular environments. During the first few years after 1879, the knowledge gained was nothing more than a generalization of experience from the numerous wells drilled, leading to the understanding that artesian (flowing) wells could not be expected at altitudes higher than 12.8 m above the sea level at Honolulu. The best known geohydrological concept applicable to Hawaii is the phenomenon of the floatation of fresh water on underlying salt water. In 1909, Carl Andrews, an engineer in Hawaii, worked out the mathematical expression without knowledge of the work done in Europe by W. Badon-Ghyben and B. Herzberg. Another important contribution of Hawaii was the type of well development which took place in Maui in 1898: a system consisting of a shaft leading from the surface to a pump chamber just above the water table, from which infiltration galleries extended.

The first and most important organized hydrological and geological survey on Hawaii was initiated in 1928 by the United States Geological Survey at the request of the government of the Territory of Hawaii. Harold T. Stearns and his colleagues, including G. A. Macdonald, K. N. Vaksvik and J. H. Schwartz, at various times and in different groupings, mapped the geology and described the ground-water resources of the islands in 12 volumes during the period 1935 to 1947. The surveys and the volume on Kauai island were completed by G. A. Macdonald, D. A. Davis and D. C. Cox in 1960. These detailed and informative documents are the essential references. In the meantime, W. O. Clark pursued the investigation of high-level tunnel systems for the development of dyked impounded ground water, under the auspices of the Hawaiian Sugar Planters' Association. Geohydrological investigations were also initiated by the Honolulu Sewer and Water Commission in 1925 and have been sustained to the present day by its successor, the Honolulu Board of Water Supply, which was created in 1929 as the single semi-autonomous agency responsible not only for investigations but for conservation, development, and operation of a drinking-water system for Oahu. C. K. Wentworth performed important work as the hydrologist and geologist for Oahu. The United States Geological Survey has continued its ground-water investigative role under the co-operative arrangement with the Hawaii State Department of Land and Natural Resources. The Water Resources Research Center was established at the University of Hawaii in 1964 to conduct research pertinent to all aspects of Hawaiian water resources, including ground water.

Ground-water prospection

Methods of prospecting for ground water in Hawaii have been the classical scientific hydrogeological methods, augmented in recent years by modern geophysical, remote sensing, isotopic, and geochemical methods.

Detailed hydrogeological mapping is normally preceded by examination of aerial photographs and regional geological maps, followed by rapid ground reconnaissance. Electrical resistivity was used successfully to delineate fresh-water/salt-water boundaries as early as 1940 by J. Schwartz of the United States Geological Survey, but a range of geophysical methods was not tested until the period 1967-1970. The electrical resistivity method proved most useful. Aerial infra-red thermometry has been used in locating offshore spring water on Hawaii island. Test drilling and pumping tests are routinely conducted. Geophysical logging of wells, particularly the electrical conductivity and temperature traverses, has been found to be most useful and is routinely used in monitoring the rise and fall of zones of transitional saline water underlying thick freshwater lenses. A radioisotope laboratory capable of assaying low-level environmental tritium and radiocarbon has been established at the University of Hawaii. These isotopes and associated chemical quality parameters have been used in determining the residence time and movement of ground water on Oahu to augment information developed by conventional geohydrological investigations.

Various geohydrological concepts have evolved in Hawaii in response to the need to understand and predict the behaviour of the basal lens induced by natural and man-made stresses. Further, simulation models have been developed for the Oahu basal lens, including a hydraulic sandbox model for optimal ground-water development, and numerical mathematical models for predicting long-term head fluctuations.

Aquifers

The principal aquifers in Hawaii are composed of assemblages of highly permeable and thin basaltic flows. Rainfall is the sole natural source for ground-water recharge in Hawaii.

Swarms of nearly impermeable, vertical or nearly vertical intrusive dykes along the rift zones transect the basaltic flows and impede ground-water movement.

Dyke compartments behave as small aquifers in which the percolating water is impounded. The best dyked impounded reservoirs are at higher elevations beyond the reach of salt water.

In the dyke-free basaltic flows fresh-water lenses occur principally as the result of direct recharge by rain water and by seepage from the high-level dyke-impounded water. These lenses float on the underlying salt water and have a fresh-water/salt-water interface as large as the surface area of the aquifer because no evidence of a lower confining aquiclude in the zone of hydraulic flow has been found. The general direction of ground-water flow in the basal lens is from inland areas of high recharge towards the coast. The natural gradient is characteristically nearly flat, ranging from about 0.2 m/km for highly transmissive aquifers in a low recharge area to about 4 m/km for the older rock formations. The coastal caprock platform, wherever it occurs, retards the seward escape of ground water, causing the basal fresh-water lens to thicken and also to be artesian. The fresh-water lenses underlying the Honolulu coastal sediments are very large, having at present heads 6-8 m above sea level and total thicknesses of about 240-320 m. In those regions lacking an effective caprock, the lenses in permeable basalt are shallow, of the order of 20 m thick. Where recharge is low, the basal lenses degenerate into brackish-water lenses. Potential salt-water encroachment by hydrodynamic dispersion induced by movements of the interface is ubiquitous. The zone of transition varies in thickness from 3-4 m for thin lenses to 350 m for thick lenses.

Perched aquifers occur in Hawaii on poorly permeable basaltic flows, buried soils or volcanic ash. But perched aquifers are generally small and are not nearly as widespread as basal aquifers.

Springs occur both as basal and as high-level springs. Copious basal springs occur, for example, along the inner shore of Pearl Harbor, Oahu, where the thin edge of caprock has been breached, and at Waiakea bordering Hilo Bay, Hawaii island. High-level springs emanate from either perched or dyke aquifers, many of which have significant discharges.

Endowed with the favourable combination of permeable basalt and high rain-fall occurring in recharge areas, the ground-water recharge in each of the major islands is substantial. On an island-wide basis, the recharge rates have been computed as the remainder of rainfall after subtraction of evapotranspiration and streamflow. In cubic metres per second they are: Oahu, 28.7; Maui, 36.6; Hawaii, 188.4; Kauai, 16.6; and Molokai, 3.9. Sustainable yields are invariably and considerably less than these quantities. The largest ground-water storage is in the basal lenses, but ground-water distribution varies widely from region to region on each island.

The major aquifers with substantial development are listed in table 15. However, there are many known and productive aquifers such as the basal lens between Hilo and Laupahoehoe on Hawaii island that are at present either not, or barely, developed for lack of water demand. Throughout the state, except for Oahu island, there are ample water resources to meet foreseeable needs. The cost of development, however, is the chief limiting factor governing the availability of water for use.

Table 15. Hawaii: summary of aquifer characteristics

Formation	Location	Ground-water development types: Wells	Ground-water development types: Basal infiltration galleries	Ground-water development types: High-level infiltration galleries	Depth of well (m)	Specific yield of well (l/sec/m)	Hydraulic conductivity (m/day)
OAHU							
Koolau and Waianae basalt	Pearl Harbor	X	X		< 200	20-80	> 300
Koolau basalt	Honolulu	X	X	X	< 200	20-80	> 300
Koolau and Waianae basalt	Waialua	X	X		< 200	20-80	> 300
Koolau basalt	Koolaupoko	X		X	< 200	20-80	> 300
MAUI							
Wailuku basalt	Lahaina-Kaanapali	X	X	X	< 250	1-200	> 300
Wailuku basalt	Waihee-Waikapu	X		X	< 250	1-200	> 300
Kula and Honomanu basalt	Kahului-Paia	X	X		< 250	1-200	> 300
Hana and Kula basalt	Nahiku			X	< 250	...	> 300
KAUAI							
Waimea basalt	Kekaha-Mana	X	X		< 250	1-200	> 300

Ground-water quality

The quality of the natural fresh water in Hawaii's basaltic aquifers is excellent. The water is soft, low in mineral content and potable without disinfection. During its passage to the basal lens, rain which is already slightly charged with sea salt acquires, principally by solution of basalt, silica, calcium and magnesium. The biological cycle contributes carbonate and intruding sea water adds sodium, chloride and sulphate. The acquired concentration of these minerals is considered low by all standards.

A typical fresh-water sample from a basal lens free of salt water encroachment and other contamination ordinarily has a temperature of 21° C, pH 7.9, and specific conductance 205 micromhos, and carries in solution the following, in milligrammes per litre: SiO_2, 36; Ca, 8; Mg, 6; Na, 20; K, 2; HCO_3, 65; SO_4, 5.5; Cl, 22; PO_4, 0.20; F, 0.07; and NO_3, 1.1. The water satisfies the drinking water standards for iron, heavy metals and pesticides.

Ground-water quality is endangered by the availability of salt water for mixing, a process readily indicated by sharp increases in chloride and sodium. Chloride has been traditionally used as the indicator. Another concern is return irrigation water from sugar-cane culture; aquifers receiving it have an uppermost layer of water with high concentrations of chloride, nitrate and sulphate overlying the main saturated zone. Potassium and phosphorus are not indicators of return irrigation water as they are effectively retained or removed in the soil zone. Cesspools appear to add slightly higher than normal mitrate concentrations to down-gradient ground water.

The fresh water in the basalt aquifer is free of coliform bacteria and meets United States drinking-water standards. Sewage-borne coliforms and pathogenic enteric viruses are effectively removed by the passage of water through a metre of Oxisol, a common agricultural soil order found on all islands except Hawaii.

Water-quality monitoring is routinely conducted by the Honolulu Board of Water Supply, the United States Geological Survey, and the Hawaii State Department of Health. Considerable ground-water quality and pollution research, including land disposal and treatment of waste waters, has been conducted by the Water Resources Research Center of the University of Hawaii.

In spite of a century of ground-water utilization and numerous previous studies, there are considerable gaps in ground-water resource knowledge and much need for further research and investigation. These needs arise as exploitation of the aquifers intensifies. To their traditional role as fresh-water supply are being added the demands of land treatment and disposal, geothermal energy, and the use of brackish water as an alternative water source. Research and investigative needs are listed below, but not by priority:

(a) Geological and hydrogeological aspects:

(i) Anisotropy of basaltic flows;

(ii) Thickness of permeable basaltic flows below sea level;

(iii) Structure, extent and density of occurrence of dykes;

(iv) Hydrological properties of sediment deposits;

(b) Hydrological aspects:

(i) Rainfall distribution in high rainfall recharge areas;

(ii) Relation between actual and potential evapotranspiration and pan evaporation in moderate to high rainfall areas;

(iii) Head and water-quality distribution in the up-gradient and deep portions of basal lenses;

(iv) Mechanics of discharge from dyke impounded water to basal lenses;

(v) Flow régime in the unsaturated zone of basalt flows;

(vi) Tidal effects on dispersion in basal lenses;

(c) Resource evaluation:

(i) Re-evaluation of refinement of sustainable yields;

(ii) Prospecting and evaluating geothermal energy sources;

(d) Engineering systems:

(i) Modelling of transport-dispersion phenomena in basal lenses under water development and waste injection conditions;

(ii) Ground-water hydraulics of high-level tunnels and skimming tunnels;

(iii) Surface-water catchment and recharge system;

(iv) Recharge consequence of converting to drip irrigation from furrow irrigation;

(e) Economic and ecological aspects:

(i) Economics of recharge and reuse;

(ii) Impacts of ground-water development on surface-water ecology;

(iii) Consequences of forest management on recharge;

(f) Information utilization system for planning, regulatory and operations agencies.

Ground-water development

General

During the 25 years after the discovery of artesian water on Oahu, the pace and magnitude of development and wastage were so phenomenal that the territorial legislature found it necessary to exercise stronger control and management of ground water, culminating in the creation in 1929 of the powerful Board of Water Supply of the City and County of Honolulu. About 50 years later, in 1977, the much increased total demand from both public and private sectors on several major ground-water aquifers coupled with several low rainfall years prompted an overall assessment of water situations by a special State Water Commission appointed by the Governor. At the same time an amendment dealing with water resources was added to the State Constitution. The Commission's recommendations and the constitutional mandate are at present being implemented by the legislative and executive branches of the state government to achieve a state-wide system for the control of water resources.

Galleries and wells

The modes of ground-water development consist primarily of horizontal infiltration galleries (skimming tunnels) and vertical wells tapping the basal lens, and horizontal tunnels penetrating dykes at high elevations to the dyke impounded water. Perched water development is achieved by tunnels and wells and requires special skill. Among the three sources, basal water development is by far the greatest.

Both government and private agencies are actively engaged in ground-water development. The principal agencies include the United States military forces, the state and county governments, the sugar-cane industry and the electric power industry. In terms of volume of ground water produced, the sugar-cane industry and the City and County of Honolulu are paramount.

The United States Navy develops water for most of its demand from the Pearl Harbor aquifer. The United States Army develops ground water in Honolulu, but its principal source is a high-level aquifer at Wahiawa, Oahu.

Water-resources organizations

The state of Hawaii's principal programmes are concerned with data collection, investigation, planning, and co-ordination on a state-wide basis. Not until 1979 did the state begin to exercise statutory power to control ground water use in the heavily stressed Pearl Harbor aquifer. The county governmental agencies, on the other hand, are responsible for developing water to meet municipal demands. These are the Board of Water Supply, City and County of Honolulu, for Oahu; the Department of Water Supply, County of Maui, for Maui, Molokai and Lanai; the Department of Water Supply, County of Kauai, for Kauai; and the Department of Water Supply, County of Hawaii, for Hawaii island.

The Board of Water Supply, City and County of Honolulu, provides municipal water for about 80 per cent of the state's population. It also supplies commercial and industrial demands. The Board determines the policies and prescribes regulations for the operation of all the municipally-owned water systems on Oahu, including the location, development, conservation, protection and distribution of water supplies. It engages in research and development in the fields of water resources and public water supply. Its authority extends to issuance of permits for the drilling of wells for the development of ground water. The Mayor appoints the Board members, who in turn appoint the manager and chief engineer to administer the affairs of the department. The Honolulu Board of Water Supply is semiautonomous and is self-financed by the sale of water and the issuance of revenue bonds.

The Honolulu Board of Water Supply has a staff of 634, including 90 professionals (engineers, geologist-hydrologists, accountants, chemists, microbiologists and computer specialists) and 43 technicians. The laboratories and facilities include chemical and microbiological laboratories, water meter testing and repair shop facilities, and computerized systems for operations and finance. It operates 197 wells and infiltration galleries. The responsibilities are distributed among eight divisions: automotive, computer services, customer service, field operations, finance, land, planning and engineering, and plant operations.

In contrast to the Honolulu Board of Water Supply, the water departments of Hawaii's three other counties are much smaller in size, operations, and professional and technical capabilities. However, they receive considerable assistance from the state.

The state government's role in ground water is carried out by two state departments: water quantity by the Division of Land and Water Development (DOWALD) of the Department of Land and Natural Resources; and water quality by the Division of Environmental Health of the Department of Health. DOWALD is headed by a manager and chief engineer and is divided into four branches: Water Resources and Flood Control, Project Development, Design and Construction, and Water Distribution and Maintenance. It has a staff of 52, including 26 professionals (civil engineers and a geologist) and six technicians. The Department of Health administers water quality standards and water pollution control of all waters including ground water. The Division of Environmental Health is headed by a deputy director of the Department of Health. The Division has six branches, two of which are pertinent to pollution: Pollution Technical Review, and Pollution Investigation and Enforcement. The Division has a staff of 232, including 62 water quality related professionals (engineers, environmental health specialists, a geologist and microbiologists) and 35 water quality related technicians. The Department of Health operates a complete set of water quality laboratories.

Ground-water drilling

Water well drilling organizations are exclusively commercial firms. At present, there are three large water well firms which operate from Oahu. They serve not only Hawaii but other Pacific islands. Almost all drilling for water in Hawaii is through hard rock. Water Resources International operates with three large rotary rigs and drills, on the average, 10 wells a year with an average depth of 150-180 m and a diameter of 41 cm. Water Resources International has a staff of 50, including three supervisors with more than 25 years of experience. Most were trained on the job in Hawaii; only a few have had training in geology, hydrology and engineering. This kind of training and background also applies to the other two companies. Roscoe Moss drills exclusively with six cable tool rigs and, in addition, has two pump rigs. Annually, it drills four to five deep wells, ranging from 250 to 300 m, and 12-15 shallow wells, ranging from 60 to 250 m, with diameters ranging from 30 to 36 cm. The company also drills annually 15-20 injection wells less than 60 m deep. Roscoe Moss has a staff of 24, including four supervisors with 40 years of experience. Roscoe Moss manufactures all drilling tools and casings for its own use and supplies other firms. PR Drilling Company specializes in shallow wells in sediment and coral in addition to hard rock, drilling on the average 6-10 water wells of 15 cm diameter a year, with depths less than 60 m. It owns six truck-mounted rotary rigs and has a staff of 15, including two supervisors with 40 years of experience. It also performs injection well and offshore drilling, and mobilization by helicopter to reach otherwise inaccessible sites.

Ground-water development

On a state-wide basis, the largest water demand is for sugar-cane irrigation and the distant second is for municipal use. Most water demands occur on Oahu and Maui. These demands are met by both surface- and ground-water sources. On a state-wide basis, the gross water requirements for the period 1970-1975 were about 78.8 m^3/sec, of which ground-water sources provided about 33.7 m^3sec. On Oahu, the quantities of water by sectors for 1975 were, in cubic metres per second: municipal, 5.914; industrial, 2.191; agricultural, 10.733; military, 1.752; the total being 20.590. Ground water provided 17.524 m^3/sec (1977 data), or approximately 85 per cent of total Oahu requirements. Of particular importance is the Pearl Harbor aquifer, which provides 10.514 m^3/sec for sugar-cane irrigation, and municipal and military uses.

The Honolulu Board of Water Supply provides drinking water for Honolulu and all rural communities on Oahu. Other island departments of water supply also take care of both urban and rural communities. The per capita consumption of water in the Waikiki District, a world-famous tourist destination, is high and increased from 1.325 m^3/day in 1968 to 1.893 m^3/day in 1971. On the other hand, the remainder of Oahu experienced an increase from 0.66 to 0.71 m^3 during the same period.

Agricultural water supply is principally developed for and by the sugar-cane plantations with their own development facilities: wells, infiltration galleries and high-level tunnels. Pineapple plantations also develop ground water but in small amounts in comparison with the amount developed for sugar-cane irrigation. Diversified agriculture (vegetables and melons, fruits other than pineapple, coffee, macadamia nuts, flowers and horticulture) requiring small quantities of irrigation water, either develops its own supplies or makes purchases from the large water purveyors. Agricultural water is also developed by the state government, but only to a very limited extent, notably through three irrigation systems located on Molokai, Hawaii and Oahu.

The chief industrial water supply is developed by the plantations for sugar-cane processing. Brackish ground water is exploited for cooling water by some industries, including electric power companies. The largest electric company, however, uses ocean water for most of its cooling, but also uses Waianae spring water.

Projected needs for Oahu for the year 2000 are, in cubic metres per second: municipal, 9.638; industrial, 2.410; agricultural, 10.952; military, 1.971; the total being 24.971, an increase of 4.381 over the 1975 demand. This demand, if it is to be satisfied by ground-water resources alone, would commit the sustainable yields of all Oahu ground-water sources. State-wide, demand for the year 2000 has been projected to be about 78.800 m^3/sec.

Problems

The principal kinds of ground-water problems are salt-water encroachment, the demand approaching sustainable yields for several of the most developed basal aquifers on Oahu and Maui, and water pollution. Neither land subsidence nor drainage is a problem. Salt-water encroachment affects a basal lens but not the high-level dyke impounded or perched waters. For thick lenses there is considerable room for management strategies to achieve the theoretically possible sustainable yield for a pre-selected head under steady state conditions; however, this mode of operation has not yet been practised or experimented with in Hawaii. Hawaii's thick lenses have not yet been intruded by salt water to the extent that wells in massive numbers have had to be abandoned. However, gradual but steady increases in the chloride concentration of the pumped water from most basal aquifers and declining heads over the past several decades in both the Honolulu and Pearl Harbor aquifers are matters of concern. Thin lenses are more susceptible to salt-water encroachment by localized up-coning than by area-wide shrinkage of the lens as a result of intensive draught of closely spaced wells or even of a single well. However, the effects of up-coning in thin lenses are often temporary and can be reversed with timely reduction in draught.

Sustainable yields for the basal lenses in Honolulu and Pearl Harbor (Oahu), Lahaina-Kaanapali (West Maui) and Kekaha-Mana (Kauai) have almost been reached under present rates of extraction. However, all other basal lenses in Hawaii have not been similarly stressed.

Other than the minor effects induced by return irrigation water from sugar-cane culture and the local concentration of cesspools, adverse changes in ground water by surface contaminants have not been reported. Subsurface disposal of treated sewage effluent, thermal effluent and storm water is permitted in Hawaii by means of injection wells only in coastal areas overlying non-potable ground water. Because of the ubiquitous seaward gradient of ground-water flux, the injection discharges are regulated so as not to contaminate coastal waters.

Integrated development of water resources

Integrated use of surface and ground water has been practised for many years by sugar-cane plantations to provide irrigation water. However, little conjunctive use has been found feasible for municipal water supply thus far because of the quality and easy developability of ground water compared with the cost of collecting and treating surface water. Artificial recharge so far has been limited to incidental recharge such as seepage from temporary holding reservoirs and from return irrigation flows. Incidental recharge is substantial under furrow irrigation (about 50 per cent of applied irrigation water). Ground-water recharge of municipal waste-water effluent by irrigation of sugar-cane and grassland in Oxisols has been ascertained to produce substantial percolating water of acceptable quality. This practice is being actively encouraged to increase both the sustainable yield and the agricultural water supply in Hawaii.

Several solutions to the water problems occurring on Oahu and Maui as recommended by the State Water Commission are useful for all islands with similarly limited water resources. Briefly stated, these solutions are (a) stabilizing or reducing per capita consumption of municipal water; (b) emphasizing development of new and alternative water resources; (c) moderating population growth; (d) establishing a permit system for water development and use; (e) formulating a state water code; (f) satisfying water information needs; and (g) optimizing water development.

Conclusions

Ground-water resources are vital to the economic and social welfare of all islands in Hawaii. Through the past century of ground-water development and utilization, Hawaii has been able to develop and establish a large agricultural sector requiring intensive water use, to accommodate phenomenal urban and population growth, and to develop a world-famous tourist industry welcoming almost four million visitors a year. All of these accomplishments have been achieved as a result of bountiful water resources. Hawaii will continue to depend on ground-water resources in the future. The sustainable yields of Oahu's ground water can meet future demands at its present growth rate until the end of the year 2000 and can be stretched to meet the needs of the year 2020 if stringent water conservation is practised to keep the per capita consumption at a level of 0.767 m^3/day. For other islands, ground-water development will generally provide the main water source to meet economic and social needs.

The present cost of ground water at the well is still modest. According to the 1977-1978 Honolulu Board of Water Supply statistics, the unit operating cost, which includes labour, power and supplies, was \$0.02/m^3. However, it should be noted that the unit operating cost was mostly electric power cost (76 per cent), which can be expected to increase inasmuch as 92 per cent of Hawaii's energy is at present imported and most alternative energy sources are only at the research stage.

In terms of developability of ground-water resources for Oahu and parts of Maui, most of the more easily developable ground-water sources have been tapped. Moreover, additional ground-water resources are located farther from population centres, thus requiring additional transmission cost. For Oahu, not only the unit operating cost but also the water rate to be paid by the municipal consumers will increase. The rate is \$0.17/m^3 (July 1979), which is to be increased to \$0.20/m^3 a year thereafter.

Prospecting for ground water should pose no serious problem because the occurrence of ground water is reasonably known and the more developable aquifers (permeable basalt) have been delineated for most of the islands. However, Kauai has more complicated hydrogeology than other islands and requires very careful exploratory study. Further, useful methods for exploration in Hawaii are reasonably well in hand. Exploratory drilling is still necessary.

The main problems really lie with the estimation of sustainable yields and the methods of development that can attain the sustainable yields. On Oahu and many parts of Maui where most of the more easily developable basal aquifers are already at different stages of development, more sophisticated methods of assessment and more appropriate technology of development are required to attain and increase the sustainable yield while protecting the basal lens from salt-water encroachment. Many less developed aquifers are not so transmissive; therefore, the yields can be expected to be less than those at present near full development. For other islands, water demand and development of ground water would normally proceed in increments, thus permitting time to gather additional data on the aquifers by further exploration and to refine the estimate of sustainable yield before the next demand increments occur.

Selected references

Fujimura, F. N. and W. B. C. Chang, eds. 1980. Groundwater in Hawaii: A Century of Progress. Honolulu, Hawaii, The University Press of Hawaii, 260 p.

Hawaii, Department of Land and Natural Resources. 1980. State Water Resources Development Plan. State of Hawaii, Honolulu, Hawaii, 165 p.

________. Department of Planning and Economic Development. 1967. State of Hawaii Data Book: A Statistical Abstract. State of Hawaii, Honolulu, Hawaii, 447 p.

Hawaii Water Resources Regional Study. 1975. Surface and Ground Water Resources. Study Element Report, 431 p.

Macdonald, G. A., D. A. Davis and D. C. Cox. 1960. Geology and Ground-Water Resources of the Island of Kauai, Hawaii. Bulletin 13, Hawaii Division of Hydrography, 212 p.

State Water Commission. 1979. Hawaii's Water Resources: Direction for the Future. A report to the Governor of the State of Hawaii, 40 p.

Stearns, H. T. 1946. Geology and Ground-water Resources of the Island of Hawaii. Bulletin 9, Hawaii Division of Hydrography, 363 p.

________, and K. N. Vaksvik. 1935. Geology and Ground-water Resources of the Island of Oahu, Hawaii. Bulletin 1, Hawaii Division of Hydrography, 479 p.

________, and G. A. Macdonald. 1942. Geology and Ground-water Resources of the Island of Maui, Hawaii. Bulletin 7, Hawaii Division of Hydrography, 344 p.

Takasaki, K. J. 1978. Summary appraisals of the nation's ground-water resources: Hawaii region. Professional Paper 813-M, United States Geological Survey, 29 p.

University of Hawaii, Department of Geography. 1973. Atlas of Hawaii. Honolulu, The University Press of Hawaii, 222 p.

Visher, F. N., and J. F. Mink. 1964. Ground-water Resources in Southern Oahu, Hawaii. Water Supply Paper 1778, United States Geological Survey, 133 p.

Water Resources Research Center. University of Hawaii, Honolulu, Hawaii.
1969. Collected reprints. vol. I, 1966-1968, 120 p.
1971. Collected reprints. vol. II, 1969-1970, 203 p.
1975. Collected reprints. vol. III, 1971-1974, 489 p.
1978. Collected reprints. vol. IV, 1975-1977, 164 p.

INDONESIA

Area: about 1,900,000 km2 (land area)

Population: 143,000,000 (United Nations estimate, 1977)

General

Indonesia is an archipelago lying between south-east Asia and Australia and extending between latitudes 6° N and 11° S and longitudes 95° E and 141° E. It comprises the island of Sumatra, Kalimantan (the southern part of the island of Borneo), the island of Sulawesi (Celebes), Irian Jaya (the western part of the island of New Guinea), the islands of Java, Bali, Lombok, Sumba, Sumbawa, Flores, Timor and Bangka, and thousands of smaller ones (see map 18). The heights of islands vary between near zero and 5,030 m. The greater part of the archipelago is built up of Tertiary and Quaternary deposits of elastic material, marls and limestones and other materials of volcanic origin.

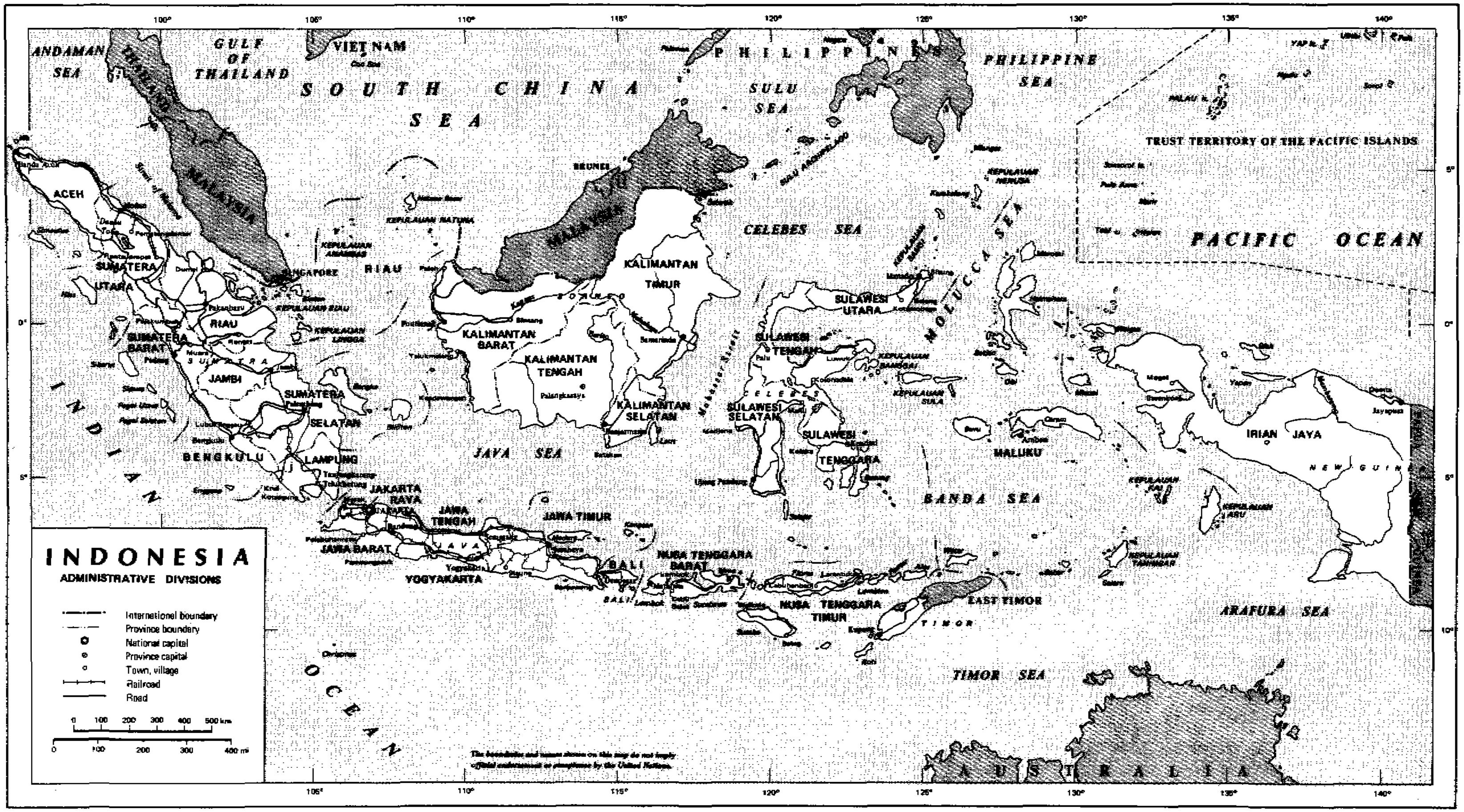
Geology

Within the context of the southern Pacific area, the Indonesian archipelago covers three large units: the Sunda Shelf area, the Sahul Shelf area, and the area in between, which is an intervening belt of deep-sea basins and island arcs. The main physiographical features are the continental platforms, the oceanic basins (or engulfed borderland) and the orogenic belts. Table 16 presents the main physiographical and geological units of Indonesia.

Tertiary and Quaternary formations have a much wider distribution than pre-Tertiary rocks. These formations gave the region its present physiography. Little information is available on pre-Tertiary rocks, since three quarters of the surface is composed of sediments and volcanic deposits of Cenozoic age (Tertiary and Quaternary).

Indonesia, the most volcano-prone country in the world, has more than 500 young strato-volcanoes, 128 of which are considered to be active. For this reason, a large part of the country is covered by Quaternary volcanics, especially the central part of the inner arc, that is, the arc running from Sumatra through Java, Bali, Lombok, Sumbawa, Flores and Maluku to Sulawesi. These volcanic products, consisting of lava and pyroclastics, are mostly of andesitic to basaltic composition.

MAP 18



MAP NO. 3044 UNITED NATIONS
MAY 1979

Table 16. Indonesia: subdivisions of the main physiographical units and the main regional geological units of the Indonesian archipelago and its surroundings

PHYSIOGRAPHY

1. The Sunda area

   (a) The Sunda Shelf and smaller islands

   (b) Larger Sunda Islands bordering the Shelf sea

   (Kalimantan, Sumatra, Java and Madura)

2. The circum-Sundra orogenic belts

   (a) Sin Cowe Reefs in the South China Sea

   (b) The Philippine Archipelago

   (c) Sulawesi

   (d) Maluku (Moluccas): Northern Maluku and Southern Maluku

   (e) Lesser Sunda Islands

   (f) Ridges south of Java and west of Sumatra

   (g) Andamans and Nicobars

3. The circum-Australian belt

   (a) New Guinea

   (b) Sahul Shelf with the Aru Islands

   (c) Christmas Island

REGIONAL GEOLOGY

1. The Sunda area

   (a) Sunda Shelf

   (b) Smaller islands on the Sunda Shelf

   (c) Kalimantan (Borneo)

   (d) The Malay Peninsula

2. The circum-Sunda orogenic systems

   (a) The Philippines

   (b) Northern Maluku

   (c) Sulawesi (Celebes)

   (d) Southern Maluku (Banda Arcs)

   (e) Lesser Sunda Islands

   (f) Java

   (g) Sumatra and the islands to the west thereof

   (h) Andamans and Nicobars

3. The circum-Australian orogenic systems

   (a) New Guinea

   (b) Christmas Islands

4. The Sahul area

   (a) The Sahul Shelf

   (b) The Aru Islands

The Quaternary sediments, consisting of recent alluvial and Pleistocene sediments, are distributed along the coastal plains of the larger islands, in intra-montane basins and along river plains. These areas are mostly settlement areas.

The Tertiary formations consist mainly of marine sediments. Terrestrial and neritic facies are also found in several parts of the larger islands. These Tertiary sediments are often mixed with or intercalated between volcanic products such as submarine tuffs, eruptive breccia and lava flows. In some places the Tertiary sediments are composed of or associated with limestone.

Climate

The Indonesian archipelago lies completely between the tropics and within the Indo-Australian monsoon. The climate is characterized by high temperature (with small daily and annual fluctuations) high humidity (the mean annual humidity is about 80 per cent), cloudy skies (the average sunshine in the coastal plains is 50-70 per cent) and abundant rains, except in the south-east. Owing to the influence of the continents of Asia and Australia, the archipelago is the most typical monsoon region in the world. The wet monsoon (with high rainfall) changes to the dry monsoon (with less rainfall), and vice versa, with a transition period in between. The mean annual rainfall of the Indonesian archipelago is about 2,000 mm, the range being between 750 mm and 7,000 mm per year.

The Indonesian archipelago is not entirely subject to a hot, humid and tropical climate. Some areas enjoy a mild climate, while a small part of the country has a cold climate (namely), the highest mountain area in Irian Jaya, which is covered by eternal snow). These differences are not due to changes of monsoon, but to altitude. The changes in monsoon climate are caused by wind and rainfall. The monsoons are known as the "west wind direction monsoon" or the "dry monsoon" and the "east monsoon" or the "wet monsoon". The month in which rain starts to fall varies from place to place.

Occurrence and distribution of ground water

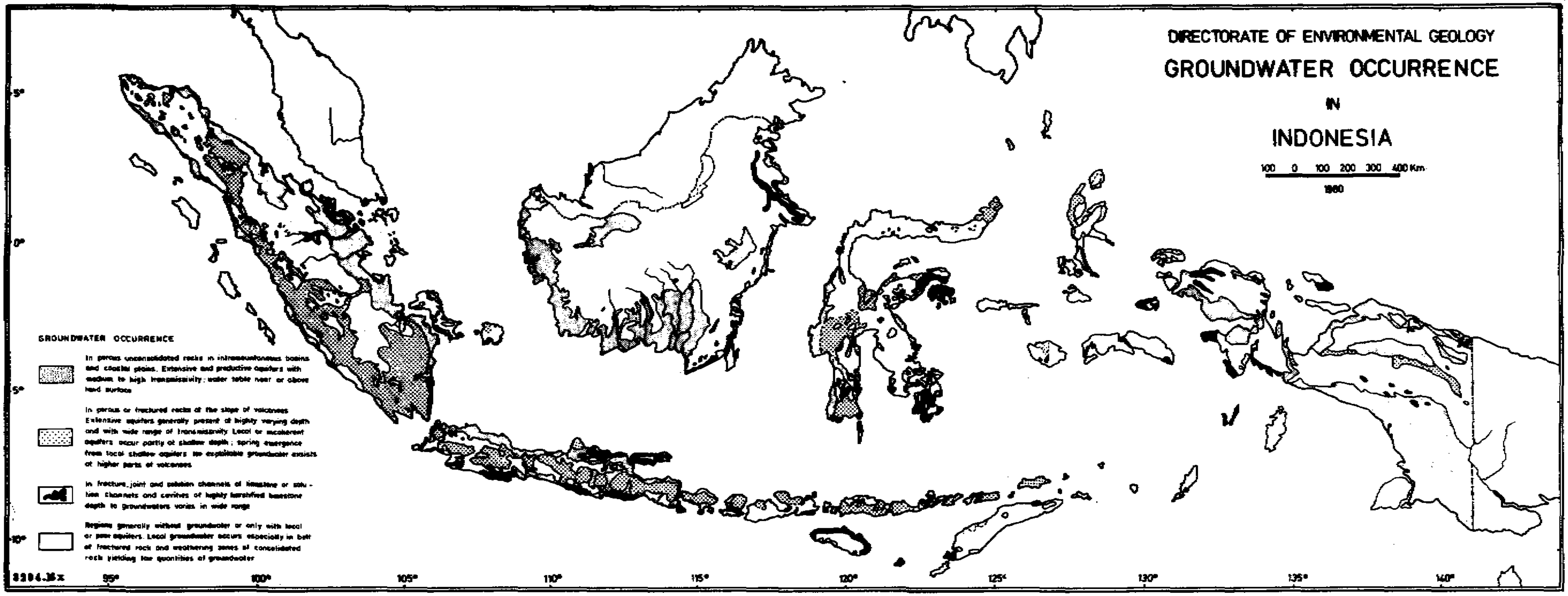
Based on the geological and hydrogeological conditions affecting the occurrence of ground water, four ground-water provinces may be distinguished, namely, the folded pre-Tertiary and Tertiary mountain ranges, the limestone terrains, the volcanic terrains and the alluvial plains (see map 19).

Folded pre-Tertiary and Tertiary mountain ranges

These mountain ranges are generally of low ground-water potential and, furthermore, the ground water is often highly mineralized, especially in areas of dominant claystone and marl layers. Small quantities of fresh ground water occur locally along the fractured and weathered zones of consolidated rocks.

The folded pre-Tertiary and Tertiary mountain ranges are distributed along the central parts of larger islands, generally underlying Quaternary volcanic products or sediments. Some of the Upper Tertiary sediments in Sumatra and Kalimantan consist of semi-consolidated clastic rocks that are largely permeable.

MAP 19



Map 19. Indonesia: ground-water occurrence

Limestone terrains

In limestone terrains, ground water is unevenly distributed and its potential depends mainly on the intensity of solution channelling.

Tertiary limestone formations are karstic with solution fissures and caverns. Limestone crops out along the northern coast of east Java and in Madura, and in an extensive belt stretching from the Southern Mountains of Java through southern Bali, Lombok and Timor.

Among the limestone terrains of considerable ground-water potential, so far known, are the Gunung Kidul area in central Java and the limestone terrains of Madura Island.

Volcanic terrains

Aquifers related to volcanic terrains generally consist of porous or fractured volcanic products such as coarse-grained pyroclastics and fractured or jointed lavas.

On the slopes of volcanoes, aquifers occur at highly varying depths and generally are governed by the topographical setting. At higher elevations the aquifers are deep seated, while at lower elevations they may be found at shallower depths.

Springs may emerge locally, either issuing from the lava tongue or from perched water. In general, recharge takes place at the higher parts of the strato-volcanoes, which normally receive higher rainfall.

In situ and reworked pyroclastic deposits derived from the Quaternary volcanoes comprising tuff, sand, gravel and clay, may be mentioned. These volcaniclastic deposits form extensive plains on the flanks of the volcanoes. Some of the interbedded clays are montmorillonitic and dispersive in character. On the slopes of volcanoes deposits of tuff breccia and volcanic mudflow with large boulders, occur, as well as lava beds.

Coastal plains

Coastal plains of high ground-water potential are commonly built up of thick Quaternary (Pleistocene to Holocene) alluvial sediments. Aquifers generally consist of thin gravel or sand layers intercalated between clay layers. Examples of such coastal plains are the Jakarta artesian basin, the northern coast of central Java and the artesian basins of Medan and Padang in Sumatra. In those coastal plains saline or brackish water-bearing layers are often found above as well as blow the fresh water aquifers.

Among the best aquifers are the Pleistocene alluvial formation (Kabuh) in east and central Java, which occurs on the flanks of and beneath the Quaternary volcanoes and is composed partly of cemented fine to coarse sandstones and pebble beds with interbedded tuffaceous clay; and the Tertiary and Pleistocene sandstone formations of a shallow marine facies, which occur in, for example, eastern Lampung, south Sumatra and south-west Bali; the sandstone is mainly fine- to medium-grained and moderately cemented.

The main impermeable formations are Tertiary clays and clayey alluvium derived from the Tertiary sediments. Quaternary deposits are good or excellent aquifers. With local exceptions, mainly in respect of limestone, older formations are poor to very poor aquifers. Most of the alluvial plains along rivers and coasts of the islands, as well as those found in sites of sub-Recent lakes, may be considered good water-bearing layers. Ground-water quality varies, especially in coastal areas, where contact between fresh water and saline water occurs.

The best aquifers are lava flows and limestones. Karstic waters, however, present problems of accessibility, including the depth, to the water-table. Lava flows are restricted to the vicinity of volcanoes. The Southern Mountains in central and east Java are one of the famous karst areas with thousands of typical conical hills and underground rivers. Another extensive karstic area is to be found in the Ajamaru region in Irian Jaya.

Ground-water investigations

Shallow ground water has probably been used for centuries by means of dug wells, especially in Java, as has spring water for domestic and small-scale irrigation systems. The first drillings were carried out in and around Java by the Dutch army as follows: at Prins Frederik Fortress, in 1843, to a depth of 83 m and at Onrust Island, in 1854, to a depth of 101 m, both locations in the Jakarta Bay area; at Semarang between 1840 and 1858 and at Gresik in 1859. The results were far from successful. Drillings carried out from 1872 onwards gave better results, from the point of view of both the quantity and the quality of the water. At a later date 11 wells were drilled for the water supply of the city of Jakarta, and others were drilled on Sumatra island. The first investigation on ground water was initiated by the Mining Bureau in the artesian basin of Jakarta. In 1930, the study of the geohydrology of Brantas Plain in east Java was initiated and continued with investigations in Bandung and Madium ground-water basins using drilling data.

Hydrology investigations were also carried out in Madura and Sumba after the Second World War by the Geological Survey of Indonesia in co-operation with the Geological Survey of the Federal Republic of Germany. The first preliminary map on ground-water resources in Java (on the scale of 1:1,000,000) was published by the Geological Survey of Indonesia in 1960. A hydrological map of Bali was issued in 1970.

Systematic investigations on ground water and extensive ground-water development have been undertaken since 1971. At that time the Groundwater Development Sub-Project of Gunung Kidul, a karst area, was initiated. Several other ground-water development sub-projects were also developed; for example, for Madura island, the Kediri-Nganjuk area (Brantas Basin), Lombok island, Madium-Solo, east Java, Bali island, Timor island, central Java and west Java. In some areas, the study of ground-water potential and development is also carried out under sub-projects of the Directorate General of Water Resources Development, in conjunction with the study of surface water. For example, there have been studies on the possibility of ground-water development and ground-water potential in the Pemali-Comal area (north-western part of central Java), the Djratum Seluna area (north-eastern part of central Java), the Serayu Basin area (south-western part of central Java), Lampung (southern part of Sumatra island), south Sulawesi etc.

Institutional framework

Several authorities are concerned with ground-water resources, studies, exploration and development (see fig. I). While the Water Resources Law of 1974 (No. 11/1974) placed the main responsibility for conserving and managing water resources on the Ministry of Public Works, the Ministry of Mines and Energy is responsible for the management of ground-water resources, and has been since the enactment of the Water Resources Law of 1936. According to that Law, permits should be submitted to the local governor prior to the execution of drilling deeper than 15 m. In addition, any repair of an existing drilled well is also subject to the consent of the local governor.

Licences are issued by the governor on the basis of a technical recommendation given by the Ministry of Mines and Energy. In practice, however, the technical recommendation is issued by the Geological Survey of Indonesia (in accordance with a circular of the Minister of Mines, dated 18 November 1971). At present, preparation of technical recommendations is the task of the Directorate of Environmental Geology.

Directorate of Environmental Geology

The Directorate of Environmental Geology (DEG) is one of the four units of the Geological Survey of Indonesia (GSI). Among its responsibilities is the administration of the ground-water resources of the country. This includes ground-water data collection, ground-water pollution monitoring and the preparation of technical recommendations for ground-water exploitation so as to avoid any undesirable effects of that exploitation. The work is mainly carried out by the Sub-Directorate of Hydrogeology of DEG. The organization chart of DEG is shown in figure II.

In carrying out its responsibilities, DEG conducts hydrogeological investigations which may be classified into three distinct programmes as follows:

(a) Systematic hydrogeological mapping

Hydrogeological maps are required for regional development planning since they provide basic data on the mode of ground-water occurrence, and the availability and quality of ground water. DEG is the only government agency involved in the national hydrogeological mapping programme. Each sheet is on a scale of 1:250,000 and covers an area of 1°30' by 1°.

Figure I. Indonesia: partial organization chart showing authorities concerned with water -well drilling and investigation

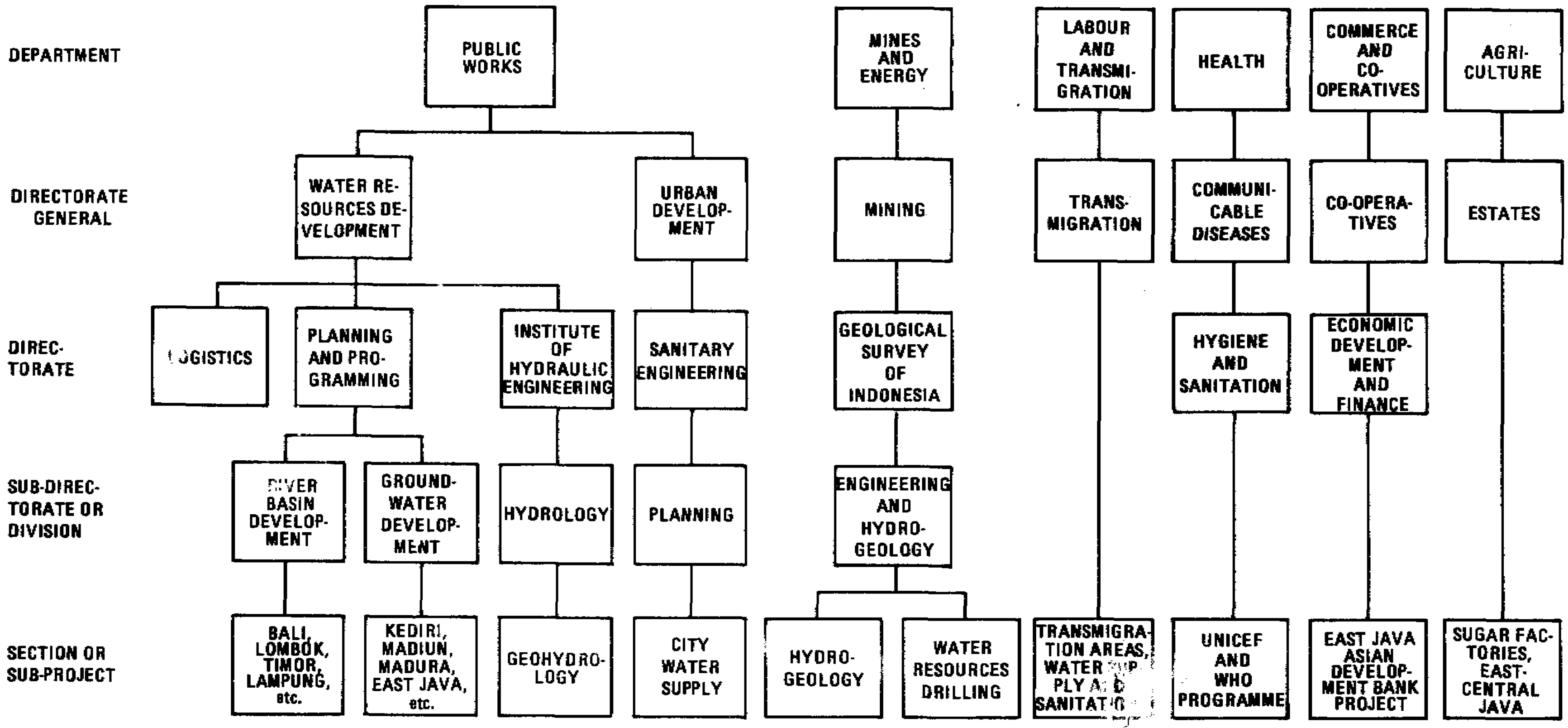


Figure I. Indonesia: partial organization chart showing authorities concerned with water-well drilling and investigation

Figure II. Indonesia: organization chart of the Directorate of Environmental Geology

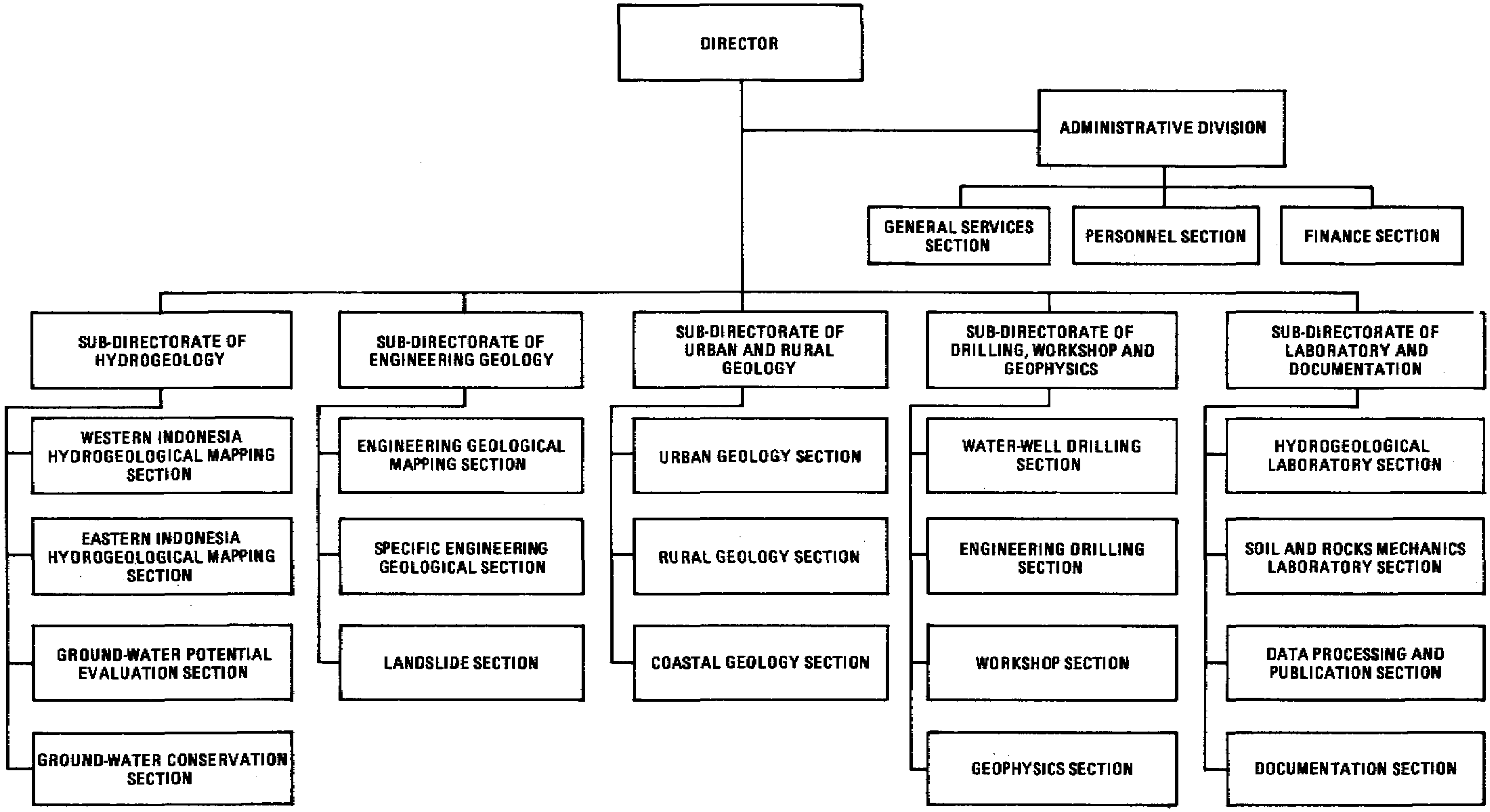


Figure II. Indonesia: organization chart of the Directorate of Environmental Geology

The hydrogeological maps published as at March 1980 are listed in table 17.

Table 17. Indonesia: published hydrogeological maps

Title	Scale	Year of publication	Remarks
Tentative ground-water map of Java and Madura	1:1,000,000	1960	Geological Survey of Indonesia (with explanatory note)
Hydrogeological map of Madura Island	1:250,000	1962	Geological Survey of Indonesia and the Bundesanstalt für Bodenforschung of the Federal Republic of Germany
Hydrogeological map of the Isle of Sumba	1:250,000	1965	Geological Survey of Indonesia and the Bundesanstalt für Bodenforschung of the Federal Republic of Germany
Reconnaissance hydrogeological map of Bali	1:250,000	1970	Geological Survey of Indonesia and the Bundesanstalt für Bodenforschung of the Federal Republic of Germany
Reconnaissance hydrogeological map of Lombok	1:400,000	1972	Geological Survey of Indonesia and the Bundesanstalt für Bodenforschung of the Federal Republic of Germany (with explanatory note)

Table 18 shows the areas hydrogeologically mapped during the period 1977-1980. Some 25 to 30 per cent of the area of the country has been covered by the mapping programme.

Table 18. Indonesia: areas hydrogeologically mapped, 1977-1980

Province	Sheet
Aceh	Calang, Meulaboh, Langsa
North Sumatra	Natal
Riau	Pakanbaru
Jambi	Jambi, Muarabungo
South Sumatra	Palembang, Lahat
Lampung	Sukadana
South Sulawesi	Majene, Palopo, Ujungpandang
South-east Sulawesi	Kendari
South Kalimantan	Banjarmasin, Amuntai

(b) Evaluation of ground-water resources

Areas of potential ground-water resources identified during hydrogeological mapping are further investigated in order to assess those resources.

In Indonesia, potential ground-water resources can normally be found at the base of Quaternary volcanoes and in intra-montane basins. Some coastal plains underlain by relatively thick Quaternary sediments and some limestone terrains are also suitable for ground-water occurrence.

To obtain the required data for the evaluation of the ground-water resources, geophysical measurements and drillings are also executed in addition to detailed hydrogeological surveys.

Evaluation of the ground-water resources was conducted during the period 1977-1980 for the areas shown in table 19. Some of those areas were jointly investigated with the hydrogeological advisory group of the Federal Republic of Germany (Project CTA-40).

Table 19. Indonesia: areas covered by the ground-water resources evaluation programme, 1977-1980

Province	Areas
Aceh	Banda Aceh Basin, Tanah Pasir-Pantonlabu and Lhokseumawe-Bireun
Jambi	Kuala Tungkal and Rimbo Bujang
West Sumatra	Solok Basin and Padang
South Kalimantan	Kandangan-Tanjung and Banjarbaru-Martapura
South Sulawesi	Sidenreng-Rappang
West Java and Jakarta	Jabotabek (Jakarta artesian basin)

(c) Management and conservation of ground-water resources

Investigations are carried out in areas where ground water is heavily exploited for domestic and industrial purposes. The aim of the investigation is to seek proper management of the ground-water resources, so that the abstraction of ground water will not cause undesirable effects, such as sea-water intrusion and land subsidence.

The effects of ground-water exploitation, that is, the changes in water level and water quality, are to be continuously monitored. For this purpose, DEG constructed a number of monitoring wells in areas where ground-water resources are heavily drawn on.

In addition, since 1979, DEG has monitored the existing wells in the Jakarta artesian basin and in the Semarang coastal plain. Recently the programme was extended to the northern coastal plain of west Java and will be continued until sufficient data are obtained.

The following authorities are also concerned with ground-water resources:

Ministry of Public Works, through the following units:

(a) Directorate of Hydraulic Engineering of the Directorate General of Water Resources Development, which established a geohydrology section in 1971;

(b) Directorate of Planning of the Directorate General of Water Resources Development, which initiates ground-water development projects for irrigation;

(c) Directorate of Sanitary Engineering of the Directorate General of Housing, Building Planning and Urban Development, which is responsible for the improvement of urban water supplies;

(d) Institute of Hydraulic Engineering in Bandung.

Ministry of Health

The Directorate of Hygiene and Sanitation of the Directorate General of Communicable Diseases Control, under the Ministry of Health, is responsible for the improvement of the rural community water supply.

Ministry of Agriculture

The Ministry of Agriculture engages consultants to carry out feasibility studies on ground water, especially in connection with the establishment of sugar plantations.

Ministry of Labour and Transmigration

The Ministry of Labour and Transmigration carries out some important projects for the implementation of a water supply system, often based on ground water, in areas assigned for transmigration in various parts of the country.

Ground-water resources

Quantitative aspects

In Indonesia the evaluation of ground-water resources is normally carried out on a basin-wide basis and priority is given to basins with potential for future development. Until the present time, only a small number of basins and alluvial plains have been investigated in sufficient detail. The total area investigated is relatively small compared with the total land area of the country. Therefore, it is not yet possible to present a complete picture of the ground-water resources of the country.

Attempts have been made, however, to give rough estimates of the ground-water resources of each province of the country (see table 20). In this connection, the rate of ground-water recharge has been assessed based on the average estimated permeability values of the rocks and the infiltration potential, that is, the difference between rainfall and evaporation.

Investigations have been conducted to evaluate the confined ground-water resources of some basins and alluvial plains. In addition the unconfined ground-water resources of some alluvial plains have also been evaluated (see table 21). It can be seen that intra-montane basins are generally most favourable for ground-water accumulation.

Ground-water quality

Along the northern coastal plain of Java and the eastern coastal plain of north Sumatra, confined fresh-water aquifers are often found intercalated between saline-bearing layers. In the coastal plains of west and south Kalimantan, ground water is generally saline. Substantial amounts of fresh unconfined water derived from local rainfall occur in the southern coastal plain of central Java and in the coastal plain of Ujung Pandang, south Sulawesi. Further inland the ground water is generally fresh except for the ground water of the deep water-bearing layers in areas underlain by dominant claystone and marl layers of Tertiary age. The fresh ground water of the volcanic terrains is generally low in hardness and total solids. The iron ion content, however, is frequently rather high. Hard water is often found in limestone terrains.

Table 20. Indonesia: estimated ground-water resources of provinces

Province	Amount of rainfall in excess of evapo-transpiration (mm/year)	Area of high permeability a/ (km^2)	Area of medium permeability b/ (km^2)	Total land area (km^2)	Estimated rate of ground-water recharge (l/sec/km^2)	Total available ground water (millions of cubic metres per day)
Aceh	1 900	5 990	11 980	55 392	4.8	22.97
Sumatra Utara	1 450	14 220	7 110	70 787	4.6	28.13
Sumatra Barat	1 900	2 128	4 257	49 778	2.4	10.32
Riau	1 021	49 634	55 838	94 562	8.1	66.18
Jambi	1 150	9 322	12 430	44 924	3.7	14.36
Sumatra Selatan	1 465	23 628	110 265	103 688	9.3	83.32
Bengkulu	1 950	2 230	4 459	21 168	4.9	8.96
Lampung	900	1 439	4 318	33 307	1.8	5.18
Jawa Barat	1 536	9 829	19 658	46 300	7.8	31.20
Jawa Tengah	1 837	6 871	10 306	32 206	8.2	22.82
Yogyakarta	1 309	325	975	3 169	4.0	1.10
Jawa Timur	750	9 590	16 783	47 992	3.6	14.93
Bali	624	562	125	5 561	1.2	0.58
Nusa Tenggara Barat	330	2 174	6 522	20 177	1.0	1.74
Nusa Tenggara Timur	250	4 889	9 778	47 876	0.4	1.65
Kalimantan Barat	1 850	39 267	31 413	146 760	8.2	103.98
Kalimantan Timur	1 350	20 262	81 048	202 440	5.1	89.20
Kalimantan Tengah	1 500	46 966	62 621	152 600	9.5	125.25
Kalimantan Selatan	850	10 338	12 405	37 660	4.3	13.99
Sulawesi Utara	922	4 586	6 878	19 025	2.0	3.29
Sulawesi Selatan	1 122	7 750	23 251	72 781	3.5	22.01
Sulawesi Tangah	1 000	6 700	16 750	69 726	2.9	17.47
Sulawesi Tanggara	440	3 875	9 687	27 686	1.2	2.87
Maluku	1 120	915	1 372	74 505	2.5	16.09
Irian Jaya	1 800	210 990	126 594	421 981	14.8	539.59
Timor Timur	200	1 680	3 360	14 874	0.7	0.90

Source: M. Notodihardjo and others, 1979.

a/ Recharge through the highly permeable area is estimated at 40 per cent of total available water resources (the amount by which rainfall exceeds evapotranspiration).

b/ Recharge through the area of medium permeability is estimated at 20 per cent.

Table 21. Indonesia: ground-water resources in areas investigated

(Millions of cubic metres per year)

Area	Ground-water resources
Intra-montane basin	
Bandung	72.8
Garut	2.9
Ponorogo-Madiun	166.6
Kediri-Nganjuk	198.4
Bondowoso	10.7
Lumajang-Jember	23.6
Foot of volcanoes	
Purwokerto	6.8
Surakarta-Sragen	21.2
Yogyakarta (unconfined water)	8.2
Probolinggo-Paitan	11.8
Situbondo-Asembagus	7.8
Banguwangi	12.8
Telukbetung	15.7
Tertiary sediments	
Banjarbaru-Martapura	1.3
Rantau-Barabai	2.5
Coastal/alluvial plain	
Cilegon	6.2
Serang-Tangerang	15.7
Jakarta	42.1
Krawang-Indramayu	39.3
Tegal-Pekalongan	32.8
Kendal	7.8
Semarang	10.5
Demak-Pati	9.2
Cilacap (unconfined water)	5.9
Kebumen-Purworejo	5.7
Jombang-Mojokerto	10.5
Banda Aceh	2.8
Medan-Tebingtinggi	53.5
Padang	5.6
Palangkaraya (unconfined water)	0.9
Sidenreng-Rappang	5.9
Aroki	5.1

Ground-water utilization

In urban and rural areas of Indonesia shallow ground water has been used for many centuries to meet the demand for domestic water. For this purpose the shallow dug well is the most widely used system for ground-water extraction.

The utilization of water from deep aquifers began in the middle of the last century for the purpose of supplying water to military camps and to the European community in the city of Jakarta.

As a result of the success of drilling operations in the Jakarta artesian basin, a number of artesian wells were constructed in other parts of the country. By 1969, when Indonesia launched its first Five-year Development Plan, approximately 1,490 wells had been drilled by the Mining Bureau and its successor, the Geological Survey of Indonesia. In addition, approximately 1,000 wells were drilled by private drilling companies. Total ground-water extraction from the deep-seated aquifers was estimated at 0.43 million m^3/day in 1969.

At present, the utilization of water from drilled wells is increasing rapidly to meet the growing demand for water for domestic, industrial and irrigation purposes.

Ground-water utilization for community water supply

The total population of Indonesia is at present about 143 million people, about 70 per cent of whom live in rural areas, and the remainder in urban areas.

In rural areas the amount of water used for domestic purposes is estimated at 5.98 million m^3/day, assuming a per capita water demand of 60 l/day. About 90 per cent of the domestic water used in rural areas, or about 5.38 million m^3/day, is obtained from ground-water sources, mainly shallow wells.

In urban areas the amount of water used for domestic purposes is estimated at 6.40 million m^3/day, assuming a per capita water consumption of 150 l/day. The municipal waterworks supplies 1.81 million m^3/day. About 4.59 million m^3/day have to be supplied from other sources, mainly private wells.

The total domestic water demand is expected to increase to 21.44 million m^3/day by the year 2001 since the population is estimated to increase to between 210 and 235 million. Part of that amount would have to be obtained from ground-water sources.

Ground-water utilization for industrial purposes

The total amount of water used for industries was estimated at 390,000 m^3/day in 1975. It was primarily used for the textile, paper and metal industries. It is expected to increase to more than 2 million m^3/day by 2001.

Present ground-water abstraction for industries is not known except in a few cases. For example, the Krakatau Steel Factory at Cilegon, west Java, draws some 11,000 m^3 of ground water a day from 25 drilled wells; textile factories in Bandung currently utilize 34,000 m^3/day and industries in Jakarta consume about 43,000 m^3/day.

Ground-water utilization for irrigation

Shallow ground water has been used for irrigation for several decades in the Klaten area, central Java, and in the Kediri-Nganjuk area, east Java. A large number of dug wells and collecting pits have therefore been constructed in those areas.

In the Madiun basin, about 700 driven wells had been constructed by 1974. They produce about 27,000 m^3 of water per day which is used for secondary crop irrigation during the dry season. The wells, which tap the shallow confined aquifer, are of the artesian flowing type.

The Ground-water Development Project of the Directorate General of Water Resources Development has started pilot schemes in four areas, as follows:

Area	Number of wells	Duration of execution	Total irrigated area (hectares)
Gunung Kidul	28	1980-1982	1,000
Kediri-Nganjuk	70	1980-1982	3,500
Madiun-Solo	44	1980-1983	2,800
Madura	30	1980-1982	1,500

In addition, the Ground-water Development Project has also started investigations in six other areas, namely, west Java, central Java, east Java, Bali, Lombok and Timor.

Conclusion

It is estimated that Indonesia's population will increase from 142 million to 210 million people during the period 1980-2001. By the year 2001, the volume of water required may be in the range of 12 million m^3/day for urban water supply; 9 million m^3/day for rural water supply; between 400 million and 450 million m^3/day for irrigation; and 2 million m^3/day for industrial water supply. It is likely that a substantial part of these amounts will have to be developed from ground-water sources, especially in areas of insufficient surface water.

A number of basins have been recognized as suitable for large-scale ground-water development. The potential of the remaining basins is still unknown. To meet the increasing demand for water, ground-water investigations will have to be conducted more extensively and co-operation between agencies involved in ground-water exploration and development will have to be strengthened.

In addition, it is necessary to improve the exchange and flow of ground-water data, which requires the setting up of a national data bank within DEG. Technical co-operation ventures in the field of ground-water investigation have been established with several countries and with international organizations. Further co-operative efforts are needed to improve the capability of government services, to upgrade their activities and to meet the ever-increasing demand for ground water.

Selected references

Directorate of Environmental Geology. August 1980. Ground water in Indonesia. Report prepared for the Economic and Social Commission for Asia and the Pacific at its thirty-seventh session.

Djaeni, A., and S. Puspowardoyo. 1979. The present use of ground water in Indonesia with special reference to the islands of Java and Madura. Unpublished report of the Directorate of Environmental Geology.

Notodihardjo, M. 1979. Water resources planning in Indonesia.

Purbo-Hadiwidjojo, M. M., ed. 1967. The water resources of Indonesia, their potentials and utilization at present. International Conference on Water for Peace, May 1967, Washington, D.C., document 25.

______________. 1977. The status of ground-water research and development in Indonesia in 1975. Bulletin of the Geological Survey of Indonesia, vol. 3, No. 1, pp. 36-39.

Puspowardoyo, S. 1979. The state of the art of hydrogeological research in Indonesia. Unpublished report of the Directorate of Environmental Geology.

Soenarto, B. October 1980. Geology and ground water in Indonesia. Unpublished report of the Institute of Hydraulic Engineering, Ministry of Public Works, Bandung.

JAPAN

Area: 372,313 km^2

Population: 144 million (United Nations, estimate 1977)

Conditions of ground-water occurrence

Main geographical features

Japan is an island country which extends in an arc shape along the eastern fringe of the continent of Asia. It consists of the four main islands of Hokkaido, Honshu, Shikoku, and Kyushu and many smaller islands (see map 20). The area of the four large islands accounts for about 97 per cent of the total area of the country.

Areas surrounding Japan are the continent of Asia westwards across the Sea of Japan and the East China Sea and northwards across the Sea of Okhotsk; the western hemisphere eastwards across the Pacific Ocean; and the Philippines and Micronesia southwards across the Pacific Ocean.

Mountain ranges and mountainous areas account for 75 per cent of the total area of Japan. They run the length of the four long slender islands like a spine, dividing the country into the Pacific Ocean side and the Japan Sea side.

Mountains more than 3,000 m high are found in the central part of Honshu. Here a massive fault depression, the Fossa Magna, traverses Honshu from the Sea of Japan to the Pacific Ocean, geologically dividing the country into a south-western part and a north-eastern part.

Japan has many volcanoes, about 40 of which are active, but dormant. The major volcanoes, including the highest, Fuji-san (3,776 m), number about 200 and belong to several volcanic belts.

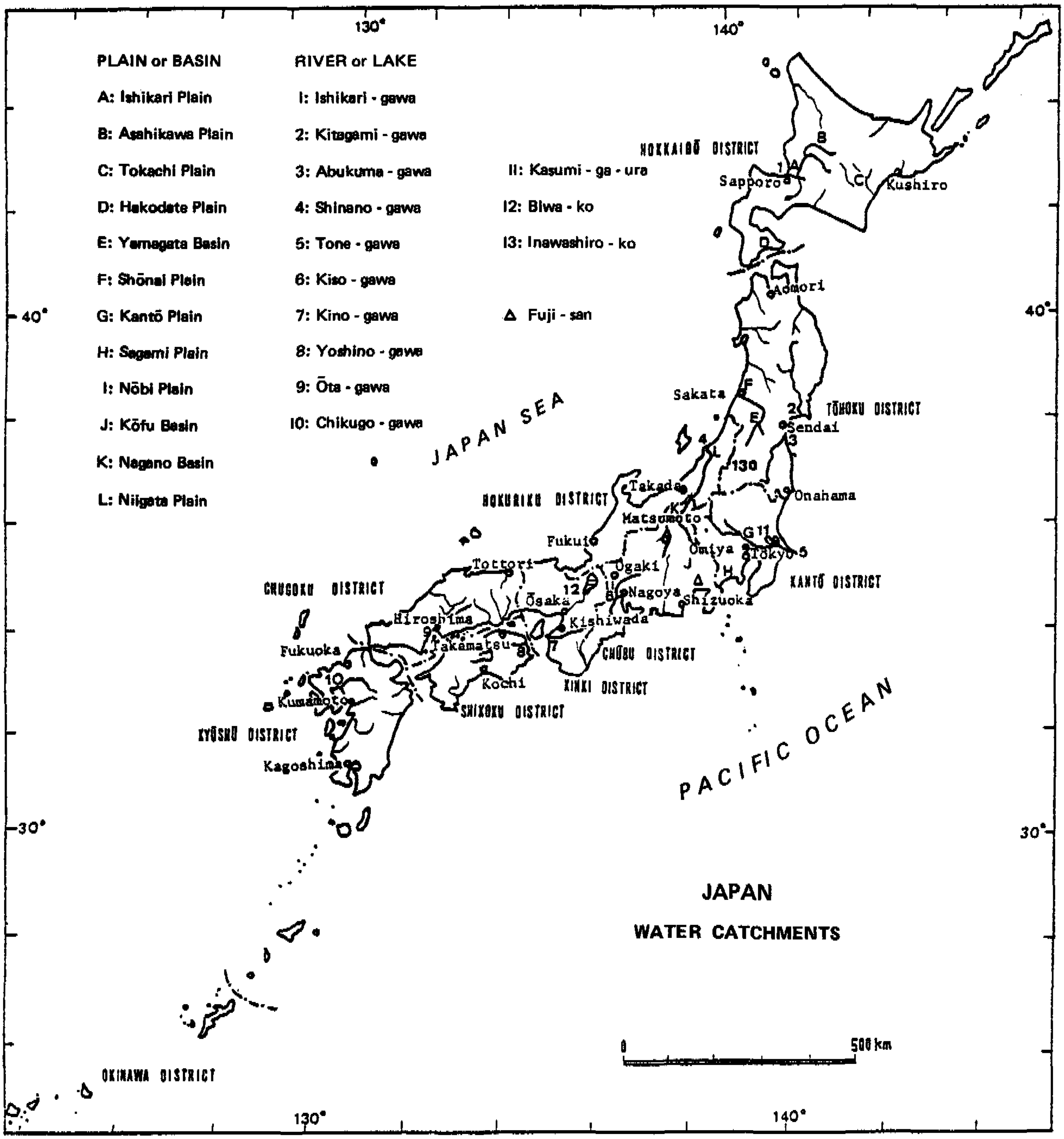
The mountain slopes in Japan have steep gradients, thus the rivers are short and steep.

The flat lands, where most of the population live, are made up of small plains and basins which have been formed by rivers. The total area accounts for about 25 per cent of the land area. There are plains of different kinds. For instance, the Kanto plain was formed by the uplift of a shallow sea-bed, the Kinokawa plain and the Yoshinogawa plain extend along the rivers (kawa or gawa) of the same name. The Ishikari, Niigata, Nobi and Tsukushi plains are delta plains. The plains, in general, are composed of low-lying lands, terraces and hilly lands. Most basins having many alluvial fans and piedmont hills are aligned in the mountainous areas.

The coastline of the Japanese islands is generally indented. There are numerous peninsulas and bays along the Pacific Ocean. The shores of the Sea of Japan are largely sandy, with less indentation; sand dunes occur locally.

Map 20. Japan: water catchments

MAP 20



3204.J7x

In addition, areas of land have been reclaimed or drained, mainly along the coast of the Pacific Ocean.

Climate

Japan extends from about latitude 20° N to latitude 45° N. It is situated in a wide area having a difference of 25 degrees in latitude and 31 degrees in longitude.

The greater part of the land of Japan, belonging to the temperate climate zone, receives a great deal of rain; humidity is generally high and there are distinct seasonal changes in climate. The southern part of Japan has a subtropical climate, whereas the northern part has a subarctic one.

The Pacific Ocean side of Japan receives a great deal of rain in summer; in winter, the weather is dry and windy. The Japan Sea side receives heavy snow in winter. The difference in climate between the two sides is caused by the summer monsoon which blows from the Pacific Ocean bringing warmer temperatures and rain and the winter monsoon from the Asian continent, which brings snow to the last and dry windy weather to the west. In the basins surrounded by mountain ranges or mountainous areas, however, there is little rain and the difference in temperature between summer and winter is greater.

Generally, the climate is temperate in the south-west and cold in the north-east. The rainy season is longer and the rainfall more abundant in the south-west than in the north-east. Typhoons frequently strike the area between Kyushu and Kanto during summer and autumn. A summary of the climate in various locations is provided in table 22.

Surface water

Restricted by the land form, which is narrow, long and steep, Japanese rivers (kawa or gawa) are generally short and steep.

In south-western Japan, especially rivers flowing towards the north, have smaller drainage basins and the length of the main part of their course is shorter than those flowing towards the south.

The discharge of a river is strongly affected by the climate, and fluctuates seasonally to a great extent. The rivers on the Pacific Ocean side reach a maximum discharge in the rainy season (summer) and the typhoon season (autumn). The rivers on the Japan Sea side discharge a great deal of water in spring, when the snow melts.

A summary of the principal rivers is presented in table 23.

Table 22. Japan: precipitation and temperature of principal locations

(average for 1941-1970)

Number	Location	Altitude (m)	Annual precipitation (mm)	Annual temperature (°C)
1	Sapporo	17.2	1 141	7.3
2	Kushiro	31.7	1 112	5.5
3	Aomori	3.0	1 424	9.6
4	Sakata	3.1	1 954	11.8
5	Sendai	38.9	1 245	11.6
6	Onahama	3.2	1 396	12.8
7	Tokyo	5.3	1 503	15.0
8	Shizuoka	14.1	2 355	15.7
9	Nagoya	51.1	1 540	14.7
10	Takada	13.4	3 038	13.0
11	Matsumoto	610.0	1 058	11.0
12	Fukui	9.1	2 472	13.8
13	Tottori	17.3	2 042	14.3
14	Osaka	23.1	1 390	15.6
15	Hiroshima	29.3	1 644	14.8
16	Takamatsu	8.7	1 185	14.9
17	Kochi	0.8	2 645	16.1
18	Fukuoka	2.5	1 705	15.7
19	Kumamoto	37.7	1 939	15.9
20	Kagoshima	4.3	2 433	17.0

Source: Rikanenpyo, 1978.

Table 23. Japan: principal rivers and discharge, 1976

River	Area of drainage basin (km^2)	Length of the main part of the river course (m)	Mean annual discharge (m^3/sec)	Gauging period	Gauging station
Ishikari-gawa	14 300	262	615	1954-1973	Ishikari-ohashi
Kitakami-gawa	10,250	249	243	1952-1973	Tome
Abukuma-gawa	5,400	239	99	1956-1973	Iwanuma
Shinano-gawa	12,050	367	393	1951-1973	Ojiya
Tone-gawa	16,840	322	130	1938-1973	Kurihashi
Kiso-gawa	9,100	209	221	1951-1973	Inuyama
Kino-kawa	1,660	136	47	1952-1973	Funato
Yoshino-gawa	3,650	194	85	1955-1973	Chuo-bashi
Ota-gawa	1,690	103	45	1953-1973	Kumura
Chikugo-gawa	2,860	143	96	1950-1973	Senoshita

Source: Rikanenpyo, 1978.

More than 600 lakes (ko, numa or ike) are scattered among the seaside districts and the volcanic zones. The major lakes in the country are Kasumi-ga-ura, which is close to the mouth of Tone-gawa in the Kanto plain; Biwa-ko, which lies in the inland basin near Kyoto in central western Honshu; and Inawashiro-ko which is one of the lakes dammed by a volcanic eruption in north-western Honshu (see table 24).

Table 24. Japan: principal lakes

Lake	Location (prefecture)	Area (km^2)	Maximum depth (m)	Altitude of water (m)
Kasumi-ga-ura	Ibaraki	167.7	7.3	0
Biwa-ko	Shiga	673.9	103.4	85
Inawashiro-ko	Fukushima	103.9	93.5	514

Source: Rikanenpyo, 1978.

Water resources

The average annual precipitation available as water resources is 1,800 mm which is equivalent to a total volume of 670 billion m^3 for a mean water-year. About 20 per cent of that, 123 billion m^3, evaporates and the rest flows out as surface and ground waters. Water is utilized during the outflow process.

Maximum precipitation occurs in the early summer (rainy season) and torrential rains fall late in summer and early in autumn (the typhoon season). The rain water runs off rapidly in flood, except in the case of snowy areas on the coast of the Sea of Japan, where winter precipitation, mostly in the form of snow, exceeds that of summer.

Furthermore, the amount of available water resources in a wet water-year is 29 per cent more, and, in a dry water-year, 26 per cent less, than the amount available in the mean water-year.

According to hydrological calculations, the theoretically maximum possible amount of utilizable surface water is roughly estimated at 200 billion m^3/year, 40 per cent of the total run-off of rivers. At the present technical level, however, even if the river water is controlled more efficiently, the amount of utilizable surface water is estimated at 135 billion m^3/year.

Before surface-water resources can be properly controlled, it is most important that the social, economic and legislative problems involved in the development of water resources are solved.

It has been estimated that, in 1973, the amount of water used for domestic water supply, irrigation, and industry was 81.9 billion m^3. Surface water contributed about 68.8 billion m^3, equivalent to 56 per cent of the amount of usable water. Ground water contributed about 13.1 billion m^3, equivalent to 48 per cent of the water recharged by precipitation and surface water.

It is reported that, in respect of surface water, 8.7 billion m^3 (13 per cent) per year is used for domestic water supply, 7.1 billion m^3 (10 per cent) per year for industry and 53.0 billion m^3 (77 per cent) per year for irrigation.

Since the major cities and industrial areas of Japan are situated on the coastal plains, water shortages occur frequently. And since the rivers are polluted by waste water and water treatment is an expensive process, the cost of water increases every year.

Geology

The Japanese islands are situated in the circum-Pacific orogenic zone and represent the summit of a great mountain system of complicated structures.

A rough estimation of the areas covered by various rocks in Japan is presented below.

Sedimentary rocks	Area covered (percentage)
Quaternary	20.7
Tertiary	18.9
Cretaceous	2.7
Jurassic	1.0
Triassic	0.3
Palaeozoic	12.2
Undifferentiated Mesozoic and Cretaceous-Palaeogene	5.3
Other rocks	
Quaternary and Tertiary volcanic rocks	20.4
Acidic intrusive rocks	13.3
Basic and ultrabasic intrusive rocks	0.9
Diabase, porphyrite	0.7
Mica schist, gneiss	0.9
Crystalline schist, phyllite	2.7

The oldest rocks ascertained in Japan are Palaeozoic ones, and fossil evidence dates clearly the lowest part of the Gotlandian. Among them, those in Later Mesozoic and in Neogene time have had the greatest effect on the present geological structure. Igneous activity accompanied the crustal movements, and considerable metamorphisms occurred.

The Japanese islands are arranged, on the whole, in an arc shape stretching from north-east to south-west. The general trend of the north-eastern wing of the arc is NNE-SSW and that of the south-western wing is NEE-SWW. The south-west of Japan, divided by the Fossa Magna, is constituted chiefly of Palaeozoic and Mezozoic rocks, and has Cenozoic rocks in rather limited areas. The north-east of Japan, on the other hand, is widely covered by Cenozoic rocks in which pre-Tertiary rocks appear in many isolated land masses.

In Hokkaido, the south-western peninsular part is simply an extension of north-eastern Japan, while the remaining main part belongs to another arc of the folded mountains stretching from Sakhalin.

The Quaternary formations are closely associated with ground-water resources. They consist of various kinds of sediments: clay, silt, sand, gravel, pebbles and cobbles. They are unconsolidated, compared with the Tertiarty or pre-Tertiary sediments lying under them.

The Pleistocene deposits are generally of a higher grade of consolidation, compared with the Holocene deposits. Some of the Pleistocene deposits are volcanic or are of a lower grade of consolidation, such as terrace sediments or loam layers on the upland. Sand and gravel beds in the Pleistocene deposits are generally water-bearing, but they are filled with silty materials; the gravel beds are especially rich in fine materials in their lower parts.

The Holocene deposits in the river basins contain various kinds of materials appearing in the upper reaches of the rivers: decomposed sand from a granitic region, lava blocks with ash and sand from a volcanic region, cherty or arkose pebbles from the Palaeozic and Mesozoic mountainous lands, phyllitic or hornfelsic fragments from metamorphosed zones. In many cases, the river floor and sides are composed of gravel, sand or silt; in some cases the Holocene deposits on the seashore are dunes composed of fine to coarse sand.

The Holocene deposits often show low bearing strength at, for example, present or former river mouths and bends of rivers. Land subsidence through compaction of soil due to lowering of the water level occurs in such places.

Ground-water resources

Brief historical investigation

As many cities and villages in Japan were built on the lowlands, alluvial fans and uplands, the sources of water supply for domestic use, apart from river waters, were springs and shallow or flowing ground water. The construction of a public-water-supply system, the source of which was a spring, was first achieved in Tokyo, in 1590.

In ancient times, people had little knowledge about getting ground water from wells. More than 1,000 years ago, Buddhist priests, on pilgrimage to various parts of the country would instruct the people on how to exploit the ground water and to dig large-diameter wells. Some of these old wells still exist.

The first recorded report of an artesian well was of a flowing well 18 m deep in Tokyo in 1729. The drilling machinery was made of wood and driven by hand. After that time, well drilling machinery utilizing the flexibility of the bamboo indigenous to Japan, with bamboo casing pipes and mud water, was devised and improved in all parts of the country. The popular drilling method named the "Kazusa-Bori" was used until about 1960.

Many flowing artesian wells for domestic and irrigation purposes were drilled by that method in coastal plains and inland basins. In areas of unconsolidated materials: clay, silt, sand and fine gravel, it was feasible to drill up to 300 m.

In 1883, the first report concerning ground water was published by Edmund Nauman in the Annual Report of the Geological Survey of Japan.

In 1912, a water-well drilling company was established and the following year in Tokyo, an industrial water well was successfully drilled, 320 mm in diameter and 90 m in depth, by means of an imported rotary machine. This well was the first to be drilled by a modern drilling machine and had a flowing discharge of 360 m^3/day.

As the drilling of flowing artesian wells became easier and cheap, artesian water became the source of public water supplies. The ground-water resources in the major cities were therefore investigated by experts of the Geological Survey of Japan. The annual reports of the Geological Survey contain 22 reports on the ground water of the areas investigated; for instance, Oiso-machi (town) (1912), Sakai-shi (city) (1914), Tsu-shi (1916), Hirosaki-shi (1917), Fukuyama-shi (1918) and Okayama-shi (1925).

In 1919, in Osaka, water-well drilling by the California stovepipe method was successful. At that time, the water of most of the artesian aquifers in the country was under higher pressure than at present, so that this method was used until 1953.

Moreover, since a great deal of water was required for the spinning and dyeing industries, many cable-tool percussion machines used in oil fields were used for drilling water wells. The dye works at Osaka drilled a water well 298 m deep in 1921 and another 510 m deep in 1931. These flowing wells existed until quite recently.

Around 1929, the combination machine, known as the "Beam-type", was introduced, incorporating the best features of the "Kazusa Bori" method, and using mud water and the California stovepipe method. This type of machine is adequate as far as drilling the unconsolidated materials in Japan is concerned; so it is still widely used. Thus, in the 1910s and the 1920s ground-water development began and was continued.

The years 1928-1934 marked the beginning of Japanese hydrogeology. Technical papers on geohydrology and hydrology, for example, The Utilization of Ground Water as the Sources of Water by Y. Yoshida, and The Geology and Hydrology in Mt. Fuji by S. Kanbara, were published during that period.

Ground-water studies continued to be undertaken in the period 1935-1945. The outstanding event with respect to ground-water investigations was the brisk activity in the fields of civil engineering, agricultural engineering and geophysics. Especially noteworthy was the "well theory" (1943) of R. Nomitsu and K. Yamashita, geophysicists, which was the same as the Theis (nonequilibrium) equation. In the same period, the idea of artificial recharge - construction of a subsurface dam - was introduced by K. Kachi, an agricultural engineer. Surveying by the seismic refraction and electrical resistivity methods had been used in geological investigations for railroad construction. These methods were also applied to ground-water investigations during that period.

Immediately after the Second World War, ground-water development was crucial for agricultural production and the reconstruction of industries. From 1946-1960, newly developed farmlands were irrigated by ground-water supplies, and the areas where a great deal of ground water was available for development were industrialized. Ground-water surveying in hydrogeologically unknown areas was carried out using both geophysical and geochemical techniques. Thus, the areal investigations concerning the feasibility of the optimum production of water and the approach to quantitative investigations were continued throughout the period.

From 1961 to the present, land subsidence and/or sea-water intrusion in coastal areas and a rapid lowering of the water level in inland basins have occurred, because of over-draught of the ground water that had contributed to the remarkable growth of industries and the expansion of agricultural production. With the aim of solving these ground-water problems, new legal regulations and ordinances were applied to some ground-water consuming areas. From the standpoint of ground-water management, hydrogeologists are carrying out investigations to evaluate the safe yield of ground-water basis and are conducting experiments concerning artificial recharge.

Prospecting method utilized

The common aquifer, consisting of sand and/or gravel, is of the Quaternary in coastal plains and inland basins and of the Pliocene in some other areas. Since about 1965, when tourist or summer resorts were developed at the foot of mountains, the source of water has been ground water in fractured zones or volcaniclastic materials.

When the submersible pump came into wide use, it became possible to pump water economically from greater depths. Water-supply systems for villages on uplands and hills could therefore be constructed.

Given the conditions of ground-water occurrence in Japan, the electrical resistivity method is adequate for surveying ground water, compared with the other geophysical methods, and is the one most commonly used.

The electrical resistivity method was introduced in 1930, and was applied in 1937 to ground-water surveying for the supply of water at Shirakawa Station (Japanese National Railways).

Since 1946 this method has been indispensable in preliminary investigations of ground water.

Resistivity logging is used to determine the pumping capacity of the aquifer. In certain cases, temperature and electrical conductivity loggings are used in new wells. These loggings provide extensive information about the existence of salt-water, geological boundaries and the like.

The seismic refraction method was used with the resistivity method before 1940, but has become so costly that it is used only in certain cases. For instance, in locations where the ground-water level is particularly deep, it is more successful than the resistivity method. In the regional investigations at the foot of mountains (e.g., Fuji-san) and the intake areas of alluvial fans (e.g., Hadano-shi, Matsumoto-shi and Yamagata-shi), the seismic refraction method was applied.

Attempts have been made in mountain areas consisting of granites or lavas to survey the location and the magnitude of a fault or fracture zone by means of the radio-activity method. Locations where the magnitude of radio activity is stronger, are not always ground-water bearing zones, and there are some instances of ground water being discovered in blind areas.

The geology of Japan is so complicated that the quality of the ground water varies from one area to another. The hydrochemical method is appropriate for ground-water investigations. Of importance is the fact that it is possible to find out the sources of water by graphical interpretation of the data analysed. The determination of stable isotopes of hydrogen and oxygen in ground water is particularly valuable in classifying the sources of water in the ground-water system (precipitation, river water or mixed water). This is being attempted in the regional investigation of the Nobi plain, because it was observed that there was a difference between the oxygen-18 content of ground water recharged from precipitation and ground water recharged by river water (from the Kiso-gawa) in the north-eastern part of the plain.

Tritium has been used to study the movement of free ground water and shallow artesian water, leakage from dam sites, and the means of recharge to the ground-water system. Tritium measurements in Japan began around 1967 and gave information on the time of recharge to the systems of the Kanto plain, Fuji-san, the Osaka plain and the Saga plain. Most of the waters pumped, however, are mixed ones, of different ages and having a widely different tritium content. It is clear that the rate of tritium content is reliable in wells which have little discharge and which tap a single aquifer, because the water of these wells is unmixed.

Main aquifers

The cities and industrial areas in Japan are situated on coastal plains and inland basins which are composed of the unconsolidated materials of the Quaternary and the Pliocene, storing a large volume of fresh ground water (see table 25).

Shallow aquifers have been developed since ground-water utilization began. As the amount of water required for public supplies and industries increased, drilling rigs were improved and the development of deeper aquifers became possible. Furthermore, extensive information on subsurface geology could be collected. In mountainous areas, especially, at the foot of volcanoes, hydrogeological information on water in fissures and fractures has become obtainable, as deeper aquifers have become easily accessible by means of the submersible pump.

Regional occurrence of ground-water

Hokkaido District

In this district, 40 per cent of the total area is of post-Miocene age. There is a higher percentage of younger formations than in Honshu. One third of the Quaternary area is covered mainly by volcanic material, such as ash and pumice.

Since the post-Miocene topography is flat and composed of highly permeable water-bearing formations, the area has become heavily populated.

It is estimated that at present the flow of ground water in the whole area amounts to about 2 million m^3/day. But in Hokkaido the population density is lower than that in Honshu, and the alluvial plain is widely underlain by the Quaternary and the Pliocene; thus the development of ground water is at an early stage, except at Sapporo-shi and its environs.

Unconfined ground water is distributed in the alluvial plains, alluvial fans and upper diluvial terraces. Particularly at Sapporo-shi, situated on the Toyohira alluvial fan, and in the Ishikari, Asahigawa and Tokachi plains, ground water of good quality is available in abundance. However, in the lower land of the middle and lower reaches of the Ishikari-gawa, Teshio-gawa, as well as other rivers, where the thick peat layers peculiar to Hokkaido are distributed, ground water is high in ions, and ammonia derived from organic matter. However, in areas covered thickly with volcanic ash and pumice, the chemical quality of most ground waters is good.

Since precipitation in Hokkaido is less than that in Honshu, and recharge to ground water is low in winter, the land becomes dry in the months of February and March; in April, it becomes wet due to snow melting. The level of the water cable therefore fluctuates widely according to the season.

Table 25. Japan: outline of topography, geology and water-bearing properties

Topography	Geology: System	Geology: Series	Geology: Deposits	Water-bearing properties
Coastal plain, flood plain, fan and talus	Quaternary	Holocene	Sand, gravel, silt, organic mud, peat, shells	Highly permeable. Yields more than 1.45 l/sec. per well in the vicinity of the river. Specific capacities of wells range from 11.6 to 34.8 l/sec/m of drawdown. Contains water generally under water-table conditions. Water is fresh except near shore line.
Lower slopes of Quaternary volcano		Pleistocene-Holocene	Volcanic ash, sand, scoriae, boulders, pumice, tuff, breccia, lava	Generally permeable. At the foot of mountains, contains water under artesian conditions. Yields large quantities of artesian water or springs (e.g., Fuji-san and Aso-zan).
Terrace, upland and fan		Pleistocene	Sand, gravel, clay, pumice, loam, peat, shells	Moderately to highly permeable. Yields large quantities of water for industrial, agricultural and public water-supply purposes. In the plain, water is contained under artesian pressure, and flows in underflow conditions in some areas. Some wells flow, yielding as much as 0.96 l/sec. Specific capacities range from 300 to 500. Water is generally of excellent quality except where contaminated by salt water: in the Seto inland sea and in the natural gas and oil fields of north-east Japan.
Hilly land and lower mountain land	Tertiary	Upper Pliocene	Sand, gravel, shale, tuff, lignite, shells	Moderately permeable. In the plain, water is under artesian conditions; some wells flow. Individual wells yield as much as 0.48 l/sec. Specific capacities reach as much as 100. The source of ground water is mainly rainfall; the piezometric surface has rapidly declined in some areas, owing to heavy pumping. Water is of good quality except for a high iron content.
Mountain land	Tertiary, Mesozoic and Palaeozoic or older		Bedrock	Relatively impermeable. Contains some water in fractures, caverns, fault zones and weathered zones, but impracticable to develop. Pliocene deposits contain saline water in the plain. There is abundant water in limestone caverns.

The principal artesian aquifers are a few sandy gravel layers of the lower Pleistocene underlying the alluvial plains. The artesian aquifers of the Pliocene, consisting of coarse sand stone conglomerate and tuff, are inferior to those of the Pleistocene in yield capacity and chemical quality, so that the aquifers have been developed in some areas only. These artesian waters are under flowing conditions.

In the Ishikari plain, including the Yuhutsu-genya (wilderness), a great deal of artesian water has been utilized and, from a hydrogeological standpoint, it is thought that large quantities of water still remain to be developed.

The Tokachi plain, the second largest in Hokkaido, is a large ground-water basin. The bottom of the basin is below Obihiro-shi, where the artesian water is under high pressure.

The Hakodate plain, the Asahi-gawa basin and the Konsen plain are also artesian water basins. Most artesian wells are up to 300 m deep.

Many volcanoes of Quaternary age are thickly covered by volcanic materials and are very permeable under hydrogeological conditions. Rainfall therefore infiltrates deeply into the volcano body, flows downwards to its foot and discharges as springs. Many large springs emerge at the base of the Tarumae, Yotei, Koma-ga-dake, Shari and Mashu volcanoes. Submarine springs flow out from the sea-bed, particularly around the volcanic island of Rishiri-to.

Many of the springs discharge up to 40,000 or 60,000 m^3/day. The total discharge rate of 18 springs at the foot of Yotei-zan is estimated at about 400,000 m^3/day.

Tohoku District

In this district the ground water which is economically usable is borne in the lacustrine or fluviatile deposits of the Holocene, the diluvial gravel of terraces, and the semi-consolidated materials of the Pliocene which constitute the lower hills bordering the terraces. The dune sand on the coast of the Sea of Japan also has usable water-bearing formations. The rocks of the Miocene, constituting the hilly lands on the coast and in the inland basins, are also water-bearing formations, but with small yield. However, in some of these formations the reservoirs of thermal springs occur; the temperature of the water is high and the mineral content is similar to that of hot springs.

Most of the other areas are mountainous, composed of hard rocks, making access to water difficult. Some springs, however, in areas of limestone, slate and volcanic rocks of the Quaternary, flow out at a rate of a few tens of thousands of cubic metres per day.

At Sendai-shi in Tohoku, ground water is utilized in large quantities for industry and air-conditioning. The principal aquifer is Pliocene tuffaceous sand. Since the density of wells in the city is extremely high, the artesian head has been declining and is at present just over 200 m below the ground surface.

In farming areas, ground water is utilized in quantities for irrigation and water supply; as a result, the water level declines in summer and rises in winter.

In the inland basins of Yamagata Prefecture, in particular, the artesian water level of some irrigation wells falls below the ground surface during summer and rises above it during winter.

In the areas of heavy snow of the northern part of the district and on the coast of the Sea of Japan, ground water of about 13° to 20° C is utilized to melt snow on the main roads and the railways. However, since recharge to ground water is less during winter, discharge is higher than recharge most of the time.

In this district, important supplies of water are obtained from the underflow in the river beds. For instance, along the Abukuma-gawa (Shirakawa-shi, Koriyama-shi and Fukushima-shi), 10,000-20,000 m^3 of water a day are taken from collecting galleries less than 10 m in depth. Other rivers provide 3,000-6,000 m^3 of water a day, obtainable from large wells.

In the Aomori plain, flowing artesian water occurs in a thick formation of sands and gravels of the Pleistocene. Wells are about 500-600 m in depth and each yields 2,000-3,000 m^3/day.

There is a possibility that fresh ground water may exist up to a depth of 1,000 m at Sakata-shi on the Shonai plain, which is situated on the coast of the Sea of Japan.

The artesian wells of the table lands and hilly lands are 100-250 m deep and each yields 500-1,000 m^3/day.

The water in the inland basins is fair as far as chemical quality is concerned. On the other hand, on the coast of the Pacific Ocean, salty artesian water exists, and water with a high ferrous content (from organic matter) is stored in the Shonai plain.

Kanto District

This district has two ground-water systems, one in the Kanto plain and the other in the Sagami plain.

(a) Kanto plain

The ground water recharged from precipitation and river water flows towards the centre of the major ground-water basin between Omiya-shi and Iwatsuki-shi, and discharges on the sea-bed of the Pacific Ocean through Tokyo Bay. The ground water in the western part of Chiba Prefecture flows towards the Bay.

Holocene deposits. Near the bottom of the river channel, the sides are composed of sand and gravel. This gravel formation functions as a bank storage, especially in the upper and middle reaches. Recently, however, this function has been diminishing owing to the lowering of the river beds.

Pleistocene deposits. The upper formations are of gravel typified by the terrace deposits, and the ground water is under water-table conditions. These formations function directly as recharge areas. The middle formations are exposed on the terraces and piedmont hills, and gradually become thicker and deeper towards the centre of the basin. The formations consist of sand and gravel and are the major artesian aquifers in the basin.

Pliocene and older Pleistocene. The formations distributed in the western and eastern parts of the basin and in part of the Bosohanto (peninsula) are the main artesian aquifers. The formations in the centre of the basin are not pumped because they contain natural gas and salty water.

The total thickness of fresh-water-bearing formations is as much as 750 m in the centre of the basin. But this is a densely populated, highly industrialized area, and severe land subsidence has occurred as a result of pumping large quantities of water. Since 1959, pumping has been strictly limited by laws and ordinances.

Volcanic products. At the foot of the Akagi-san, Haruna-san and other volcanoes, many springs are utilized for water supplies; ground water is also used to meet the demands of tourist resorts in summer.

Miocene. Artesian water is obtained from Miocene sand and gravel in some areas between Kumagaya-shi and Takasakishi.

(b) Sagami plain

The plain is low-lying land that has been formed by the Sagami-gawa and the Sakawa-gawa. On the reaches of the Sagami-gawa, the principal aquifers exist up to 80 m in depth, but are contaminated by salty water near the mouth of the river. The ground water along the Sakawa-gawa is recharged in large quantities by river water. The artesian head is so high that there are many flowing wells up to 100 m deep.

Chubu District

In this district, there are three major ground-water systems: in the coastal plains of the Pacific Ocean; in inland basins and valley plains; and at the foot of mountains.

(a) Coastal plains

Ground water from the coastal plains has been utilized in large quantities for centuries.

There are small-scale ground-water basins in the coastal plains of four rivers: the Fuji-gawa, the Abe-gawa, the Oi-gawa and the Tenryu-gawa. The ground water is recharged by water from these rivers and is under flowing artesian conditions. The more highly permeable aquifers are the sand and gravel layers of the Holocene and the Pleistocene. Artesian wells are a maximum of 200 m deep. The quality of water is excellent near the rivers, but the chloride content of the water increases with distance from the rivers.

The Nobi ground-water basin is the second largest in the country, the largest being the Kanto basin. The principal sources of ground water are the waters of three rivers: the Kiso-gawa, the Nagara-gawa and the Ibi-gawa. The lower land is underlain by the Pliocene and the Quaternary, consisting of three highly permeable sandy gravel layers. They are distributed at or near the ground surface in the eastern and northern parts of the basin, and become deeper to the south-west. The ground water is derived from the Pliocene and the Quaternary in the eastern and northern parts, and from the Quaternary in the south-western part. Formerly, there were many flowing wells 30-200 m deep tapping the Quaternary and Pliocene aquifers. At present, however, they are in operation only at Ogaki-shi.

Pumpage is currently regulated by laws and ordinances, since land subsidence has been caused by overdraught in the coastal areas.

(b) Inland basin and valley plain

The Kofu, Matsumoto and Nagano plains are underlain by the Holocene and the Pleistocene. Most formations consist of gravel, but a chiefly clayey one occurs in the lower Pleistocene. The water-bearing formations of the Pleistocene are more than 100 m in depth and the ground water is under flowing artesian conditions.

In the Hime-gawa valley plain along the Fossa Magna and the Inadani valley plain, the fluviatile deposits are under water-table conditions.

(c) Volcanic area

Fuji-san and Yatsu-ga-dake are covered with thick volcanic material. Springs discharge around their bases. The numerous springs at the foot of Fuji-san are larger. Their total discharge rate is estimated at about 1.2 billion m^3/year, equivalent to 40 per cent (about 3 billion m^3) of annual precipitation. The Mishima springs and the Fuji-no-miya springs, which issue from the southern part of the foot of Fuji-san, are the largest.

The Fuji lavas are distributed in the coastal plain at the southern part of Fuji-san. They are very porous and highly permeable, and the ground water is under flowing artesian conditions. Until 15 years ago, one well near the sea flowed out at a rate of 5,000-7,000 m^3/day.

The water level fluctuates seasonally. It is low in winter, when snow blankets the ground, and high in summer, when the snow melts.

Hokuriku District

This district comprises Niigata, Toyama, Ishikawa and Fukui Prefectures. Heavy snow falls on the side of the Sea of Japan. Annual precipitation is estimated at about 2,000 mm or more on the plain. The alluvial fans are formed by the rivers having small drainage areas and steep gradients (exceptions are the Shinano-gawa and the Agano-gawa). The ground water in the fans, therefore, is a valuable water resource.

(a) Niigata Prefecture

The areas in which moderate to large quantities of usable water can be obtained from wells are (1) the lower reaches of the Ara-kawa and the Tainai-gawa; (2) the basins of the Agano-gawa and the Hayade-gawa; (3) the middle reaches of the Shinano-gawa; and (4) the basin of the Seki-gawa.

In the low-lying damp land of the Niigata plain, most of the ground water is salty except for water-table water in the natural levees and the coastal dunes. Natural gas is dissolved in artesian water.

Areas (1) and (2), mentioned above, belong to a ground-water system of the alluvial fan type. The intake area and the conduit area are under water-table conditions and the discharge area is under flowing artesian conditions. In area (3) the fluviatile deposits of valley plains are permeable aquifers. In the coastal plain of area (4), the ground-water basin is composed of five stratiform aquifers. The waters of the uppermost, second and third aquifers have a high ferrous content; those of the fifth have a high chloride content. Only the waters of the fourth aquifer, which occurs about 300 m below the surface of the centre of the basin, are of good quality.

(b) Toyama Prefecture

Principal water resources are the ground water in the fan, formed by the rivers Kurobe, Satsuki, Joganji and Sho-gawa, which have no run-off during the dry season.

The ground water, replenished by surface water and irrigation water on the fan, emerges in the form of springs at the discharge area, and flows out from the wells on the coast. The artesian aquifers 200 m deep are Pleistocene sand and gravel.

(c) Ishikawa Prefecture

There are two ground-water systems: in the Tedori-gawa and Sai-gawa alluvial fan, and in the Ochi-gata plain.

The system in the fan is of the water-table type. Water level is high in summer and low in winter, so that springs dry up. In the coastal plain, the largest in Japan, flowing wells 50-70 m in depth are distributed widely and are supplied from Pleistocene aquifers. The pumped aquifer in the fan and the Ochi-gata plain is composed of sandstone of the Pliocene. The only source of ground water is precipitation, thus the discharge rate is much less than that of the Quaternary.

In the western part of the plain, water with a high chloride content exists more than 100 m below the ground surface.

(d) Fukui Prefecture

Principal ground-water areas are to be found in the Fukui plain, the Tsuruga plain and the Awara tableland.

The river waters of the Kuzuryu-gawa and Asuwa-gawa recharge the ground water of the Fukui plain, in which there are two or three exploitable artesian aquifers up to 150 m deep, consisting of sandy gravel contained in thick clay layers of the Quaternary. In the Ono basin of the middle reaches of the Kuzuryu-gawa, large springs from thick alluvial fan deposits are utilized for domestic purposes.

The ground-water system in the Tsuruga plain is of the alluvial fan type. The artesian aquifer consists of sandy gravel of the Pleistocene and is usable up to a depth of 100 m.

The ground water in the Awara tableland is under water-table conditions. Its source is precipitation. The water level is constantly held at about 10 m above sea level, since when it rises above that, water flows out as springs from the lower edge of the tableland.

Kinki District

Principal ground water areas in this district are distributed in the inland basin, for instance, the lakeside of Biwa-ko, the Kyoto basin and the Nara basin, and in the coastal plains, such as the Osaka, the Wakayama and the Hyogo plains. Pumpage in Osaka and a part of Hyogo Prefecture has been limited by laws for the prevention of land subsidence.

(a) Lakeside of Biwa-ko

Most raised bed rivers run off during the rainy season only. Artesian flows are obtained from Pleistocene aquifers 30-100 m in depth. The Quaternary is estimated to be 100-150 m thick and basal rock occurs at a depth of 410 m below the surface at Kusatsu-shi.

(b) Kyoto basin

The Katsura-gawa, the Uji-gawa and the Kizu-gawa come together in the basin. The underflow channel of the older Kamo-gawa through Kyoto-shi joins the underflow of the Katsura-gawa.

The underflow and artesian water of the Pleistocene of the Kizu-gawa, and the artesian water of the Kamo-gawa form one flowing artesian basin in the south-western part of the basin.

Some of the artesian water flows out into the Yodo-gawa and the rest flows into the Osaka plain through an underflow conduit.

(c) Osaka coastal plain

In the Osaka area the overburden is composed of unconsolidated alluvial materials. The usable artesian water comes from the underlying Plio-Pleistocene sands. Because of the excessive pumping of that water for industry and for air-conditioning, land subsidence has occurred in the upper portion of the overburden. Until about 1967, subsidence was confined to the urban area of Osaka, but after that it spread for miles. Since 1962, ground water laws have strictly limited the purposes for which water can be pumped.

(d) Hyogo Prefecture

The ground water in the southern coastal plain has been exploited for all purposes. That of the eastern part is under the control of the industrial water law. Some of the coastal ground water supplied from granitic rocks from Nishi-no-miya to Kobe-shi is calcium-rich mineral water, which, since it is of the optimum quality for brewing sake, is protected.

In the coastal area between Akashi-shi and Kakogawa-shi, there are numerous irrigation ponds, since precipitation is low and river basins are small. Each well yields only a few hundred cubic inches of water a day.

In the Himeji coastal plain, most of the usable ground water is underflow and is extractable to a depth of 40 m below the ground surface.

(e) Nara basin

The basin, a tectonic one, is also a ground-water basin. Artesian water occurs in large quantities in the northern part of the basin, but only in small quantities in the southern part. Most of the artesian wells are 100-200 m in depth. The water-table water along the slope of the ground surface flows out into the Yamato-gawa.

(f) Wakayama Prefecture

The principal aquifer is composed of the fluviatile deposits of the Kino-kawa and the Arita-gawa. But the ground water near the sea is salty and therefore not usable.

Chugoku District

The ground water is distributed in (a) a valley plain; (b) a coastal plain; (c) volcanic areas; and (d) limestone areas. As the divide of the Chugoku mountain range is located on the side of the Sea of Japan, the area of river basin on this side is smaller than that of the Seto-Naikai (inland sea).

(a) Valley plain

The main aquifer is very permeable, alluvial and under water-table conditions. The Pleistocene sediment is clayey and less permeable.

(b) Coastal plain

The artesian water in this plain is generally salty, thus fresh water occurs only in the river-sides or in older river beds. A great deal of water has been obtained from collecting galleries.

(c) Volcanic areas

There are many springs around Dai-sen, some of them yielding about 10,000 m^3/day. On the western side, especially, ground water in the amount of 200-300 m^3/day is obtainable from wells 80-200 m deep. On the coast, artesian wells are under flowing conditions.

(d) Karst region

Limestone is distributed in the mountainous area. The discharge from cavern springs fluctuates seasonally, so that the springs are used on a small scale for domestic and irrigation purposes only.

(e) Ground water in drifts

In the western part of the district, at Ube-shi and Onoda-shi, it is possible to utilize the ground water in drifts of former coal mines. Since the mines were shut down, water has been accumulating in drifts and is under flowing conditions.

Shikoku District

Since the rivers discharging into the Seto-Naikai (inland sea) have small basins and steep gradients, alluvial fans have formed on the coastal plains. Other rivers have larger basins and most of the other coastal plains in the District are smaller, except for the Tokushima and the Kochi plains.

(a) Kagawa Prefecture

Annual precipitation in this area is only about 1,200 mm, which is almost the same as annual evaporation. The main aquifer is composed of Quaternary sands and gravels. Permeable formations occur only near rivers. Except for the ground water in these formations, ground water is high in ferrous and ferric ions, up to 100 mg/l in many cases. Total thickness of unconsolidated materials is up to 130 m.

(b) Ehime Prefecture

There are many springs in the discharge area of the Kamo-gawa and the Nakayama-gawa fans, and numerous flowing wells in the low-lying land of the coast. The artesian aquifer utilized is composed of Pleistocene gravels at a depth of 30-40 m below the ground surface. In the other coastal plains, the water-bearing formations of the Quaternary are less permeable except when they occur in river-sides.

(c) Tokushima Prefecture

Fluviatile deposits are highly permeable aquifers. In the coastal plain, the permeable water-bearing formation is the gravel of the Pleistocene, 30 m deep and recharged by river water. Underlying formations contain salty water in the Tokushima coastal plain and in the other plains they are composed of impermeable basal rocks.

(d) Kochi Prefecture

Large supplies of ground water are obtained from alluvial gravels near rivers. The Pleistocene sediment, being clayey, yields only small amounts of water.

Kyushu District

Based on the hydrogeological conditions in the district, ground water occurrence is classified into six types.

(a) Important ground-water supplies in large quantities come from volcanic material and the Pleistocene (areas: Isahaya, Kumamoto, Tamana and Sendai), as well as from volcanic material alone (areas: Kobayashi, Miyakonojyo and Osumi); these areas account for half the total supplies.

(b) The main artesian aquifer is the Pleistocene which is distributed in the plains and basins (areas: Buzen, Bungo, Saga, Yatsushiro and Hitoyoshi).

(c) Small supplies are obtained from the Quaternary (areas: Kita-kyushu, Oita and Nobeoka); at Kita-kyushu, since the coal mines have been shut down, all the drifts are full of water.

(d) Ground water is derived from the fractures and fissures of basalt and andesite or volcanic sand and gravel (areas: Matsuura, and Iki and Fukue islands).

(e) Water stored in the fractures of reef coral of the Plio-Pleistocene is utilized for the supply of Okinoerabu-jima (island) and Yoron-jima.

(f) Volcaniclastic materials of the Quaternary have water-table water and underlying rocks have artesian water in volcanic areas (Tara-dake, Simabara, Aso-nango-dani, Kuzyu and Takeda), plains and the volcanic platform of the basins (areas: Izumi and Satsu-nan).

Okinawa District

The district, consisting of Okinawa-jima, the Sakishima-shoto (archipelago) and the Yaeyama-shoto, is covered with Palaeozoic and Mesozoic rocks, and reef coral of the Plio-Pleistocene, so that ground-water occurrence varies locally. What is peculiar to these islands, compared with Honshu, is that there is no distribution of the Quaternary, and the water-bearing formation is of younger limestone.

(a) Okinawa-jima

Drilled wells yield small supplies of fresh water, locally from Tertiary sandstone, and of salt water in some areas. The principal supplies of ground water are stored in the fractures or caverns of limestone and flow out as springs. The discharge rate is estimated at about 1,800 m^3/day/km^2, but is strongly affected by rainfall. The discharge rate of the springs which are the source of the public water supply at Naha-shi is 2,160 m^3/day on the average, the maximum being 7,400 and the minimum, 1,200.

(b) Miyako-jima

This island is covered with limestone overlying the Tertiary. The ground water is stored in a lower part of the limestone.

(c) Ishigaki-jima

Most of the area is covered with Mesozoic rocks and granites and locally with Tertiary rocks. There is no limestone. All formations are impermeable, so that, in comparison with other islands, ground water is available in small quantities only. There is more surface water, however, since the area is heavily forested.

Results of ground-water investigations

Commonly, wells in Japan are 300-400 mm in diameter and of the mutli-aquifer type.

When a new well has been completed, the usual practice is to carry out pumping tests and to analyse the water to find out whether it is fit for human consumption. The tests, in many cases, are carried out by the constant discharge method (in special cases, by means of observation wells); sometimes by the step-drawdown test. Details of wells are given in table 26 below.

Table 26. Japan: results of ground-water investigations

Geological age and depth of aquifer (m)		Geographical location	Depth of wells (m)	Specific yield (l/sec/m of drawdown)	Hydrogeological parameters: Hydraulic conductivity (m/day)	Transmissivity (m^2/day)	Storage coefficient
Holocene	...	Kawasaki	15	3 840	980	9 900	0.2
	...	Yonago	26	2 550	100	560	0.5
	...	Nasuno	10	280	35	414	3.5
	5.5-11.0	Mihara	10	230	60	490	0.1
	14.5-32	Niihama	32	3 700	1 030	18 100	15
	...	Nakajo	12	526	1 800	5 800	5.7
Pleistocene	100-133	Ome	200	140	15	460	0.2
	...	Ichihara	55	94	18	334	0.17
	186-227	Chiba	250	180	7	285	0.1
	...	Kawasaki	25	345	135	2 700	0.8
	...	Nasuno	70	1 300	23	810	1.2
	73-128	Sakura-mura	150	260	6	240	0.05
	...	Tokyo	149	360	8.5	370	0.3
	...	Hiratsuka	80	80	17	380	0.02
	20-30	Mihara	31	500	58	580	0.03
	...	Sendai	100	200	16	170	...
Pliocene	...	Sendai	130	58	2	44	...
Miocene	...	Sendai	250	15	0.7	21	...

Chemical quality

The chemical quality of ground water is affected by the kinds of rocks in a river basin, their sedimentary condition and that of water replenished by precipitation and river water. The chemical quality therefore differs from one ground-water basin to another (see table 27). Complicated geological conditions, small river-basins and ground-water conditions also affect chemical quality. In general, in the plains, the quality of artesian water is better than that of water-table water.

Water-table water recharged by river water, except for acid water, is of the calcium bicarbonate type and artesian water is of the sodium bicarbonate type. The water in Quaternary volcanic areas and coal fields is of the calcium chloride or calcium sulphate type. The water of marine sediments is of the sodium chloride type.

In the plains of Hokkaido and in the coastal plains of the Sea of Japan, most of the ground water is high in ammonia and ferric ions, derived from peats or organic matter in clay layers.

Water in the mountain ranges from Tohoku to Kanto is high in acidity, because of the acid volcanoes of the Quaternary. The north-east of Japan, which is extensively covered with Tertiary rocks, and the Chugoku district, composed of granites, yield silicate-rich ground water, which is quite effective in growing paddy rice. Ground water in the area of metamorphic rocks in the Shikoku district is high in manganese and zinc ions. In granite regions and areas of Quaternary volcanoes, ground water contains fluorine ion. The Palaeozoic and Mesozoic areas supply ground water with a low mineral content.

With respect to average salinity values of river waters, the calcium content in Japan is nearly half that of the rest of the world; the waters have a high sodium and chloride content, since the country is surrounded by sea.

The average salinity values of river waters in the area of sedimentary rocks are similar to those of the rest of the world, but in volcanic areas, the sodium and sulphate content are both quite high.

Water temperature varies with the temperature at the particular location, the sources of replenished water and the chemical quality. The temperature of water-table water is equivalent to the average annual temperature at the location, that is, 8°-10° C in Hokkaido and 18° C in southern Kyushu.

The temperatures of both water-table and artesian waters in the river beds fluctuate very widely. For instance, that of water-table water is high in autumn and low in spring, whereas that of artesian water is high in winter and low in summer. In the north-eastern coastal plains of the Sea of Japan, the water temperature is higher than elsewhere, because the clay formations containing organic matter are very thick.

The thermal gradient is normally 3°-4° C per 100 m.

Table 27. Japan: chemical analysis of artesian ground water

(Milligrams per litre)

Location	Depth of aquifer (m)	Temperature (° C)	pH	HCO_3	Cl	SO_4	Ca	Mg	Na	K	Electrical conductivity (micromho/cm)
Sapporo	111-141	11.1	7.8	171	25.6	0	18.8	10.8	30.0	6.6	200
Kushiro	115-132	9.3	7.9	48.9	13.8	4.4	6.4	3.2	12.0	3.3	100
Aomori	239-259	15.0	7.6	51.6	10.0	7.0	5.5	2.3	11.5	1.3	108
Sakata	28-50	12.5	6.8	21.8	24.1	6.0	1.6	3.6	8.8	2.5	100
Sendai	211-245	23.0	7.4	137.0	5.2	32.2	4.0	1.6	48.5	0.03	240
Tokyo (Omiya)	607-629	22.0	8.4	97.2	22.3	0.1	31.0	9.6	25.0	3.0	...
Shizuoka	157-173	15.5	7.6	49.7	6.0	2.8	30.1	2.1	6.6	0.57	185
Ogaki	212-228	15.0	7.0	41.2	2.0	2.1	11.3	1.7	4.8	1.1	...
Takada	261-310	18.7	7.5	106.0	27.8	3.1	17.8	5.7	19.7	4.3	340
Matsumoto	114-136	...	6.5	40.3	9.6	4.7	15.8	7.9	8.8	1.9	...
Fukui	56-86	17.1	7.1	92.6	9.4	5.0	20.1	9.02	9.5	0.5	155
Tottori	50-73	...	7.4	93.9	65.0	0	10.4	5.4	55.2	3.8	...
Kishiwada	261-288	22.5	7.5	149.9	4.3	8.5	10.5	5.8	27.0	7.5	...
Takamatsu	49-71	17.5	6.6	69.1	11.0	10	11.2	4.8	18.8	1.3	163
Kumamoto	67-147	19.1	7.0	67.1	12.9	37.3	16.5	8.4	12.5	4.9	228

Ground-water resources: gaps in knowledge

The Japanese take the matter of ground-water resources very seriously, because they recognize from their own experience in its use over a long period of time that during the drought season ground water is more stable in quantity than surface water.

Ground water has already been exploited in the densely populated and heavily industrialized areas along the Pacific Ocean. Since 1960, it has been developed also in the cities and new industrial areas on the Sea of Japan and in north-eastern Japan where large quantities of water are in demand.

It has been observed that pumpage has exceeded the safe yield (in some areas throughout the year and in other areas during certain seasons) which frequently causes ground-water problems. In order to solve these problems, self-governing bodies have been issuing their own ordinances since 1963. Such ordinances are concerned with the prevention of land subsidence; they prohibit the drilling of new wells near the public-supply well, set limits on land development, and regulate pumping.

In addition, 26 users' counter-measure associations have been established with the assistance of the Ministry of International Trade and Industry (MITI)) in the major districts having industrial areas. Their objectives are to prevent land subsidence, sea-water intrusion and extraordinary depression of the ground-water level. They have regulations on limiting the pumpage, drilling wells and so on, and have spared no effort to save water and reduce pumpage. While the ground-water ordinances and the users' counter-measures in the various areas differ widely in principle and the degree to which ground water may be exploited, the regulations facilitate ground-water management in the public interest. In some districts, most of the ground-water problems are solved as a result of a rise in the ground-water level.

The exploitation of ground water, however, varies according to the amount of rainfall and increases in agricultural and industrial production. The fact remains that it is difficult to put theory into practice as far as the management of ground-water resources is concerned.

Ground-water development

According to Japanese law, while surface water is controlled by the Government, ground water belongs to land-owners and can be developed by them.

Farms, industries and cities which require water in large quantities, utilize surface water, but in cases in which the amount of water required is less than 10,000 m^3/day, ground water is generally utilized.

If there is insufficient surface water for irrigation, water wells can be drilled with the aid of government subsidies. The same applies to the public water-supply facilities, since it is the responsibility of the proper authorities to maintain a safe and sufficient water supply. Should such drilling be required, the Government will draw up plans and a budget, and private organizations will undertake the work involved.

The central Government has two laws relating to ground-water management, one concerning water for industry and the other concerning water for air-conditioning. These laws are aimed at protecting effectively against land subsidence caused by overdraught of ground-water basins. In the areas designated by the laws, surface water, supplied by public industrial-water systems, is substituted for ground water. For the purpose of evaluating the limit of pumping draughts, measurement of ground surface levels and observation of water level are carried out by the Government on a continuous basis. Up to the present, as the water level has risen, land subsidence has gradually begun to decrease.

Since 1965, MITI has had the responsibility of carrying out preliminary investigations to evaluate the safe yield in specific ground-water basins where ground water will be exploited in the near future, or where minor ground-water problems exist. The Ministry further advises users to organize counter-measure associations for utilizing the ground water within the safe yield. The spacing, depth and pumpage of wells are regulated by the associations. Most of the information about ground-water conditions is obtained through observation wells. Twice a year, each association prepares a report on the information it has collected.

In addition to the above policy, factories put the idea of re-use into practice under the guidance of the Water Re-use Promotion Center, established by the Ministry, with the aim of promoting the development and application of the technologies required for the reclamation and re-use of municipal sewage and industrial waste water, as well as for the desalination of sea water. As a result, ground-water pumpage has decreased at each factory by 30 to 40 per cent.

The Japanese Government has established a system for the licensing of "Consultant Engineers". If a qualified person passes the necessary examinations, he receives a licence. Examinations are held every year and candidates are tested in the fields of hydrogeology and water-well engineering. Most of these new consultant engineers become leading figures in the companies employing them.

Drilling firms and organizations

All water-wells are drilled by private companies, 22 per cent of which are members of the National Water-Well Drilling Association of Japan. The Association has eight branch offices throughout the country. Engineers employed by these companies attend a short course every year on the development of ground-water resources. When they pass the exams held by the Association, they are awarded certificates.

Ground water has been exploited mostly in the plains of the Quaternary and to a certain extent in the hilly lands of the Pliocene. Since the aquifers are unconsolidated formations of sand and gravel, water wells are drilled by the cable tool method using a tubular bit. In the Pliocene areas in the north-east of Japan, the hydraulic rotary method is used.

At present, the number of water-well drilling rigs has reached a total of 1,000 of the percussion type and 200 of the rotary type.

The diameter of wells, except those for domestic use is more than 150 mm; wells with a diameter of 250-400 mm are the most common. Before 1950, depths drilled were 30 m, 60 m and 90 m in coastal plains and basins, but since then, wells with a depth of around 200 m have become common as the demand of water has increased; there are, however, few wells deeper than 300 m.

In the areas designated by laws and ordinances, water-well drilling for industrial purposes began to decrease, but it has begun to increase for the purpose of water-level observations. In other areas, especially in north-eastern Japan and Hokkaido, water-well drilling is in great demand.

The total depth of production wells drilled is about 350,000 m/year.

Utilization of ground water

Ground-water utilization for municipalities, air-conditioning, industries, irrigation, fresh fish breeding and snow melting has continued to increase, since ground water belongs to the land owner, is characteristically constant in temperature and chemical quality, and can be utilized at low cost.

It is reported that total ground water use is estimated at 13.1 billion m^3/year, equivalent to 19.5 per cent of annual precipitation in Japan.

Ground water is used for many purposes, each with its own characteristics. A breakdown of its usage follows:

Use	Quantity (Billions of m^3/year)	Ratio of ground water use to total water use (Percentage)
Industrial water supply	4.96	41 (1975)
Domestic water supply	3.57	28 (1975)
Irrigation	3.75	6.6 (1974)
Air-conditioning	0.79	100 (1971-77)

Industrial water supply

As far as the use of ground-water for industrial purposes is concerned, a great deal of water is obtained from artesian wells concentrated in the coastal plains, and is utilized for cooling and air-conditioning. The dependency on ground water for those purposes is quite high in relation to the total amount of water required by industry.

Estimates of ground-water consumption are reported by MITI every other year. In 1958, according to the MITI report, 2.91 billion m^3, or 52 per cent of the total amount of water for industrial purposes, was contributed by ground water. This figure increased to an estimated 5.26 billion m^3 (54 per cent of the total) in 1964, and 5.58 billion m^3 (55.8 per cent of the total) in 1970, because of an increase in demand. But the amount decreased to 4.96 billion m^3 in 1975 and has continued to decrease every year since then.

This large decrease in pumpage could be explained by the fact that pumpage has been limited by the industrial water law in the industrial areas on the coast of Tokyo Bay, the Bay is Ise and the Bay of Osaka.

Since artesian water generally holds a uniform temperature below 20° C throughout the year, 50 per cent to 60 per cent of the total amount of ground water for industrial purposes is utilized for cooling and air-conditioning in factories and the rest is for washing materials, for boilers and for raw materials.

The industries which utilize 75 per cent of the total amount of water used are the paper and pulp, textile, chemical and food industries. Industries with a greater degree of dependence on ground water are small- and medium-sized enterprises, such as the spinning, food, and rubber manufacturing industries.

According to the Ministry's policy, the total amount of ground water for industrial use should be about 4.5 billion m^3/year, and factory pumpage should be decreased by a total of 1.14 billion m^3/year in the areas designated by the law.

Domestic water supply

Water supply systems have been rapidly constructed during the past 20 years, and at present 88.6 per cent of the population is served by a public or private system.

Ground water has been utilized for domestic purposes from ancient times and is the main source of supply as far as small-scale facilities are concerned.

The annual amount of ground water in domestic water supplies was estimated at 0.85 billion m^3, or 25 per cent of the total amount of water for domestic use, in 1951; the amount increased suddenly to 1.9 billion m^3 in 1965 and to 3.57 billion m^3 in 1975, more than four times as much as it was in 1951.

Since major cities have large-scale facilities for surface-water intake, the degree of dependence on ground water was only 28 per cent in 1965 and 30 per cent in 1973. In respect of small-scale facilities, however, where the population to be supplied is less than 50,000, the degree of dependence is high: 50 per cent to 60 per cent; furthermore, 75 per cent of the small-scale and private water-supply facilities utilize ground water.

The sources of small-scale water-supply facilities are as follows, in descending order of importance: springs, artesian and water-table wells and underflows. The sources of private supplies are artesian wells, springs, water-table wells and underflows.

Irrigation

In connection with the use of ground water for irrigation, the following points may be noted:

(a) During dry seasons, ground water can be used to supplement farmers' water requirements;

(b) The source is mostly water-table water;

(c) Irrigation facilities using ground water are designed on a smaller scale than those using river water;

(d) Each area irrigated by ground water is small.

The amount of ground water used for irrigation is 29 per cent of the total amount of ground water used, yet only 6 per cent of the total amount of water for irrigation.

The area irrigated by ground water is estimated at 530,000 hectares; 94 per cent of that area comprises paddy fields and the rest upland fields, orchards and grasslands.

As ground water is pumped up for irrigation, particularly during the dry season, the irrigation water replenishes the water-table water. The amount of water pumped from aquifers which are replenished represents 73 per cent of the total amount of water required for irrigation. The remaining 27 per cent comes from artesian wells and infiltration galleries in river beds and springs.

Ninety-five per cent of total annual pumpage of ground water is carried out from April to September; the economic efficiency of its use is low, because it is hardly ever exploited in wet years.

There are several areas, however, in which ground water should be the major source of irrigation because surface water has become polluted, or because utilizing it by means of intake dams has become increasingly difficult, owing to the lowering of river beds.

Air-conditioning

Ground water for air-conditioning is utilized in offices, department stores, hotels, hospitals, educational institutions and public bath houses. The amount required is roughly estimated at about one billion cubic metres per year, or 7 per cent to 8 per cent of total ground-water use.

Before 1960, ground water was pumped up in large quantities in the major cities of Tokyo and Osaka, among others. Since then, the amount has decreased year by year as the major cities have been required under the ground-water law to reduce pumping. In the smaller cities, however, there has been an increase in the quantities pumped.

Other

Large quantities of fresh-water fish have been bred in Shizuoka and Tokushima Prefectures.

The breeding of eels demands, intermittently, large amounts of ground water in May and June. On the lower reaches of the Oi-gawa and the Tenryu-gawa, the discharge rate is estimated at 2.11 million m^3/day. Since salt water, however, is favourable to breeding eels, the amount of fresh ground water actually utilized may be about 1.5 million m^3/day.

The breeding period of ayus (sweetfish or altivelis) extends from February to December. In May and September, water is required in particularly large quantities; pumping, however, is continued throughout the year. As the optimal temperature for breeding ayus is 18° C, most of the water utilized, estimated at 500,000 m^3/day in Tokushima, is under water-table conditions.

In the breeding of rainbow-trout, which requires water at a temperature below 12° C, springs in mountainous areas are utilized.

The use of ground water to melt snow began in 1963 when Nagaoka-shi in Niigata Prefecture, an area receiving abundant snow, suffered serious damage from a snowfall. By this method warm water pumped from shallow wells is sprayed on the streets by sprinkler systems when snow begins to fall. The use of ground water is an adequate and economical method of melting snow (the temperature of the ground water being higher than that of the air), compared with any other method; therefore, it has come into use rapidly and widely in all snowy areas.

The pumpage for snow-melting varies in proportion to snowfall. In Nagaoka-shi, it has been estimated that an average of 330,000 m^3/day is required, a maximum of 440,000 m^3/day being recorded in 1974 and a minimum of 110,000 m^3/day being recorded in 1973.

Ground-water problems

The principal problems arising from overdraught of ground water are excessive depression of its level, land subsidence and sea-water intrusion.

The excessive depression of the ground-water level, at more than one metre per year, is a phenomenon which can be seen in the upper reaches of rivers. Overdraught is not the only cause; it may also be caused by land development in mountainous areas, decrease in outflow of rivers, lowering of river-beds and reduction of paddy-fields or decrease in infiltration.

Land subsidence has occurred in the low-lying land of the plains and basins where the principal cities, Tokyo, Nagoya, Osaka, Yamagata, Kofu and others, are situated. These are industrial areas or highly agricultural areas of paddy-fields. Since low-lying lands consist of compressible layers, subsidence will occur as a result of a slight decline in ground-water pressure.

In the past, however, land subsidence occurred only in coastal plains in summer, since a great deal of water was pumped up for many purposes. Since 1965, however, in the districts of abundant snowfall along the coast of the Sea of Japan and in the inland areas of north-eastern Japan, subsidence has occurred fairly regularly in winter owing to the widespread use of ground water for melting snow.

The exceptional amount of sea-water intrusion into fresh ground water, which has taken place since 1960, has occurred in the areas having industries related to harbours and fresh-water fish breeding, where the ground-water level is likely to be below the sea-water level as a result of pumping large quantities of ground water.

In the coastal plains of Shizuoka and Toknshima, where fresh-water fish are bred, the area of sea-water intrusion expands in summer and contracts in winter.

The special case of fresh ground water being contaminated by exploitation of a salt-water aquifer has arisen frequently in the coastal plains. The reason is that the owner requires large quantities of water from a well, and the driller ignores the existing hydrogeological information about the aquifer.

It is possible to solve the above problems by reducing the pumpage of ground water by means of ordinances. Undesired and also unexpected problems, however, may arise as a result of recovery of the ground-water level, and several municipalities are experiencing difficulties in dealing with the matter.

One difficulty is rebound of the overburden. In Kawasaki-shi, the overburden rose a few centimetres each year, owing to rapid recovery of the ground-water level as a result of the pumpage limitation contained in the industrial water law, and was suspected as foreboding a great earthquake.

A further problem is the flowing out of salty water from artesian wells in the areas contaminated by sea-water intrusion, for example, in Fuji-shi. This problem also has been caused by the limitation of pumpage, and paddy-fields have been damaged by inflow of salty water.

Integrated use of surface water and ground water

In taking active measures to prevent hazards caused by excessive pumping, it is necessary to utilize surface water instead of limiting pumpage. The construction and running costs involved in the utilization of surface water are higher than those of utilizing ground water.

In order to prevent land subsidence in urban and industrial areas, such as Tokyo and Osaka, the source of public water supplies has been changed from ground water to surface water.

The source of public water supplies in smaller cities has been gradually changing from ground water to river water as the amount of water required has increased. Surface water is at least twice as expensive as ground water.

One of the solutions to ground-water problems is to increase ground-water storage by means of artificial recharge.

Irrigation of paddy-fields, that is, water spreading as a kind of artificial recharge, has been carried out for centuries in Japan. The period of irrigation extends from April to September; furthermore, summer is a wet season when ground water is recharged in large quantities by rainfall and infiltration through the paddy-fields.

In the snowy areas, since a great deal of ground water is pumped up for melting snow in winter, the non-recharge season, the method of direct injection of water into a well is under experiment, for the purpose of increasing ground-water storage. There are, however, many problems (e.g., costs of facilities and management and share of expenses by beneficiaries) to be solved before the artificial recharge plan can be put into practice.

Conclusion

The natural characteristics of the ground water in Japan, replenished by rainfall and river water, and mostly stored in highly permeable Quaternary, are as follows:

(a) A single well yields large quantities;

(b) Seasonal fluctuations in temperature are slight;

(c) The quality is generally good for all purposes.

Since, from a legal standpoint, ground water belongs to the land-owner, it has been exploited at low cost for many purposes.

On the Pacific Ocean side of the country, that is, in densely populated and industrial areas, ground water will be utilized effectively within the safe yield in the future.

In north-eastern Japan, utilization of ground water for melting snow will be continued, since this method is more economical than others. The amount of ground water used will increase in summer also as industries extend their activities to the north-east. In this area, in winter, there is a difference of 15 to 20 or more degrees Centigrade between the air temperature and that of artesian water, making it necessary to take into consideration the uses to which that water may be put. If feasible, artesian water will be useful for heating houses and will also facilitate the cultivation of vegetables regardless of season.

Thus, although the amount of ground water developed is less than that of surface water, it could be said that utilization of ground water having the above natural characteristics makes an important contribution to the growth of cities and the expansion of industries.

Cost of ground water

The cost of water supplied involves depreciation account, payment of loan interest, maintenance cost, wages to be paid etc., but the cost of power contributes the most to the cost of water.

The cost per cubic metre of private industrial ground water ranges widely from ¥2 to ¥10 (approximately $0.009 to $0.043 in 1980) and is about ¥5 in general, though it may differ during the life of a well. The average water charge for public industrial water supplies is twice as much.

The charge for water from public water supplies, the source being ground water, ranges from ¥30 to ¥90 (approximately $0.129 to $0.387), depending on the water-supply body.

Prospects for ground-water exploration and development

The occurrence of ground water in Japan is known to a certain extent, as a result of the investigations of a number of organizations; there are, however, some slight variations in their findings.

Investigations leading to a quantitative assessment of the resources available to meet the demand should be continued in future, as should investigations to find the optimal locations for drilling.

Studies concerning the management of ground-water basins to prevent many of the problems from arising have been initiated, but it will take time before any recommendations can be put into practice.

Selected references

General

Geographical Survey of Japan. 1977. The National Atlas of Japan, 366 p.

International Water Supply Association. 1978. AQUA, Special Kyoto Congress Issue.

Maruzen, 1978, Rikanenpyo.

Geology

Geological Survey of Japan. 1954. A Brief Outline of the Geology of Japan, 7 p.

Takai F., T. Matsumoto and R. Toriyama. 1963. The quaternary. Geology of Japan, University of Tokyo Press, pp. 173-196.

Geological Survey of Japan. 1977. Geology and Mineral Resources of Japan, third edition, 430 p.

Hydrogeological maps published

Geological Survey of Japan. 1964. 1:2,000,000 scale Hydrogeological Map of Japan, second edition.

________________. 1:100,000 scale, 150,000 scale and 125,000 scale Regional Hydrogeological Map, 29 sheets.

Geological Survey of Hokkaido. 1:100,000 scale Hydrogeological Maps of Hokkaido and explanatory text, 9 sheets.

Ministry of Agriculture, Forestry and Fishery. Regional Hydrogeological Map, 8 sheets.

Regional studies

Ministry of International Trade and Industry. Preliminary investigations of "safe yield" in ground-water basins, 48 regions. Industrial Water, Japan Industrial Water Association.

Scientific publications

Journal of the Japanese Association of Groundwater Hydrology.

Bulletin of the Geological Survey of Japan.

KIRIBATI

Area: 173 km^2

Population: 70,000 (United Nations estimate, 1977)

Kiribati comprises a number of atolls situated in the Central Pacific between latitudes 3°20' N and 2° S, and longitudes 172° E and 177° E. The major atolls are Makin, Butaritari, Marakei, Abaiang, Tarawa, Maiana and Abemama north of the equator and Nonouti, Tabiteuea, Beru, Tamana and Arorae south of the equator (see map 21). The administrative centre of the country is located at Bairiki and Betio islands on the Tarawa atoll.

The Kiribati islands are low-lying atolls. Typical coral atolls are formed by a reef of elliptical, angular or irregular shape, encircling a lagoon, and accompanied by some narrow islands. The top of the reef is generally exposed above sea level at low tide only or is permanently submerged. The diameter of atolls ranges between a few kilometres and several tens of kilometres.

Atoll islands extending along the reef are usually from a few hundred metres to two kilometres in width and rise to not more than a few metres above sea level. The following geological section is found in most atoll islands:

(a) The reef platform at the ocean side of the island, which generally emerges during low tide only or is permanently below sea level;

(b) A gravel or boulder rampart, frequently accompanied by a seaward beach, both of which are mainly composed of coral debris;

(c) A central plain and/or a central low ridge, composed of coral sand and coarser debris;

(d) A lagoon beach passing into lagoon flats which are mainly composed of fine-grained material and are usually submerged at high tide or permanently;

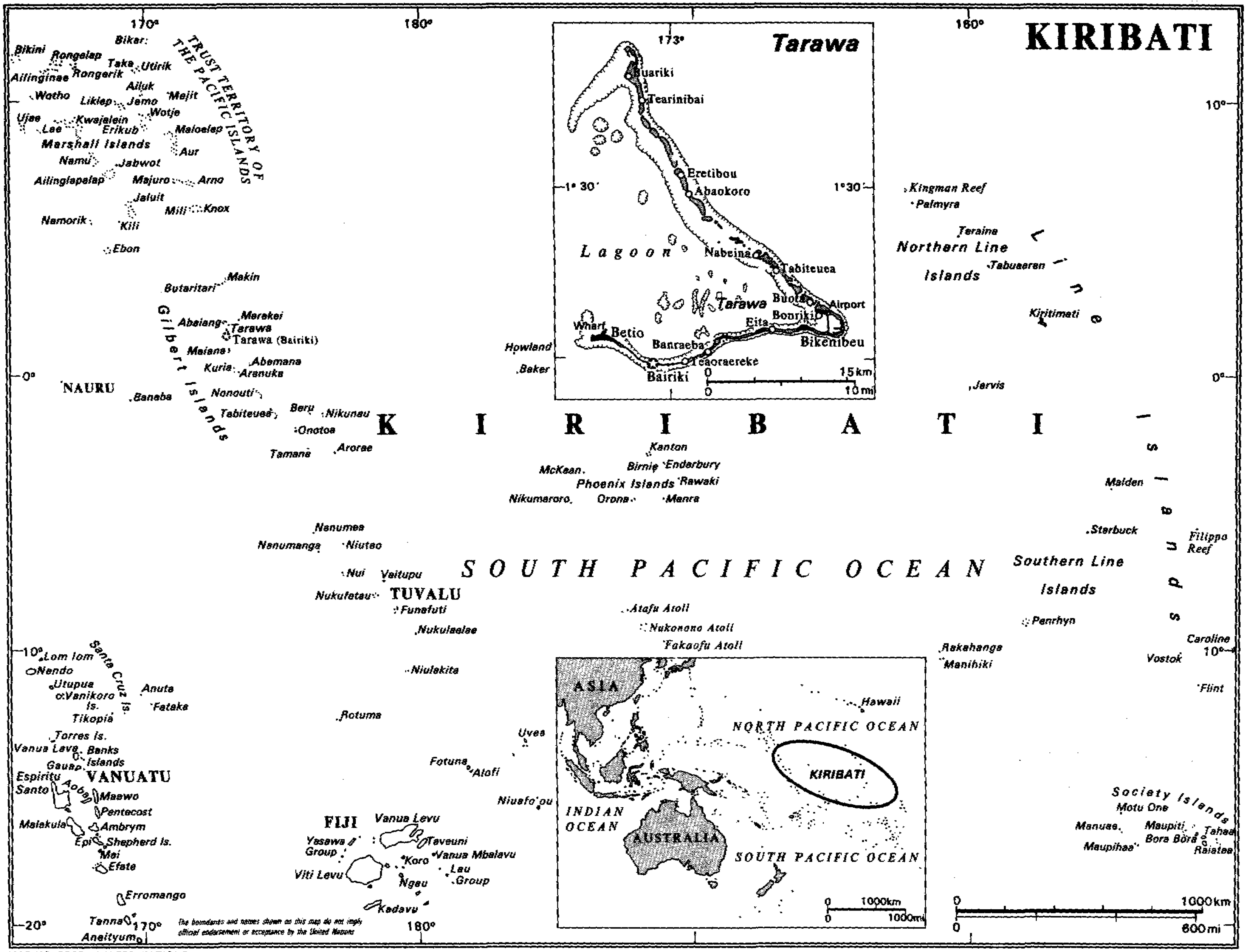
(e) Dunes of wind-blown coral sand occasionally occur on the islands.

The climate of the area is dominated by the dry equatorial zone, which extends as a narrow belt over the central Pacific, and by an intertropical front in the zone of convergence of north-easterly and south-easterly trade winds, which remains fairly constant between latitudes 5° N and 8° N.

The northernmost of the Kiribati islands are situated close to the intertropical front and receive abundant and rather regular rainfall. The more southerly located islands are affected by the relatively low and irregular rainfall of the equatorial dry zone. Annual average rainfall is more than 3,000 mm at Butaritari, and about 1,900 mm at Tarawa. Temperature, ranging generally from 24° to 30° C, and humidity, averaging about 70 per cent, remain rather constant throughout the year and the region.

No surface streams exist on any of the atolls. The surface-water bodies of the lagoons contain saline water. Fresh-water ponds occur on the northernmost atolls, Butaritari and Makin, which receive high precipitation.

MAP 21



MAP NO. 3225 UNITED NATIONS
FEBRUARY 1983

[Map 21. Kiribati]

Ground-water resources

So far, hydrogeological investigations on Kiribati have been restricted to a study of possibilities of ground-water use on the southern islands of the Tarawa atoll, and a very brief survey of the fresh-water resources of Butaritari island. Investigations were carried out mainly through observation of ground-water quality and depth-to-ground water in existing wells, water holes and drilled or excavated shallow observation holes. In some parts of the Tarawa atoll, a geoelectrical resistivity survey was executed.

Fresh ground-water occurrence of significant extent is, in general, limited to larger islands, where lenses of fresh water floating on salt water have developed. Generally, fresh-water lenses occur on those parts of the islands where coral sands form a sufficiently wide central ridge. The thickness of the fresh-water lens below sea level is controlled by the head of fresh water above sea level. According to the Ghyben-Herzberg theory, an elevation of 1 m above sea level corresponds to about 40 m of depth of the lens below sea level. Actual depths of the interface, however, seem to deviate considerably from the theoretical values on many atoll islands. These deviations are considered to be caused by inhomogeneities in the aquifer sediments and disturbance of the equilibrium through the influence of ocean tides.

The exclusive source of recharge of the fresh-water lenses is local rainfall. The rate of infiltration is generally high on the very permeable coral sands and gravels. Part of the infiltrating water will be lost again through evapotranspiration, particularly in areas having coconut plantations thickly covered with vegetation. The recharge through the remaining amount of infiltrating rain water is counterbalanced by a movement of fresh water towards the sea and the lagoon.

The mostly fine-grained sediments at the lagoon side usually have a lower permeability than the aquifers at the sea coast, which are composed mainly of coarse detritus and coral limestones. The quantity of fresh water dispersing into salt water will therefore generally be higher towards the sea. The shape of the fresh-water lens is usually asymetrical on most atoll islands, with the highest evaluation shifted towards the lagoon side.

In coral reef limestones, the permeability is usually very high and ground-water movement rapid along open hollows. Generally, only thin fresh-water lenses can form where coral limestones occur near the water table. Where thicker sand deposits extend on an island, a thicker fresh-water lens is likely to develop.

A fresh-water lens shrinks or expands with fluctuations in rainfall and in withdrawal through extraction from wells or galleries and evapotranspiration. Observations on some of the islands indicate thicknesses of fresh-water lenses ranging between 2 and 40 m.

In general, the exploitable fresh-water resources are very limited on all the atolls of Kiribati. Relatively favourable conditions for exploitation of fresh water may be expected on Butaritari and Makin atolls which are situated in a zone of high rainfall.

Butaritari island appears to be underlain almost entirely by a fresh-water lens. Fresh water is found in shallow wells as close as 15 m from the lagoon and 45 m from the ocean. The relatively wide extent of fresh water may be attributed to a high recharge from frequent rainfall throughout the year, averaging about 3,000 mm annually.

Ground-water development

Both the development of ground water and its use are mainly directed by the Kiribati Development Authority which does not, however, have the means to execute exploration of fresh-water resources or to construct works for ground-water exploitation. In the past, galleries for ground-water extraction were constructed by army engineering units or with the assistance of the Government of Australia. Hydrogeological advice was rendered from time to time by experts of the Institute of Geological Sciences (London) and of the United Nations.

The Department of Health and Welfare provides assistance in support of measures to obtain a water supply, mainly in respect of small island settlements.

Sources of water supply are shallow wells, waterholes, galleries and roof catchments collecting rain water. So far, a centrally organized water supply exists only on the southern islands of the Tarawa atoll.

For the water supply of Tarawa, about 210 m^3/day of ground water are at present pumped from galleries in three different areas. Additionally, rain water from roof catchments is supplied to the system. The present population of southern Tarawa, numbering about 15,000, can be supplied at a rate of 9.6 litres per head per day in dry periods and of 36.6 litres per head per day in periods with sufficient rainfall. In addition, a sea-water sewerage system has been installed in the densely populated island of Betio.

No detailed forecast on projected needs of water has been made. Future requirements will include a permanent and hygienically safe supply of drinking water for municipal and rural areas as well as a water supply for small industrial enterprises. Considerable stress on the limited fresh-water lenses is to be expected with increasing demand for water for domestic and industrial purposes.

The main problems in ground-water exploitation on the low atoll islands are salt-water intrusion into the fresh-water lenses through over-development, in particular during periods of low rainfall, and pollution of fresh water near settlements.

Conclusions

Ground water is the only source of water supply in Kiribati apart from very restricted possibilities of rain-water catchment and costly sources such as sea-water desalinization or importing water. Most of the islands appear to have the potential for an increase in ground-water extraction, but this is definitely limited because of the narrow extent of the fresh-water lenses, limited recharge and the danger of salt-water intrusion. Only Butaritari and Makin atolls appear to have sufficient fresh-water resources to support the development of small-scale industry. The order of magnitude of possible ground-water exploitation, however, will not exceed a few thousand cubic metres a day on any island.

Any development of fresh-water resources, apart from extraction of small quantities from isolated wells, will have to be secured by an observation system monitoring the ground-water quality.

Reference

Wagner, W. Fresh water resources on Christmas and Butaritari Islands and southern Tarawa, Gilbert Islands, South Pacific. Regional Mineral Resources Development Centre of the Economic and Social Commission for Asia and the Pacific, Advisory Services Report HG/11. Bangkok, 1977.

NAURU

Area: 22 km^2

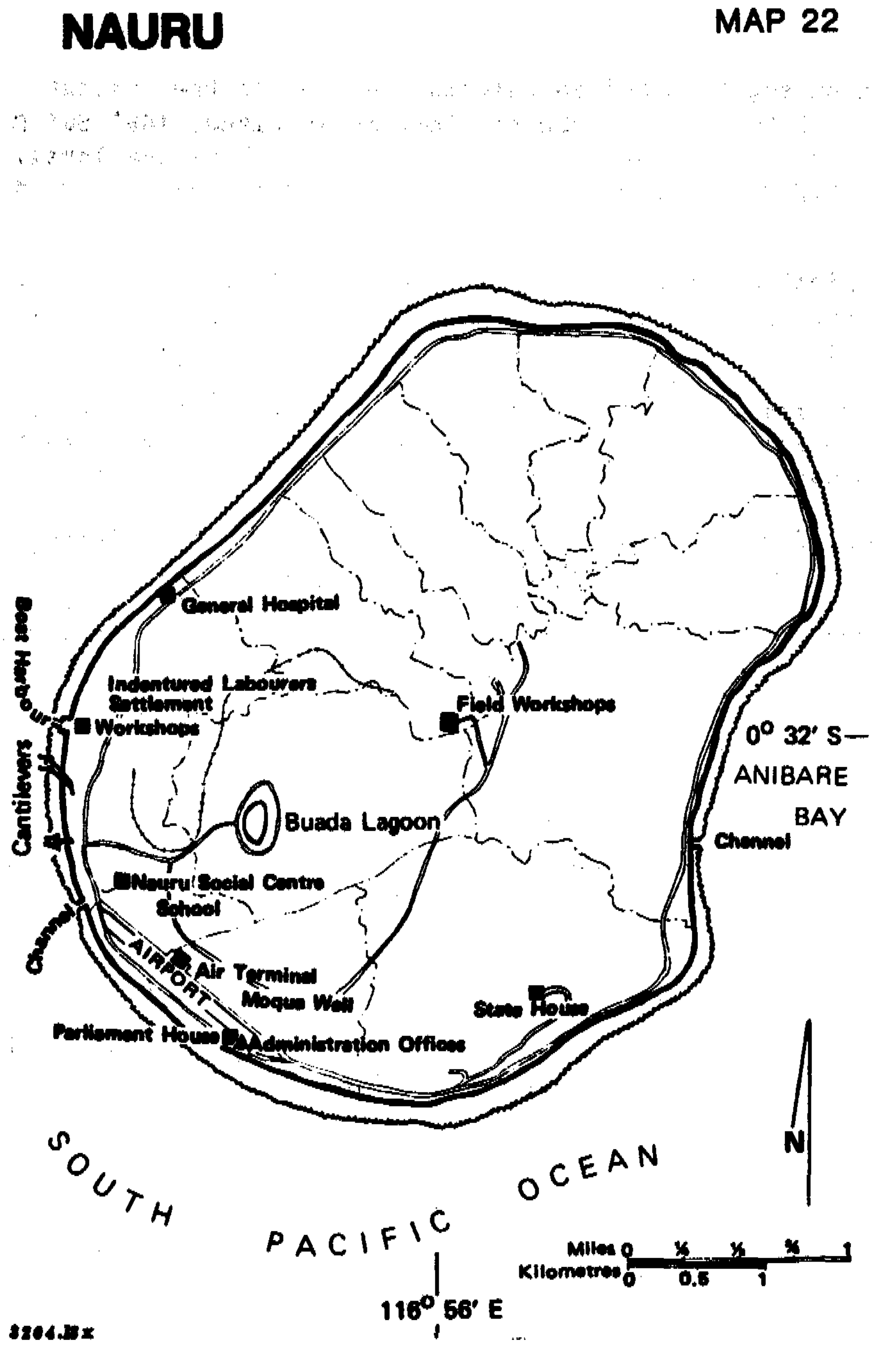
Population: 8,000 (United Nations estimate, 1977)

Nauru, an independent republic and an associate member of the British Commonwealth, is located 41 km south of the equator, at longitude 166° 56' E (see map 22). Coral cliffs rise to a coastal plateau about 60 m above sea level. The plateau is composed largely of phosphate-bearing rock. The highest point is 70 m above sea level.

The climate is tropical and tempered by sea breezes. Rainfall is about 500 mm per year, with broad interannual variations (300-4,500 mm). Most of the rain occurs from November to February. There are no rivers.

The wealth of Nauru lies in the phosphate industry. The country enjoys the highest per capita income in the world. It is estimated that, at the present rate of extraction, the phosphate deposits will have been exhausted by 1993-1995.

The water supply originates mainly from roof catchments. In prolonged droughts water is brought to Nauru by ship and pumped ashore into storage tanks. From there it is delivered by truck to households. There are some shallow wells in areas that were populated prior to the start of the phosphate mining industry, and where palm trees, pandanus fruit trees and vegetables are grown.


NAURU
MAP 22
General Hospital
Boat Harbour
Indentured Labourers Settlement
Workshops
Field Workshops
Cantilevers
Buada Lagoon
0° 32' S
ANIBARE BAY
Channel
Nauru Social Centre
School
Channel
AIRPORT
Air Terminal
Moqua Well
State House
Parliament House
Administration Offices
SOUTH PACIFIC OCEAN
N
Miles 0 ¼ ½ ¾ 1
Kilometres 0 0.5 1
116° 56' E

NEW CALEDONIA

(French Overseas Territory)

Area: 19,058 km^2

Population: 136,000 (estimate, 1977)

General

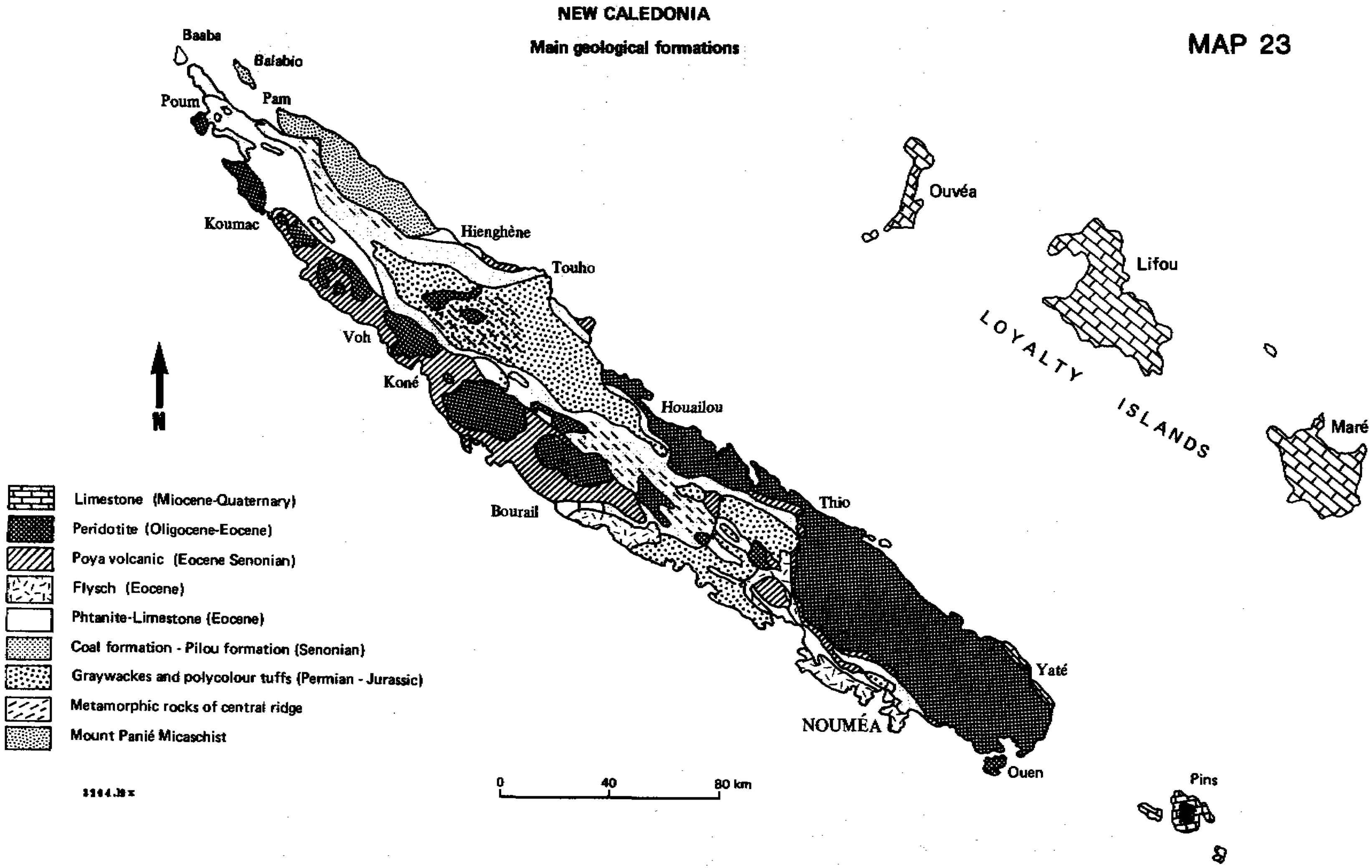
The New Caledonia archipelago comprises a large island named New Caledonia or "Grande Terre", which is about 450 km long and 50 km wide, and a number of coral reefs and islands, including Belep and Huon islands to the north and Ile des Pins (160 km^2) to the south, which are spread over a distance of about 1,000 km^2. To the east are the Loyalty Islands (Ouvea, Lifou and Mare) which have a land surface of about 2,000 km^2 (see map 23).

New Caledonia is a narrow mountainous island with a soil elevation of 600-1,000 m. A high central ridge, deeply incised by the hydrographical network, covers most of the island. To the west the coastal area consists of gently rolling plains separated by low ridges. To the east the coastline is mostly rocky and steep and is cut by several rivers with narrow alluvial plains and broad estuaries.

The climate is subtropical or tropical, with variations related to soil elevation and exposure to prevailing winds. Winds are humid on the west coast which receives a yearly rainfall of 1,800-4,000 mm. The east coast is relatively dry with less than 1,200 mm of rainfall. The rainy season occurs from December to March. The period April-May is known as "little dry season", when the air is cooler and dryer. The period June-August is known as the the "cool season", when rainfall is moderate. The dry season, with higher temperatures, extends from September to November. This pattern, however, may vary widely from year to year. Daily rainfall may reach up to 500 mm.

The average temperature is approximately 23° C (20° C in August and 26° C in March); it may be as low as 5° C on the central ridge.

Surface water is abundant and many streams are permanent, although the flow may be reduced to a trickle during dry periods. The upper courses of the rivers run over steep slopes; the lower courses pass through subhorizontal coastal plains. Flash floods are common, with flows which may exceed 1,000 m^3/sec, the average being 100-250 m^3/sec. The run-off coefficient currently exceeds 75 per cent and may be as high as 90 per cent. The infiltration coefficient is 10 per cent to 25 per cent. As a result ground water resources are modest.

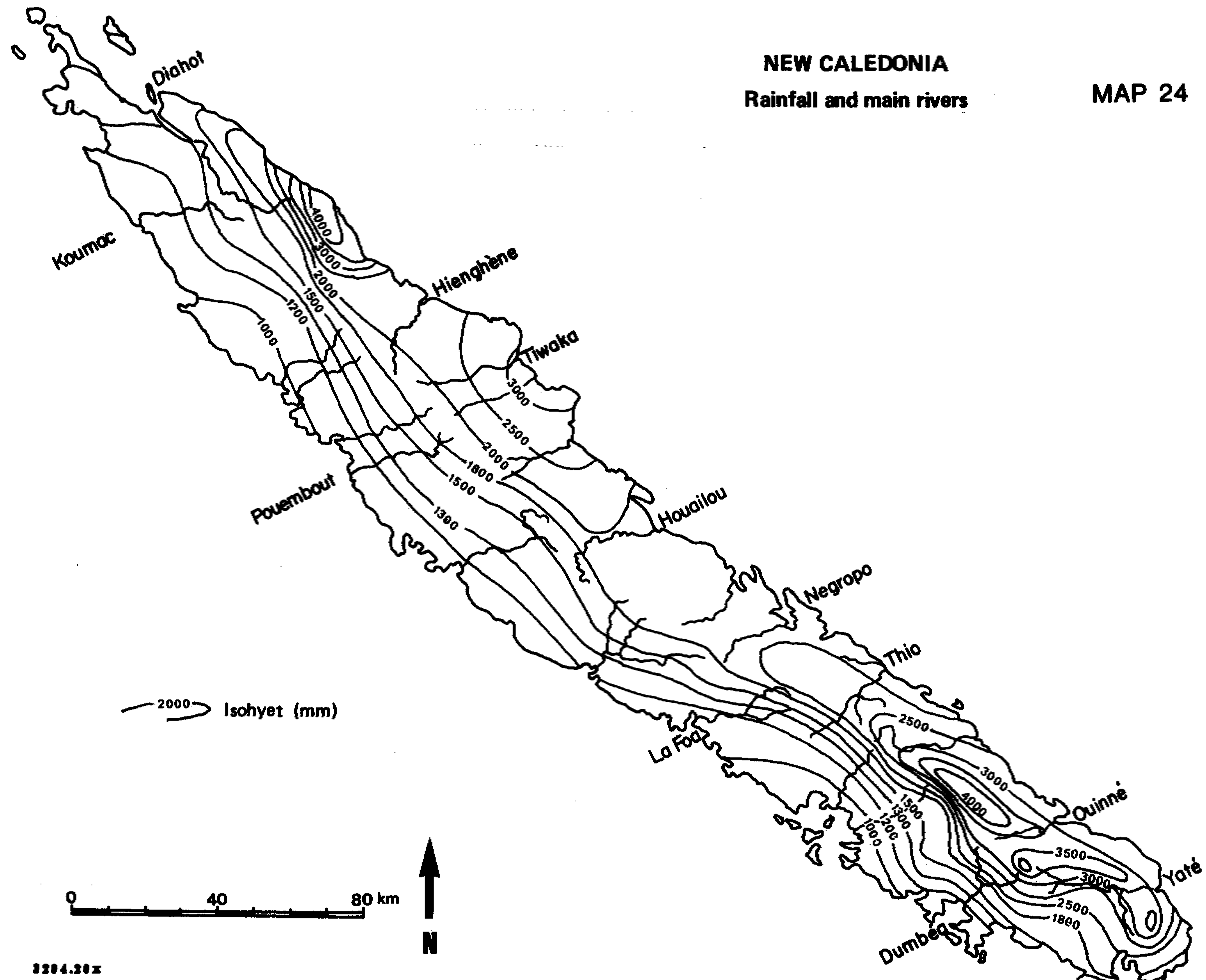


Map 23. New Caledonia: main geological formations

There are about 30 permanent rivers on the west coast. The flows of some of the more important ones, measures in 1957, are shown below. Corresponding measurements with respect to the Diahot river on the north coast and the Ouaième and Tchamba rivers on the east coast are also shown.

River	Lowest waters (m^3/sec)	Unit flow (l/sec/km^2)
West coast		
Ouenghi	0.600	2.50
Tontouta	1.370	3.60
Fonwhary	0.018	0.32
Boghen	0.120	0.89
Poya	0.178	0.87
Ouna Muéo	0.119	1.50
Rouembout	0.100	0.50
Rivière Rouge (Confiance or Pandanus)	0.014	1.00
Faténaoué	0.023	0.20
Louanga	0.015	0.07
Karembé (Oué Bouameu)	0.010	1.00
North coast		
Diahot	0.380	1.30
East coast		
Ouaième	0.930	3.0
Tchamba	0.200	2.7

Main isohyetal contours and main river streams are shown in map 24. Some small natural lakes occur in a depressed area to the south, known as Plaine des Lacs. Topographical features do not favour the siting of dams, owing to the steep profiles and the low storage potential. The only dam of sizeable dimension was completed in 1959 at Yate. The area covered by the artificial lake is 40 km^2 and the storage capacity is 313 million m^3; the waters are utilized mainly to generate hydropower (350 million kWh/year) for the needs of the city of Noumea and for the nickel industry. A smaller dam (at Dumbea) supplies Noumea with potable water. A third dam has been built on the Ouaième river. Small hill lakes have been built in recent years.



Map 24. New Caledonia: rainfall and main rivers

The population is multiracial. The main groups are Melanesians (46 per cent) and Europeans (40 per cent), with some Polynesians and Indonesians. Fifty per cent of the population lives in and around the capital city, Noumea. Mining and processing of nickel are the main resources of the Territory.

Geology

New Caleonia is formed of folded sedimentary and volcanic rocks overlying a metamorphic nucleus, probably hercynian, which crops out in the central area. The main formations are as follows (see also map 23 and fig. III):

(a) Polycolour volcanic tuff (Permian), found over a small area (25 km^2) on the west coast;

(b) Greywackes (Trias), found in the central and the southern parts of the west coast and some areas of the east coast (370 km^2); these are a type of sandstone rock containing abundant volcanic material;

(c) Pilou and Tondo coal formations (Upper Cretaceous), which crop out in the south-western part of the island (500 km^2); they include pelite and clayey sandstone, with coal inclusions and conglomerates, rhyolites and tuffs;

(d) Phtanite and limestone formation (Lower Eocene) occurring in the north-west (700 km^2) and the central ridge; it includes a variety of rocks, mainly siliceous;

(e) Flysch (Middle and Upper Eocene) in the southern part of the west coast area (Noumea and Bourail areas) and in regions east of Koumac (valley of Birachio River); the flysch is made mainly of sandstone associated with breccia;

(f) Poya volcanics (Senonian-Eocene), which extend widely in the west coast area especially between Bourail and Koumac; they are also found, but only to a limited extent, in the central ridge, the east coast and the northernmost area;

(g) Ultrabasic rocks (Eocene-Oligocene), which constitute the mining basins; the main one is in the southern part of the island; and others occur on the east coast and the west coast;

(h) Alluvium; ancient alluvia are constituted of rather thin clayey layers; modern alluvia are limited to river beds and are diversely clayey or sandy depending on the river course or the layer which is considered; in the lower part of the rivers they may be quite thick;

(i) Weathered formations; leterites are found on top of ultrabasic rocks; they may be several metres or several tenths of a metre thick.

The most productive aquifers are:

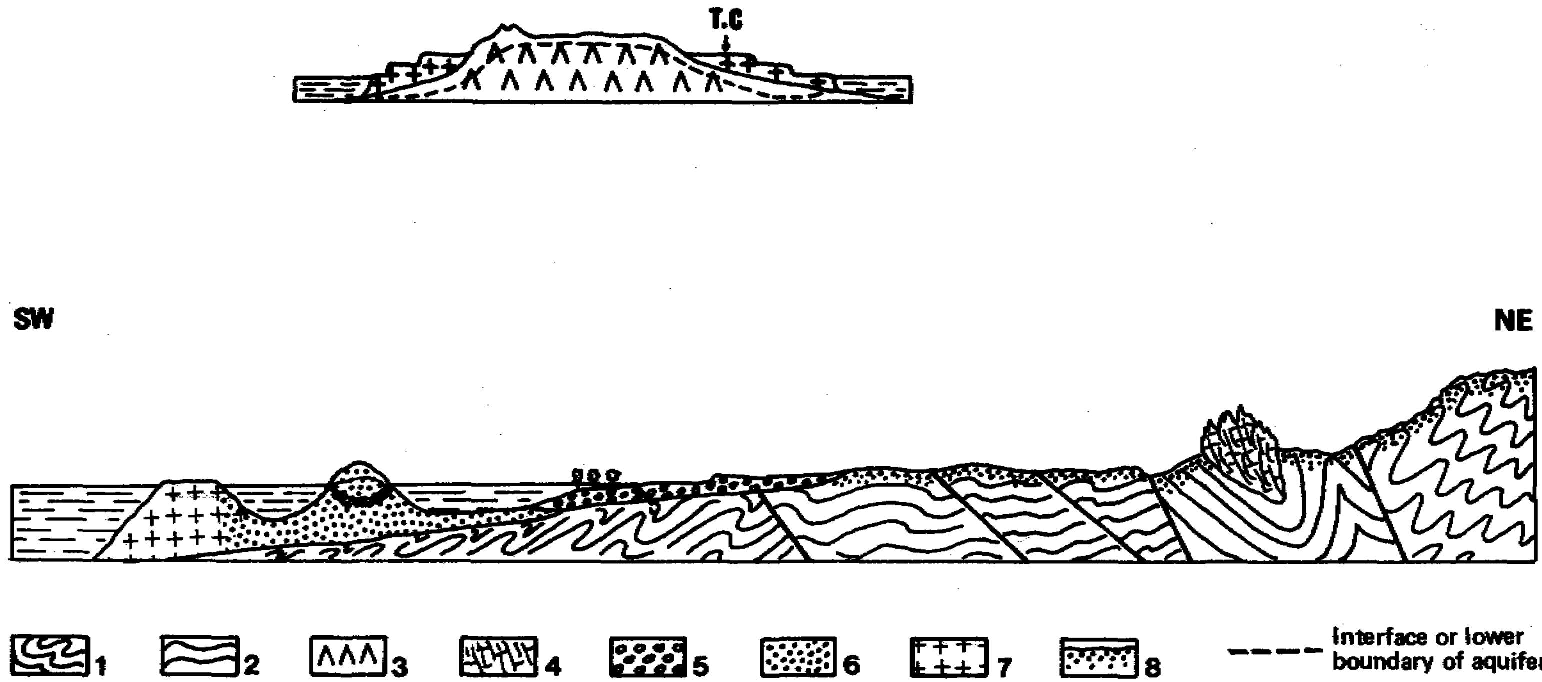
(a) Poya volcanics (1,200 km^2) covered with ancient alluvium over 320 km^2;

(b) Greywackes and polycolour tuff (500 km^2) in plains, covered with ancient alluvium over 100 km^2.

NEW CALEDONIA

Geological cross-sections

Figure III



1. Metamorphic formations of central ridge
2. Sedimentary and volcano-sedimentary formations
3. Peridotite
4. Lenses of karstified limestone
5. Alluvium
6. Coral sand
7. Coralline limestone
8. Weathered zone

3204.31x

Figure III. New Caledonia: geological cross-sections

Flysch formation (500 km^2), phtanite-limestone formation, coal and Pilou formations and metamorphics are poor aquifers.

Ancient alluvium is sterile. Recent alluvium (500 km^2) may contain interesting ground-water reserves.

Hydrogeology

New Caledonia is periodically subjected to severe droughts which may be catastrophical to rural areas. West coast and northern areas, being regions of lower rainfall, are particularly vulnerable. Systematic ground-water studies were therefore carried out between 1962 and 1967, especially in the west and north, in the form of a comprehensive inventory of water resources, which included the preparation of a preliminary hydrogeological map of the west coast on a scale of 1:50,000 (16 sheets). In 1965, a hydrogeological section was created within the Rural Works Service. The section is responsible for undertaking local studies for the siting and supervision of wells in rural areas.

Most of the rocks which constitute the backbone of the island - with the exception of rare and small occurences of karstic limestones - are compact and in the main practically impervious when unweathered. As a result, New Caledonia is a country of scattered small-scale aquifers related to modern alluvium and weathered rocks, compartmented according to surface drainage patterns. Hydrogeological characteristics of the main aquifers are shown in table 28.

Aquifers related to weathered zones

Polycolour tuffs. Thick weathering may result in porous sandy formations.

Greywackes. Weathered zones may include coarse sand grains and also compact clays.

Coal formation. Weathered zone products have little or no permeability.

Phtanites. Practically impervious; no wells have been dug.

Flysch. Weathering occurring on sandstone horizons has resulted in an opening of pores and broadening of fissures; water resources in such formations, however, are seasonal, limited to humid periods.

Limestone. Eocene compact limestone occurs as lenses, a few hundred or thousand metres in diameter; many cavities can be observed. Miocene limestone is found in the Nefoui area; its upper part is karstified down to a shallow depth.

Paleocene basalts are weathered down as deeply as 35 m. The upper part of the weathered zone is made of impervious black clays (1-10 m thick). The lower part is an aquifer, subartesian in some cases. The best aquifers are related to maximal thickness and minimal sloping. They may yield several tens of cubic metres an hour.

Table 28. New Caledonia: hydrogeological characteristics of main aquifers

Aquifer	Depth of upper boundary (m)	Thickness (m)	Location	Specific capacity (m^3/hour/m)	Hydrogeological parameters		
					Hydraulic conductivity (m/day)	Trans-missivity (m^2/day)	Coefficient of storage
Polycolour tuffs	4-20	5-20 (average 10)	...	nearly 2	10	100	0.5-5
Greywackes	4-20	5-20 (average 10)	...	0.5-3	1-10	10-100	0.5-5
Phtanites, pelites, coal formation	...	2-20	Nouméa, Païta, Tontouta	1-3	< 1	...	Very low
Flysch (Eocene)	2-10	20 (average 15)	Tontouta, Bouloupari, Bourail	0.5-7	7	170	2
Weathered basalt (Paleogene)	3-10	5-15 (average 8)	Poya, Koumac	1-5	10-100	100-1 000	1
Recent alluvium in lower river valleys	0-10	15-30	...				
Pebble and gravel				300	1 000	...	5-20
Sand				2-3	100	...	...
Sand and loam				1	10	...	1-5
Loam				...	< 1	...	...

Ultrabasic rocks play an essential role in the hydrogeology of the island owing to their regulating effect especially wherever they are eroded and covered with thick weathered formations (ferralites). The aquifer complex is represented in figure IV. Rain water falling on the upper highlands infiltrates first through lateritic hardened surfaces (see fig. IV, I). It then accumulates and flows through the underlying granular laterite, which is relatively more permeable. Due to the drainage of laterite substance, the surface of the soil is broken into "false dolines" which facilitate the infiltration of surface water. In periods of heavy rains, this aquifer discharges through temporary springs (see fig. IV, S1). Water infiltrating further reaches red laterite (see fig. IV, III) and yellow laterite (see fig. IV, IV), which are porous and permeable owing to the absence of clay minerals. However, permeability coefficient and well yields are limited owing to the fine-grained nature of the elements. Water percolates further into the saprolitic lithomargin (see fig. IV, V), which is related to the weathered and pervious peridotites. This horizon is the most likely exploitable aquifer; it yields springs (see fig. IV, S2). Ground water may be drained through channels (see fig. IV, CH) related to fractures or lithological heterogeneities. A fractured aquifer which may be clogged to a variable extent is developed within the unweathered rock. A level of springs (see fig. IV, S3) occurs as the outlet of important underflows or saturated areas. The springs may emerge as sizeable water flows. The whole hydrological system may be described as "pseudokarstic". The contact level between peridotites and serpentinites gives way to a lower level of springs (see fig. IV, S5), which are at times hidden by masses of fallen rocks. The main water courses, creeks, which issue from the peridotite massifs, originate from these springs.

Peridotite water is basically bicarbonated magnesium, with a high silica content. Water-quality data with respect to peridotite massifs is given in table 29. In the past the abundant waters were largely utilized by the Melanesian population for irrigation purposes. They are now tapped for the water supply of communities and cattle farms.

Aquifers related to alluvium

Ancient alluvium is mostly clayey and impermeable. It acts as a confining layer for underlying weathered zone aquifers. Scattered recent alluvium areas are good aquifers especially where they are thick as a result of recent subsidence movements (55 m in Tontouta delta).

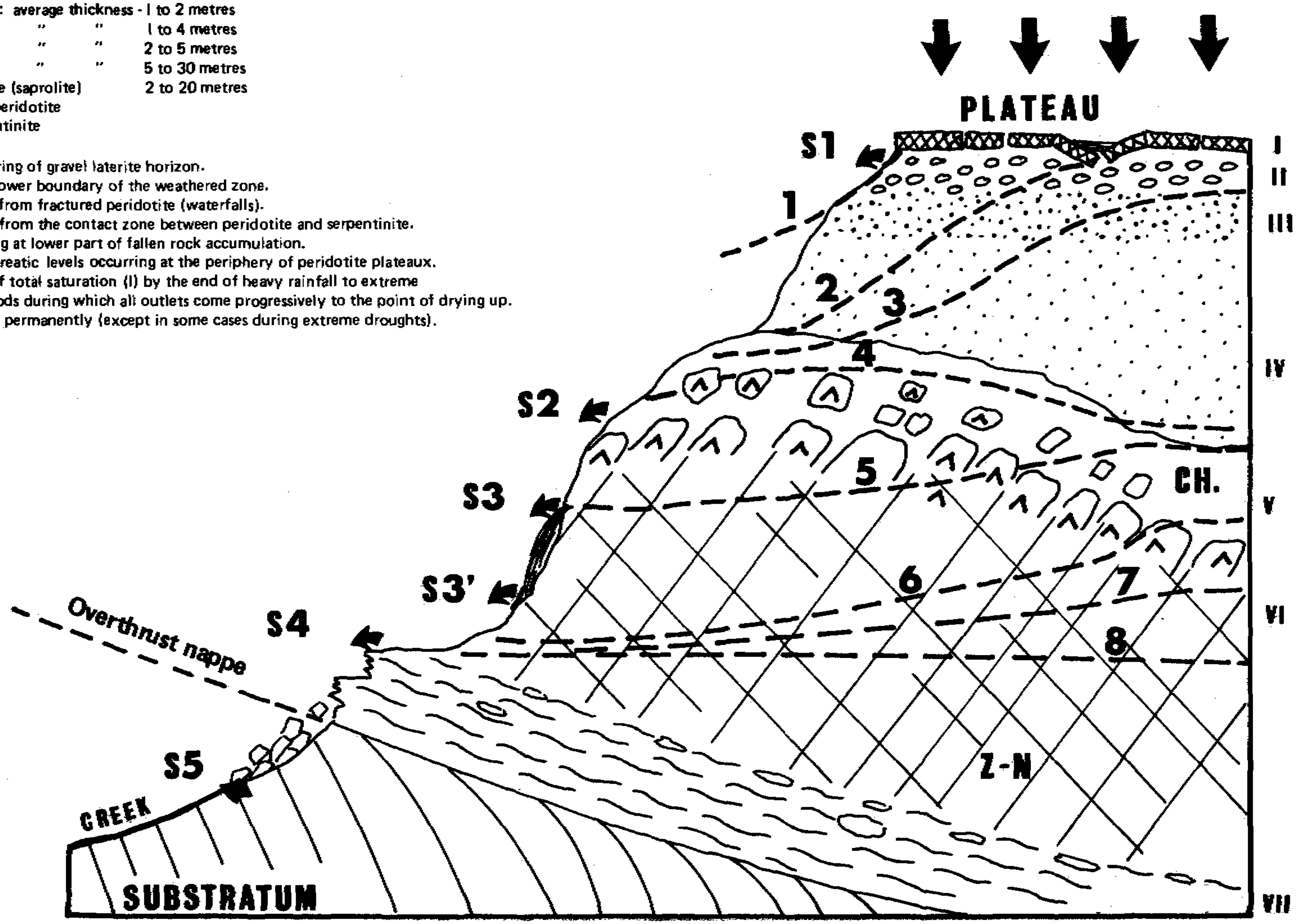
These alluvia are quite heterogeneous, mostly constituted of loamy sands, with coarse elements contained in buried channels and lenses. Yields reaching several hundreds of cubic metres an hour have been extracted from wells drilled in these formations.

NEW CALEDONIA
Hydrogeology of peridotite massifs

Figure IV

I. Lateritic crust : average thickness - 1 to 2 metres
II. Lateritic gravel " " 1 to 4 metres
III. Red laterite " " 2 to 5 metres
IV. Yellow laterite " " 5 to 30 metres
V. Weathered zone (saprolite) 2 to 20 metres
VI. Unweathered peridotite
VII. Foliated serpentinite

S_1 Temporary spring of gravel laterite horizon.
S_2 Spring at the lower boundary of the weathered zone.
S_3 S_3' Spring issuing from fractured peridotite (waterfalls).
S_4 Spring issuing from the contact zone between peridotite and serpentinite.
S_5 Same appearing at lower part of fallen rock accumulation.
1 - 8 Theoretical phreatic levels occurring at the periphery of peridotite plateaux. From stage of total saturation (I) by the end of heavy rainfall to extreme drought periods during which all outlets come progressively to the point of drying up.
Z - N Area saturated permanently (except in some cases during extreme droughts).



3204.22x

Figure IV. New Caledonia: hydrogeology of peridotite massifs

Table 29. New Caledonia: water-quality data with respect to peridotite massifs

(Parts per million)

	pH	Electrical conductivity (mho/cm)	HCO_3^-	Cl^-	SO_4^{--}	CaO	Na_2O	K_2O	MgO	SiO_2
Laterite (crust-gravel)	< 7	< 50	< 40	7	< 2	0.5	> 4	< 0.3	< 2	< 4
Weathered zone	> 7	> 83	< 50	> 6	> 3	0.3-2	> 4	< 0.3	12-15	> 10
Lower level aquifers (Plaine des Lacs)	> 7.3	< 67	< 20	> 10	< 3	0.2	> 7	0.2	15	> 12
Streams issuing from massifs (Dumbea basin)	7.7	< 110	65	6	3	1.3	4	2	20	13

Water quality

In New Caledonia ground waters are mainly of the bicarbonated magnesium calcic type, with a high silica content. The pH is in the range of 7 to 8. Except for areas close to the seashores, where the chloride content may exceed 1,000 ppm, all waters are fit for human consumption according to standards set by the World Health Organization. Alluvium water is mostly non-aggressive and very sweet, with an optimal balance of calcium and magnesium. Table 30 provides data on the quality of the water of the main aquifers.

Table 30. New Caledonia: average water-quality data with respect to main aquifers

(Parts per million)

Aquifer	Ca	Mg	Cl	SO_4	SiO_2	Total dissolved solids
Tuffs and greywackes	47	49	38	33	38	500
Flysch (Eocene)	62	50	55	19	48	480
Basalts	28	60	30	12	58	415
Alluvium	43	73	22	20	27	400

Ground-water development

As mentioned above, a hydrogeological section, with a hydrogeological engineer and a technician has been established within the Service du Génie Rural. Water-well drilling operations are carried out under contract by two firms which handle some 10 rigs. Additional equipment from mining companies is available for drilling in hard rock formations.

Most of the community water supply installations draw from springs and surface-water streams. The water supply of isolated farms or stations is mostly obtained from low-yield wells (about 1 m^3/day) and small springs and streams. Surface water is utilized in irrigation schemes. Ground water is developed mainly for cattle needs, about 1,000 tube wells and dug wells being utilized for that purpose. With the better knowledge of ground-water conditions acquired since 1962, a more adequate siting of wells has been achieved which has led to improved yields.

Needs and problems

Traditionally, local populations have used surface water exclusively for all their needs. Such waters, however, are heavily polluted and are not widely available during periods of drought. Additional ground water would therefore be helpful.

In coastal areas the salt-water wedge has a tendency to move deeply inland when coastal aquifers are not replenished by rainfall or run-off infiltration, so that wells are contaminated by salt-water intrusion. It has therefore been recommended that wells should be located some distance from the coast and that pumpings should be limited so as to "skim" the thin fresh-water resource which is floating on top of the saline ground-water bodies.

Thermomineral waters

A small spa has been developed close to Crouen river, 13 km south of Canala. The average yield is 2.5 l/sec; temperatures are in the range of 43° C, and pH is 9. The outlets of the springs are related to a fault oriented 10° N in Permojurassic greywacke and shales. Waters are of the sulphide type. Other springs of the same type but smaller are found on the east coast (Mokoué spring, 3 km east of Makety Creek, Ahvia spring and Fanama springs); on the west coast, the Prony group is worthy of mention with temperatures from 32° to 42° C. Some water-quality data are presented below.

Prony		Crouen	
Ca	22 ppm	$CaSO_4$	1.2 ppm
Mg	Traces	$CaCO_3$	7.9 ppm
Na	12 ppm	$MgCO_3$	3.3 ppm
K	3 ppm	NaCl	50 ppm
Cl	10 ppm	SiO_2	75 ppm
SO^4	Traces	$Al_2 O_3$	5.7 ppm
SiO_2	3 ppm	Fe, Li	Traces

Hydrogeology of the Loyalty Islands

The archipelago of the Loyalty Islands is located 500 km to the north-east of New Caledonia. Its land area is about 2,000 km^2, most of which (1,960 km^2) is occupied by three islands: Lifou (1,150 km^2); Maré (650 km^2); and Ouvea (160 km^2). These islands are mainly coral limestone from Neogene to Quaternary. The land rises gradually from north-west to south-east (approximately 4 m in Beautemps-Beaupré Islands, 30 m in Ouvea, 55 m in Lifou, 70 m in Maré, and 75 m in Walpole). All islands are raised atolls with a central plateau which is a former lagoon, bordered by a low ridge rising from 10 to 40 m (a former barrier reef); the filling of the ancient lagoon includes sand, lenses, muds and coral formation. The former barrier reef is made of compact limestone, including coral and foraminifers and coral sands which may accumulate in the form of dunes, 5 m high. These sands may aggregate in the form of sandstone beach slates 1-3 m thick.

Beach sand and sandstone, thin grained and homogeneous, are porous aquifers, while ancient reef limestones are fractured karstic aquifers.

Taking into account the relatively high rainfall (1,500 mm/year), the lack of drainage systems over the predominately flat topography, the high permeability and porosity of the formations, a sizeable and relatively stable fresh water lens has developed at some distance from the coastline.

Traditionally, the inhabitants would draw their water supply from "microcisterns" made of hollowed out coconut tree trunks or from deep natural holes in reef limestone, where the fresh-water lens is exposed. Such holes are frequently encountered in the coastal limestone ridges. They occur also inland up to 10 km from the shore line, as a result of the collapse of karstic structures. They are cone-shaped, broadening downwards. Their diameter close to the soil surface is between 10 and 100 m. The first European settlers dug wells 18 to 40 m deep, especially in Lifou. The wells penetrate the fresh-water lens to a depth not exceeding 1 m. In Maré, wells are fewer in number and may exceed 45 m in depth. In Ouvea, wells are almost exclusively located in coastal sands with depths not exceeding 6 m. Missionaries have constructed stone cisterns and corrugated iron is utilized to collect rainfall. Hydrogeological studies carried out in 1956-1957 permitted the shape and dimensions of the fresh-water lenses in the three main islands to be determined:

Lifou. Convexity of the lens: 4-5 m above sea level in the central part; slopes to the shores 0.8 to 0.4 per thousand; total thickness 160 m;

Maré. Less data are available. The lens is the same shape as that in Lifou, but is more homogeneous in terms of water quality, owing to better replenishment from meteoric waters and less fractured limestone;

Ouvea. This low fractured island has a heterogeneous lens deeply contaminated by sea water, especially in the northern part.

Hydrogeological investigations have confirmed that fresh water is available in abundance in all three islands, not only to meet domestic needs but also for irrigation. Data on ground-water quality are given in table 31.

After a second hydrogeological mission which took place in 1965, a vast programme of water-well drilling for investigation and development purposes was undertaken and has been developed since then.

Table 31. New Caledonia, Loyalty Islands: ground-water quality

Location	Distance from seashore (m)	Depth to ground water (m)	Salinity (grams of sea water per litre)
Lifou	300	18	2.32
	700	19.45	1.15
	1 200	32.20	0.14
	2 800	23.30	0.08
	4 300	22.60	0.07
	6 500	39.50	0.04
Maré	400	12	0.90
	800	30	0.26
	1 200	31	0.16
	3 500	46	0.08
Ouvéa (north)	120	0.50	6.29
	160	2.95	5.26
	3 500	4	7.60
	3 650	4	0.83
	4 000	9	10.76
Ouvéa (south)	200	4.30	2.81
	450	0.50	0.17
	900	1.10	0.48
	1 500	2.65	1.08
	3 000	4	0.88
	4 800	20	2.57

Conclusions

Hydrogeological studies so far have been limited to the west coast of New Caledonia and to the Loyalty Islands. Elsewhere, water needs are modest and can be satisfied by tapping surface-water sources. Morphological and geological conditions are not favourable to the occurrence of large capacity aquifers. The best conditions are found in the alterites of ultrabasic massifs and in coralline islands.

Selected references

Avias, J. 1949. Hydrogéologie des sources thermales de la Negropo-La Crouen, station thermale. Num. spéc. Bull. Ass. Médicale, Nouvell-Calédonie, Nouméa, pp. 43-59, 6 fig., 1 carte.

_______. 1952. Contribution à l'étude stratigraphique et paléontologique des formations antécrétacées de la Nouvelle-Calédonie Centrale. Sciences de la Terre. Tome I, numéros 1 et 2, 276 p., 117 fig., 16 tab., 26 pl., Nancy.

_______. 1956. Sur le recul récent de la nappe d'eau douce de la Côte Ouest en Nouvelle-Calédonie. XIXe Congr. Géol. Intern. sect. III, pp. 393-401, 2 fig.

_______. 1968. Note sur les facteurs contrôlant la genèse et la destruction des gîtes de nickel de la Nouvell-Calédonie. Importance des facteurs hydrologiques et hydrogéologiques. C.R. Acad. Sc. Fr., 268, p. 244-246, Paris.

_______. 1971. Major features of the New Guinea, Louisiade, New Caledonia, Norfolk Arc system. Proceedings of the Pan Pacific Science Congress 1971, pp. 113-126, 4 fig. The University of Western Australia Press.

Chevalier, J. P. 1968. Géomorphologie de l'île Maré. Les récifs de l'île Maré. Expédition Française sur les récifs de la Nouvelle-Calédonie. Edit. Fondation Singer-Polignac, Paris, vol. III, 158 p.

Coudray, J. 1965-1966. Rapports inédits du Service du Génie Rural de la Nouvelle-Calédonie.

_______. 1976. Recherches sur le Néogène et le Quaternaire marins de la Nouvelle-Calédonie. Contribution de l'étude sédimentologique à la connaissance de l'histoire géologique post-éocène. Expédition Française sur les récifs coralliens de la Nouvelle-Calédonie. Edit. Fondation Singer-Polignac, Paris, vol. VIII, 275 p.

Espirat, J. J. 1967. Etude hydrogéologique de la côte Ouest de la Nouvelle-Calédonie. Rapport d'ensemble sur les travaux effectués par le Bureau de Recherches Géologiques et Minières de 1962 à 1967. 178 p. Carte hydrogéologique au 1/50,000 en 16 feuilles H.T.

Koch, P. 1958. Hydrogéologie des Iles Loyauté. Bull. Géol. de la Nouvelle-Calédonie, n° 1, pp. 135-188.

_______. 1958. Sources thermales de Nouvelle-Calédonie et captage des sources de La Crouen. Ibid., pp. 189-203.

Routhier, P. 1953. Etude géologique du versant occidental de la Nouvelle-Calédonie entre le Col de Boghen et la Pointe d'Arama. Mém. Soc. Géol. de France, Paris, t. 32, n° 67, fasc. 1-3, 271 p.

NEW ZEALAND

Area: 268,676 km^2

Population: 3,130,000

Conditions of ground-water occurrence

Geography and physiography

The combined length of the North and South Islands of New Zealand is more than 1,600 km and the maximum width is less than 450 km. The coastline is consequently very long in relation to the area of the country.

Less than one quarter of the land surface lies below the 200 m contour, and the mountain chains parallel the main south-west to north-east land mass of the country. In the North Island the four highest peaks are volcanic in origin: Egmont, 2,518 m; Ruapehu, 2,729 m; Ngaurohoe, 2,290 m; and Tongariro, 1,968 m. Of these, only Egmont can be classed as dormant; the others have been active during the past 100 years; two others, Mount Tarawera and White Island, have erupted within historical times, with loss of human life. In the Taupo region, major eruptions of pumice and ash occurred during the past 2,000 years, but did not produce high altitude volcanic cones. The main axial mountain chain of the North Island includes (from the north) the Raukumara, Huiarau, Rushine, Tararua and Rimutaka Ranges. The Ahimanawa, Kaweka, Kaimanawa, Hauhangaroa, Rangitoto and Moehau Ranges are further west. The South Island has the Southern Alps along most of its length, with 19 peaks exceeding 3,000 m. The other ranges include the Kaikoura, Seaward Kaikoura, Spenser, Richmond, St. Arnaud, Victoria, Brunner, Lyell, Tasman and Paparoa Ranges. In all, the South Island has more than 220 named peaks exceeding 2,300 m in altitude. The Southern Alps support an appreciable glacial system which includes the Tasman, Murchison, Mueller, Godley and Hooker Glaciers east of the main divide and the Fox and Franz Josef Glaciers west of the divide.

The physiography of New Zealand was established by comparatively recent earth movements of the Kaikoura Orogeny that extended through the Pliocene and Pleistocene and continue to the present day. Earth movement has created a tectonically youthful land composed of uplifted, tilted fault blocks forming mountains that are typically rugged and craggy and composed dominantly of greywacke. Rapid erosion and transport of the highly indurated greywacke from these blocks by steeply graded spate-prone rivers during the cyclical Quaternary climate has formed large plains, coastal and intermontane, built essentially of durable greywacke gravels. From the point of view of ground water, these plains are important for two reasons: first, because in many places they are underlain by prolific aquifers and, secondly, because they are flat-lying and can therefore be cultivated and (given sufficient water) irrigated without difficulty. Their relative importance is dictated partly by the fertility of their soils and partly by the availability of surface water and ground water. The most agriculturally important areas in the South Island are the Canterbury, Waimea, Wairau and Southland Plains and the alluvial valleys of Westland; of these, the Canterbury, Waimea and Wairau Plains are irrigated to an appreciable extent by ground water. All are covered by essentially glacial (loessic) and post-glacial (fluvial) soils.

In the North Island the most important agricultural plains are the Gisborne, Heretaunga, Manawatu, Wairarapa, Waikato and Whakatane Plains, of which the Heretaunga Plains are the most dependent upon ground-water abstraction. All are covered by essentially volcanic and fluvial soils.

Climate

The New Zealand climate is characterized by its isolation in the mid-latitude westerly zone, so that winds arrive moisture laden and air temperatures are moderated by oceanic influences. The dominant winds are westerlies, associated with a cycle of anticyclones and depressions. The main ranges, aligned north-east to south-west provide a barrier to the prevailing westerlies; as the maritime air from the Tasman Sea rises to cross this barrier it often cools enough to produce clouds and rain to the west of the main divide. Rainfall on the western slopes is therefore high, exceeding 7,000 mm in places, while rainfall east of the ranges is in places below 350 mm. The average for the whole country is about 2,000 mm; for a large area, mostly in eastern regions, it is between 600 and 1,600 mm. Agriculture, particularly on the eastern plain regions, benefits from supplementary moisture during the main growing season.

The mean annual temperature exceeds 15° C in the northernmost part of the North Island, is lower than 10° C in the southern part of the South Island and is lower than 5° C in Alpine regions. January and February are the warmest months, with mean temperatures of 19° C in the north (Auckland) and 13° C in the south (Invercargill); July is the coldest month with a mean temperature of 11° C in Auckland and 4° C in Invercargill. There is an absence of extreme variations in temperature and, for a large part of the country, rainfall is spread evenly throughout the year. However, in the north, winter has almost twice as much rain as summer, and this predominance of winter rainfall is still discernible as far south as Canterbury. Deficiency in soil moisture is most common from January to March, when there is typically a combination of low rainfall and high evaporation.

Surface water

New Zealand rivers, owing to the high relief of the country, are mostly swift flowing and difficult to navigate. The largest rivers of the North Island are the Thames, Rangitaiki, Mohaka, Manawatu, Rangitikei, Wanganui, Mokau and Waikato. Those of the South Island are the Wairau, Awatere, Clarence, Waiau-uha, Hurunui, Waimakariri, Rakaia, Rangitata, Waitaki, Taieri, Clutha, Mataura, Oreti, Waiau, Grey, Buller and Motueka. Their rapid flow and dependable volume of water makes many of the rivers suitable for hydroelectric power generation. The Waikato in the North Island and the Waitaki and Clutha in the South are used for major hydroelectric schemes. Some rivers, especially those in Canterbury, are flashy, with flood flows almost 200 times greater in volume than minimum flows. The frequency of high flows is too unpredictable to permit seasonal abstraction for such purposes as irrigation. Some rivers have abstraction races for irrigation and farm stock water. River flow losses to ground-water aquifers are common, especially in reaches across alluvial plains.

Lakes in both islands are important for their scenic beauty, their function of regulating river flow and hydroelectric storage. The main natural lakes of the South Island are Brunner, Coleridge, Tekapo, Pukaki, Ohau, Hawea, Wanaka, Wakatipu, Te Anau and Manapouri; and Lake Ellesmere is the largest tidal lake. In the North Island the main lakes, situated on a volcanic plateau, are Taupo, Rotorua, Rotoiti, and Waikaremoana.

Ground-water resources

Historical

In New Zealand the earliest wells were dug and drilled for abstraction of ground water in the latter half of the nineteenth century as settlement of the country expanded, when ground water with shallow hydrostatic head was the only possible supplement to stored rain water except for users with riparian alternatives. The New Zealand Geological Survey was founded at about that time and has been giving advice on ground water availability ever since. The main role of ground-water prospector has always fallen upon well-drilling contractors who by the present time have drilled tens of thousands of wells across both islands. The concentration of wells has depended upon three factors, namely, the availability of ground water, the availability of alternative sources and the total need for fresh water. Following urban expansion many towns and cities have reticulated supplies from natural sources, such as rivers and lakes, or from artificial reservoirs. Wherever suitable ground water is available it tends to be used to supplement municipal supplies. Thus of 40 of the larger cities and towns in New Zealand, 13 utilize ground water alone, five have supplies drawn from both surface and underground sources and the remainder use surface water for their public supplies. The Christchurch metropolitan area abstracts an estimated 250,000-400,000 m^3/day and total ground-water use throughout New Zealand almost certainly exceeds 500,000 m^3/day, a considerable proportion, perhaps approaching one third, of total fresh-water use. Many rural dwellers remote from surface-water sources depend upon wells to supplement roof catchment for domestic stock and garden water. An appreciable number of rural dwellers are still solely dependent upon water tanks recharged by roof catchment, and it is common after long droughts to see mobile water carriers recharging empty tanks. Some areas are so favourably located with respect to ground-water reservoirs that even irrigation, industrial and manufacturing needs can be satisfied from that source. In terms of ground-water quantities used, the most important ground-water areas of New Zealand are the following Quaternary plains, more or less in order of importance (see map 25):

The Canterbury Plains in eastern South Island;

The Heretaunga Plains and similar neighbouring plains, in eastern North Island;

The Hutt Valley, Wellington, in southern North Island;

The Wairau Plain, in north-eastern South Island;

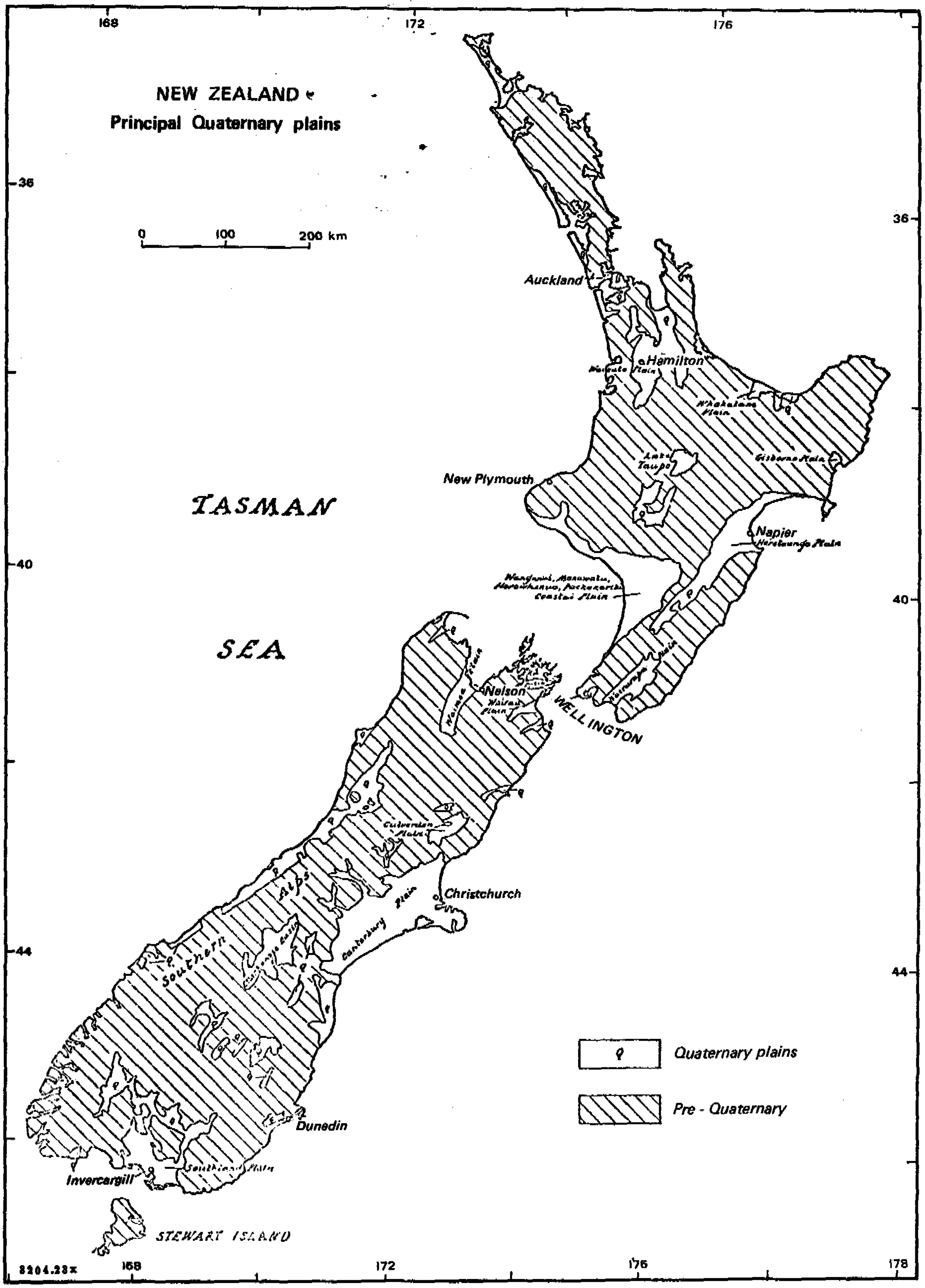
The Waimea Plain, in northern South Island.

There are several other Quaternary plains where the extent of ground-water availability is only now becoming recognized, and where future development is likely to increase the importance of ground water.

Since 1946, the New Zealand Geological Survey has been developing systems of data collection, assessing ground-water availability in various areas and advising organizations and individuals on ground-water availability. More recently, joint investigations and co-ordinated ground-water research with other branches of the Department of Scientific and Industrial Research, and with university, Catchment Authority and Ministry of Works and Development engineers have been initiated.

[map 25. New Zealand: principal Quaternary plains])

MAP 25



In 1977, the Water and Soil Division of the Ministry of Works and Development established a ground-water section to deal with aspects of ground-water distribution and quality. The statutory authority for fresh-water administration is the National Water and Soil Conservation Authority and this organization delegates to Catchment Authorities (Regional Water Boards) the task of ensuring the most beneficial use (management) of fresh water, including ground water. Each Regional Water Board is responsible for water allocation within its territory, and its decisions are normally tempered by consultation with specialist groups, including the Geological Survey.

Principal lithological groups and their aquifer potential

In terms of aquifer potential the rocks of New Zealand can conveniently be divided into four groups, as follows:

Pre-Cretaceous sediments

These are highly indurated pre-Cretaceous sedimentary, plutonic and metamorphic rocks. The sediments are principally geosynclinal and owe their induration to static metamorphism related to depth of burial and to dynamic metamorphism related to the (Cretaceous) Rangitata Orogeny which caused complex folding. The rocks typically form steep mountainous topography including the greater part of the South Island, and the main mountain axis of the North Island. They include indurated sandstones and siltstones, schists, quartzites, gneisses, marbles and plutonic rocks. Indurated sandstones and siltstones (greywacke and argillite) are dominant. Induration and cementation are typically intensive, which means that intergranular porosity is low. However, the two orogenies have created joint patterns and shattered zones and these form potential aquifers. Although these older sediments seldom yield more than limited domestic supplies, they form a useful supplement to rain storage in rural areas.

Tertiary and late Cretaceous sediments

These are consolidated but relatively soft sediments, predominantly marine, deposited during the later Cretaceous and throughout the Tertiary. They consist of sandstones, coal measures, mudstones, limestones and rare conglomerates which retain their original porosity except where cementation has occurred. These sediments, including potential aquifers such as sandstone, limestone and gravels, were originally deposited as a transgressive-regressive sequence over most of New Zealand. The whole sequence, together with the underlying indurated rocks, was folded and faulted into blocks by the Kaikoura Orogeny, which began in the late Pliocene and is still continuing. Typically these rocks form rolling to steep country, in many places with marked escarpment - dip slope - topography. They form almost half of the area of the North Island, but a much smaller proprotion of the South Island. Because in most places there are alternative sources, they have not been intensively explored or developed for ground water. Quantities developed are typically small, sufficient only for domestic or stock supplies, but the town of Patea, on the west coast of the North Island depends upon ground water from Tertiary aquifers.

Volcanic rocks

Tertiary and post-Tertiary volcanics are widely distributed in both islands. They include fragmental rhyolitic rocks covering 13,000 km^2 in north-central

North Island, the basic volcanics of Auckland and Raglan, and the principally basic volcanics of Banks Peninsula and Otago Peninsula in the South Island. The ground-water potential of volcanic rocks has not been intensively explored in the South Island, even though Banks Peninsula and Otago Peninsula are composed almost entirely of volcanic rocks. There is some reason to believe (e.g., high-yielding springs encountered during tunnel construction at Banks Peninsula) that the rocks may include reasonably prolific aquifers, and increasing needs for fresh water may result in increased prospecting. In the North Island, ground water in volcanic rocks is exploited in central and northern areas. In the central area abstraction of hot water is for the purpose of power generation and heating.

Post-glacial alluvium and glacial and periglacial outwash

These deposits comprise typically unconsolidated slope debris, moraine, outwash and alluvium built from the products of the rapid erosion that followed the creation of unstable steep slopes by the Kaikoura Orogeny. These younger deposits are by far the most important sources of ground water and form the major plains of both islands which, because of their low relief are important arable areas. They can be divided into two groups:

Post-glacial alluvium, consisting of well-sorted greywacke gravels, with wide areal distribution but typically concentrated along recent coastlines and in lower reaches of gravel-based rivers. Drilling has been carried out by percussion methods. The alluvium contains large amounts of ground water suitable for irrigation and industrial use.

Glacial and periglacial outwash, consisting of greywacke gravels, commonly in a fine-grained silty matrix with wide areal distribution. Percussion methods are used for drilling. The gravels contain ground water suitable for irrigation and industrial use. Recharge is partly from rainfall infiltrating and partly from influent seepage, the proportion of each varying from place to place.

Prospecting methods

It was evident even in the early days of settlement that Quaternary gravel plains contained ground water almost everywhere, but it took decades of drilling to establish the lateral and vertical distribution of the principal aquifers. Prediction of ground-water availability still depends on an examination of the bore logs and yields of neighbouring wells. Good relations have been established over the years between the Geological Survey and drilling contractors. Standard forms have been produced by the Geological Survey to store all relevant information for the Survey and Regional Water Boards and to encourage drillers to log wells.

The bedded sequences of Tertiary and late Cretaceous marine sediments normally underlie hill country where farm settlement is scattered, where steep slopes rule out irrigation possibilities and where surface-water resources are in many places available. So, although basic geological precepts, such as sediment porosity and sediment attitude, reveal the distribution of aquifers, demand for information in such areas is rare and when ground water is sought, the amounts needed are generally small, of the order of tens of cubic metres per day.

Shattered and jointed terrains contain the principal water-bearing zones in pre-Cretaceous rocks. Since the structure of the older rocks is complex, water-bearing zones cannot be predicted by normal geological precepts. Surface geophysical methods would be unlikely to be successful, since they do not distinguish degrees of permeability, and are hardly justified for the low-yield (rarely exceeding 0.5 l/sec) household wells that are normally drilled. Locating aquifers is therefore very much a matter of trial and error, but a remarkably high proportion of "wildcat" water wells produce modest supplies at depths shallower than 25 m.

In summary, a combination of geology, common sense and attention to the knowledge that has been accumulated through drilling is required to forecast ground water availability in the Quaternary sediments where it is most sought; stratigraphy alone is sufficient to permit accurate forecasting in volcanic rocks and well-bedded Tertiary sediments, where ground-water exploration is rare; and in the enormous tracts of New Zealand underlain by low-yielding older rocks, the drill is almost the sole arbiter of ground-water availability.

Regional distribution of aquifers

Regional availability

North Auckland

Ground water is obtained from the Taheke, Kawiti and Horeke Basalts, from wells typically up to 50 m deep. Yields rarely exceed 8 l/sec and specific capacity is in the range of 0.5 to 4 l/sec/m. Some ground water is taken from dune sands, but yields are typically low. Transmissivity is probably of the order of 1,000 m^2/day. 1/

Auckland and Waikato

Alluvium of the Hamilton and Mercer Basins provides appreciable amounts of ground water, with yields up to 30 l/sec and transmissivities up to 10,000 m^2/day. There is a small artesian system in the Hamilton Basin. Ground water is also obtained from Tertiary sediments (Waitemata Sandstone) and basic volcanics including Franklin, Bombay and Ti Point Basalts; well depths are up to 200 m, yields are typically up to 10 l/sec and transmissivity rarely exceeds 1,000 m^2/day.

Bay of Plenty

Ground water is abstracted from Quaternary dune sands and Quaternary volcanics - from the former for domestic, irrigation and industrial uses and from the latter typically for heating.

West Coast, North Island, including Rangitikei, Wanganui, Taranaki and western Manawatu

The principal aquifers are Quaternary gravels and sands and Tertiary sediments, mainly sandstones, although in Taranaki around the foot of the dormant volcano, Mt. Egmont, some ground water is obtained from aquifers formed from redeposited volcanic rock (andesitic gravel). The Quaternary and Tertiary sediments underlie the Wanganui-Manawatu-Horowhenua-Paekakariki coastal plain; they yield amounts up to 40 l/sec in places with artesian heads, and transmissivities are probably in the range of 1,000 to 10,000 m^2/day. The Tertiary sediments of the region dip at low to moderate angles, and produce moderate yields of ground water, in places artesian, from depths up to 300 m.

East Coast, North Island, including Hawkes Bay and Wairarapa

The principal aquifers are Quaternary gravels and sands. Ground water is especially important in the Heretaunga Plains of Hawkes Bay, where it is used to irrigate market gardens and vineyards and to service food processing industries. The water is recharged by influent seepage from neighbouring rivers. Over 300,000 m^3/day are removed during the summer months, from depths of the order of 50 m to 100 m. Transmissivities range from 950 m^2/day to 22,000 m^2/day. Quaternary sediments of the Wairarapa Valley have not so far been intensively developed, but yields in places are high enough (more than 20 l/sec) to permit spray irrigation, and transmissivities in such places may exceed 10,000 m^2/day.

Wellington

In the Wellington area ground water is abstracted from a gravel aquifer recharged by the Hutt River, and is used to supplement surface-water supplies. The average abstraction rate is about 70,000 m^3/day, and the transmissivity is of the order of 15,000 to 20,000 m^2/day.

Nelson, Westland, Fiordland

Ground water in the Nelson province is abstracted from greywacke gravels of the Motueka Plains and the Waimea Plains. Two separate aquifers have been recognized underlying the Waimea Plains. Total throughflow of the lower aquifer has been estimated at about 2,000 m^3/day (with transmissivity of the order of 1,000 m^2/day). Well depths are typically up to 150 m, and yields are in places sufficient for spray irrigation, exceeding 20 l/sec.

Ground water is not quantitatively significant in Westland or Fiordland fresh-water supplies, since these areas are bountifully supplied by surface streams and replenished by well-distributed high rainfall.

Marlborough

In Marlborough, the Wairau and Kaikoura Plains are built up of gravels containing large reservoirs of ground water. The Wairau Plains reservoir is recharged by influent seepage from the Wairau River. Losses to that river have been gauged at 240,000 m^3/day, but much of this amount supplies spring-fed minor rivers and it is tentatively estimated that ground-water availability is of the order of 100,000 m^3/day. Individual well yields of more than 20 l/sec are common and transmissivities are probably typically 10,000 m^2/day. Aquifers in the gravels of the Kaikoura Plains are generally of lower permeability than those of the Wairau Plains.

Canterbury

Enormous amounts of ground water are abstracted from the Canterbury Plains. Total abstraction is not known but abstraction in Christchurch probably averages at least 250,000 m^3/day, the total abstracted for smaller towns and settlements probably exceeds 50,000 m^3/day, and, at the height of the summer season, between 1 million and 3 million m^3/day are abstracted for irrigation. Average daily throughflow across the whole of the plains is probably of the order of 10 million to 20 million m^3. Transmissivities are between 1,000 and 50,000 m^2/day, and total gravel thickness probably averages 500 m, though ground-water movement is probably concentrated in a series of permeable beds each only a few centimetres thick.

Otago

Ground water is important beneath wide gravel river flats, as in the lower reaches of the Taieri and Clutha rivers. A number of intermontane basins including the Maniototo Plain, the Middlemarch Plain, the Ida and Manuherikia valleys, and the Lindis and upper Clutha valleys are underlain by Quaternary gravels that are in places water bearing. Small yields of the order of 0.1 to 0.2 l/sec are obtained from many rural wells in schist, and there are a few wells of low to moderate yield in the volcanics of Otago Peninsula.

Southland

Fresh water for the Southland region is derived mainly from surface water, but successful wells have been drilled in river alluvium, dune gravels and Tertiary sediments, and urban supplies have in places been acquired from wells and infiltration galleries in gravel flood plains. Exploration has rarely extended below about 90 m, and more typical wells are up to 30 m deep. Yields from Tertiary sediments are of the order of 2 l/sec and yields from river gravels and dune gravels can be up to 30 l/sec.

Water quality

Ground water from Quaternary gravels and sands constitutes at least 90 per cent of all ground water abstracted. It is almost everywhere of high quality and does not normally require any form of treatment, even in urban areas, such as Christchurch and Hastings, where it is the sole source of water for domestic consumption and food manufacturing. A common disadvantage in some areas is corrosiveness as a result of high proportions of carbon dioxide. Toxic wastes are not produced in great quantity in New Zealand and have not so far caused appreciable ground-water deterioration, but closer attention is currently being paid to studying quality changes near sources of liquid and solid wastes, and to the rational siting of disposal points.

Some intensive-farming practices, such as disposal of dairy and piggery wastes, irrigation, beef breeding and fertilizer application, are causing deterioration in the quality of ground water, the most disturbing effect of which is an increasing nitrate content. Septic tanks are common in rural areas, as is border dyking of community sewage effluent, both of which tend to cause a gradual deterioration in ground-water quality, though instances of bacterial contamination are fortunately rare.

Progress and shortcomings in ground-water understanding

Largely through the efforts of the Geological Survey during the past 30 years, sufficient data has accumulated to permit reasonable estimates to be made of the availability of ground water. The main task ahead is to determine the most appropriate network of wells that will permit the maximum ground-water abstraction without unacceptable water-level decline, interference among wells, or quality degradation. Since the largest ground-water reservoirs are beneath plains where, given sufficient water, irrigation is technically simple and enormously productive, conjunctive use of ground water and surface water is necessary to allow maximum agricultural use. The most practical way to attain this end without depleting either rivers or ground water is by continuing present policy which is a combination of the predictive and the empirical.

Ground-water development

Ground-water administration and servicing

Modern legislation has established the following administrative and executive framework. The National Water and Soil Conservation Authority has statutory authority to dictate broad national policy and does so through two councils, one responsible for Soil Conservation and Rivers Control and the other for Water Resources. Local administration of both councils is delegated to a network of 20 Regional Water Boards, normally Catchment Authorities. These Regional Water Boards differ in size and rateable population, and ground water is of differing importance from one region to another; in regions where ground water is vitally important, the Authorities employ engineering and technical staff to supervise its use. However, even the wealthiest Regional Water Board cannot afford to employ the wide range of skills necessary to become technically independent and must rely upon supra-provincial, perhaps national, organizations for advice. The Water and Soil Division of the Ministry of Works and Development is responsible for executing the policies of the National Water and Soil Conservation Authority, and has recently set up a ground-water section to service scientific and technical needs in that field. For specialist help the Regional Water Boards and the Groundwater Section of the Ministry of Works and Development can turn to branches of the Department of Scientific and Industrial Research, including the Geological Survey (mapping aquifer extent), the Geophysics Division, Institute of Nuclear Sciences (isotope studies), the Chemistry Division (ground-water quality) and the Physics and Engineering Laboratory (ground-water modelling).

Drilling organizations

Drilling for ground water is done almost entirely by private contractors (exceptions being wells for State-owned projects, which are on occasion drilled by State organizations), and more than 40 firms are listed with the New Zealand Drillers Federation, Inc. Clients are predominantly farmers seeking irrigation or domestic supplies, rural householders, rural industries and county and urban councils. The depth drilled annually varies with farm prosperity and with climatic trends, but averages about 10,000 m for the South Island and probably a similar figure for the North Island. Bore diameters range between 50 mm and 1,200 mm but the commonest sizes are currently 200-300 mm. Most of the larger drilling contractors make a practice of recording all borehole logs, and have been most co-operative with the Geological Survey in providing copies. Recent legislation has made the furnishing of logs to Regional Water Boards mandatory so that short-comings now hinge on log quality, not log availability; it is difficult to base accurate logs on the debris of percussion or rotary drilling.

Utilization of ground water

Of the larger municipalities, Christchurch, Palmerston North, Napier, Hastings, Blenheim and Ashburton depend entirely on ground water. Numerous smaller settlements also derive all their fresh water from underground. Auckland, Wellington, Nelson and Invercargill rely in part upon ground water. Farm houses and communities too small to have a communal reticulated supply depend upon ground water as a supplement to stored rain water or surface springs and streams. The odds of obtaining ground water from shallow (up to about 30 m) wells varies from place to place. In favourable localities, such as parts of Quaternary plains (Canterbury, Hawkes Bay, Wairau and Waimea), irrigation wells commonly yield 3,000 m^3/day; it is estimated that about 1 million m^3 of ground water is abstracted daily during the irrigation season in the Heretaunga Plains, Hawkes Bay; the estimate for Canterbury is of the order of 3 million m^3/day.

Many industries depend entirely upon ground water, and indeed the availability of ground water has in many cases been the determining factor in locating industries requiring high-quality water. Among these are the food-processing industries in Christchurch and Hastings, where individual factories use up to 20,000 m^3/day.

Forecast of future needs

It is difficult to forecast the growth rate of towns and cities or the development of manufacturing and servicing industries upon which they depend, but it is probable that there is ample ground water to service any feasible expansion in urban areas dependent on ground water, without serious stress. Demands for irrigation in water-deficient agricultural areas combined with a trend from dairy, meat and wool farming to crop, vegetable and fruit growing, is likely to accelerate, and since abstraction of water from rivers is limited by the need to maintain appreciable minimum flows, ultimate demands must involve conjunctive use. Eventually, if low-relief areas, such as the Canterbury Plains, are to be fully irrigated it may be necessary to abstract ground water to full capacity, involving overdraught during years of lean rainfall and replenishment by artificial recharge during years of plenty. To date, artificial recharge has not been attempted, because natural recharge from rivers may approximate 20 per cent or 30 per cent of total flow.

Present and future problems

On a national scale, few problems have yet been encountered. There is no evidence of overdraught, and interference among wells remains at an acceptable level. Salt-water intrusion has occurred only in regions where alternative fresh-water sources are available and has only taken place because abstraction wells have been sited unreasonably close to the interface. There is no sign of intrusion at the seaward margins of the really large reservoirs beneath the Canterbury and Heretaunga plains. No subsidence has been observed (apart from shrinkage of surface peats after drainage), but a careful watch is maintained on areas, such as Christchurch, where the stratigraphy indicates potential risk. Irrigation of some areas to overcome water deficiency has resulted in an oversupply of water "downstream", causing drainage difficulties; such problems are of relatively minor importance, and can be solved by a combination of co-operation and drainage.

Perhaps the most disturbing trend, though it is by no means uncontrollable, is that towards slow quality deterioration of shallow ground water in rural areas as a result of contamination from intensive stocking, factory farming, fertilizer application, irrigation infiltration and septic tanks. The resultant increase in nitrates and other contaminants may necessitate selective use of aquifers so that water from shallow aquifers, normally high in nutrients, is used to water pasture or crops that would benefit from the nutrients and water from deeper aquifers used for purposes for which purity is essential.

Conclusions

The costs of ground water, on the one hand, and surface water, on the other, are difficult to evaluate, depending as they do on the distance of the user from the source, on the cost of water treatment where needed and on the changing costs of power and pumping equipment. For private users far from surface sources, there is no doubt about the convenience of ground water, and there is normally far less risk of contamination in ground water than in untreated surface water. As long as rural dwellers have no reticulated communal supply, private development of ground water is likely to continue and expand, in some areas for small domestic supplies and, in others more favourably situated, for irrigation supplies. Development is likely to be more marked in comparatively dry areas of the east coast. The only constrictions are the increasing costs of energy for abstraction, if these are not matched by increasing rewards for improved production.

Notes

1/ Aquifer characteristics have been investigated by test pumping in only a few localities. Consequently the figures quoted for transmissivity (T) are estimates only. T has been estimated in preference to hydraulic conductivity (K), because the upper and lower boundaries of water-bearing sediments are rarely clear, especially in the Quaternary gravels that constitute the commonest aquifers. As a general rule K will be between one third and one tenth of T. The storage coefficient (S) of Quaternary aquifers is in the range of 0.1 to 0.3 (unconfined) and 0.001 to 0.01 (confined); for older aquifers the value is typically an order of magnitude lower. Near the boundaries of confined aquifers in western Christchurch, the values for S are midway between confined and unconfined, suggesting semi-confined, leaking aquifers.

Selected references

Brown, L. J. 1972. A preliminary account of the groundwater resources of the Wairau Plain, Marlborough. New Zealand Geological Survey, Report No. 60, 60 pp.

_____________. 1979. Geology in groundwater research in New Zealand. Proceedings of Underground Water Research Group, Lincoln College, Canterbury, 1978.

Brown, L. J. and R. B. McCammon. 1976. New Zealand water well data form. New Zealand Geological Survey Report No. 77, 30 pp.

Brown, L. J. and C. B. Taylor. 1974. Geohydrology of the Kaikoura Plain, Marlborough, New Zealand. Reprint from "Isotope techniques in groundwater hydrology - 1974". International Atomic Energy Agency, Vienna, pp. 169-189.

Collins, B. W. 1954. The occurrence and utlization of ground water in New Zealand. Publication No. 37 of the International Hydrological Association, pp. 295-307.

____________. 1954. Fluctuations of ground-water levels in New Zealand and their significance. Publication No. 37 of the International Hydrological Association, pp. 25-31.

Dicker, M. J. I. 1978. The hydrogeology of the Motueka Plains and Waimea Plains, Nelson. Section in the Annual Report of the Nelson Catchment Board and Regional Water Board.

Donaldson, I. G. 1974. Underground waters of the Lower Hutt - a model study. Journal of Hydrology (New Zealand), vol. 13, No. 2, pp. 81-97.

Donaldson, I. G. and D. G. Campbell. 1977. Groundwater of the Hutt Valley - Port Nicholson alluvial basin. DSIR Information series No. 124, 78 pp.

Grant-Taylor, T. L. 1957. Groundwater in the Poverty Bay Flats. New Zealand Journal of Science and Technology, B38, No. 7, pp. 763-772.

____________. 1967. Groundwater in New Zealand. New Zealand Geological Survey Report 24, 15 pp.

Hay, R. F. 1952. The rocks of the North Auckland Peninsula considered as potential aquifers. New Zealand Journal of Science and Technology, B33, pp. 248-257.

Henderson, J. 1942. Underground water in New Zealand. New Zealand Journal of Science and Technology, B23, pp. 97-112.

Hunt, B. W. 1975. A groundwater model study in northern Canterbury. University of Canterbury Research Report 75.10. 17 pp and figs.

Hunt, B. W. and D. D. Wilson. 1974. Graphical calculation of aquifer transmissivities in Northern Canterbury, New Zealand. Journal of Hydrology (New Zealand), vol. 13, No. 2, pp. 66-80.

Lloyd, E. F. 1975. Geology of Whakarewarewa Hot Springs. DSIR Information Series No. 11, 24 pp.

McCammon, R. B. 1976. A computer-based study of long-term well hydrograph records in metropolitan Christchurch. New Zealand Geological Survey, unpublished report No. M48. 40 pp. and figs.

Martin, G. N. and M. J. Noonan. 1977. Effects of Waste-water disposal by Land Irrigation on Groundwater Quality in the Burnham/Templeton area. Ministry of Works and Development, Water and Soil Division, technical publication No. 7, 25 pp.

Oborn, L. E. 1960. The incompetent and elastic nature of the Christchurch artesian system. New Zealand Journal of Geology and Geophysics, 3 (1), pp. 81-97.

Schofield, J. C. 1972. Groundwater of Hamilton Lowland. New Zealand Geological Survey Bulletin, 89, 71 pp.

Thorpe, H. R. and others. 1977. Movement of contaminants into and through the Heretaunga Plains aquifer. International Report, Ministry of Works and Development, Water and Soil Division.

Waterhouse, B. C. 1961. Note on Kawiti Basalt and hydrology of Kawakawa Basalt, Northland. New Zealand Journal of Geology and Geophysics, 4 (4). pp. 357-371.

Wilson, D. D. 1973. The significance of geology in some current water resource problems, Canterbury Plains, New Zealand. Journal of Hydrology (New Zealand), 12 (2), pp. 103-118.

____________. 1976. Hydrology of Metropolitan Christchurch. Journal of Hydrology (New Zealand), 15 (2), pp. 101-120.

____________. 1977. Scientific, administrative and executive involvement in groundwater resource planning, Canterbury Plains, New Zealand. Water Resource Transfer: Proceedings of the Second International Conference on Transfer of Water Resources Knowledge, Colorado, 1977, vols. 1 and 2. Water Resources Publications, pp. 599-621.

____________. 1979. Geology, hydrology and groundwater resources, Canterbury Plains, New Zealand. Proceedings of the New Zealand Institute of Engineers Annual Conference, Wellington, 1979.

NIUE

(Self-governing State in free association with New Zealand)

Area: $259 km^2$ (including the main island of Niue and several islets some 200 miles to the north-west)

Population: 6,000 (United Nations estimate, 1977)

Niue, located some 1,000 miles east of Fiji, is the largest coral island in the world (see map 26). Originally, it was an atoll, a ring of reefs and islets surrounding a lagoon. Orogenic movements pushed up the bed of the lagoon, which now forms the central plateau of the island, 30 m above sea level. The highest countour line is that of 60-65 m, which runs parallel to the coastline at a distance of 1.5 to 2.5 km. The island is oval shaped, 22 km long and 16 km wide. The population of 3,500 is entirely settled in the coastal area. The central plateau, covered with thick bush, is underdeveloped. Lime and passionfruit crops are grown in three selected areas of the central plateau where soils are recognized as suitable.

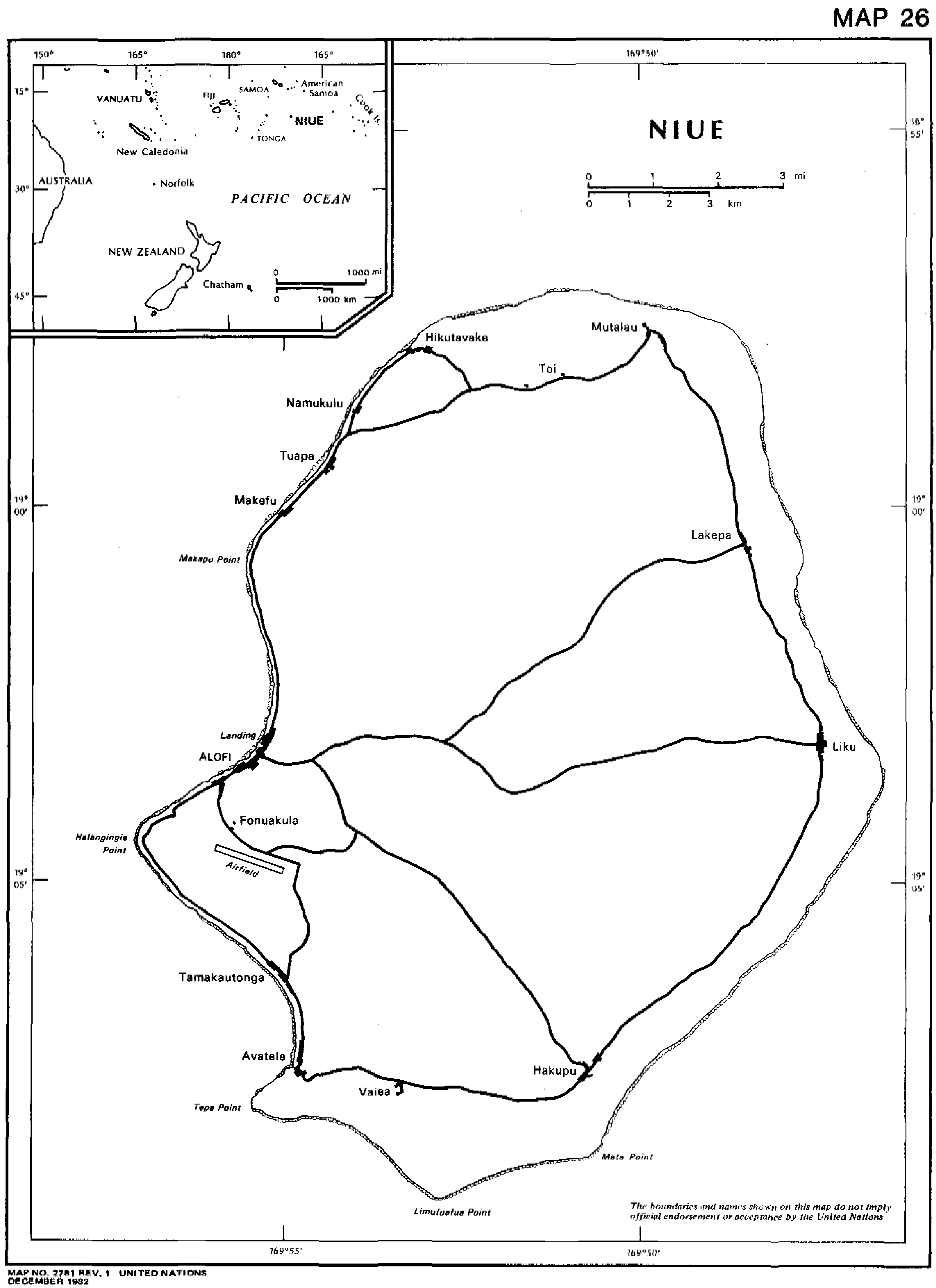
There are 12 villages including the chief town of Alofi. Traditionally, water for drinking and domestic use was obtained from natural cavities and roof catchments. In recent years one deep well has been dug and about 50 boreholes drilled. They are all equipped with reciprocating pumps which yield a maximum of 1 m^3/h. Total ground-water extraction may amount to approximately 400,000 m^3/year. The boreholes are located at an average distance from the coast of 1.5 to 2 km. Some boreholes drilled near the coast have yielded brackish water. As yet no drilling has been done in the interior. The elevation of the water table above mean sea level appears to increase inland from 1 to 4 m. In the south, for example, the water table is 4 m above sea level at a distance of 2.5 km from the coast. The effect of pumping on the water table is not known since there are no open observation wells, and since the diameter of the casings and the setting of the pumps do not permit the introduction of an electric probe into the tubewells.

Selected references

United Nations Development Programme. "Preliminary assessment of groundwater investigation programme in Niue". Report of project NIU/77/003. April 1978.

Waterhouse, B. C. The hydrology of the Southern Cook Islands, Niue and Tonga. Pacific Island Water Resources, W. R. Dale, ed. (Wellington, New Zealand, Department of Scientific and Industrial Research, 1981), pp. 57-74.

Map 26. Niue


MAP 26
NIUE
VANUATU
FIJI
SAMOA
American Samoa
Cook Is.
NIUE
TONGA
New Caledonia
AUSTRALIA
Norfolk
PACIFIC OCEAN
NEW ZEALAND
Chatham
Hikutavake
Mutalau
Toi
Namukulu
Tuapa
Makefu
Makapu Point
Lakepa
Landing
ALOFI
Liku
Fonuakula
Halangingie Point
Airfield
Tamakautonga
Avatele
Hakupu
Vaiea
Tepa Point
Mata Point
Limufuefua Point
The boundaries and names shown on this map do not imply official endorsement or acceptance by the United Nations
MAP NO. 2781 REV. 1 UNITED NATIONS
DECEMBER 1982

PAPUA NEW GUINEA

Area: 461,691 km^2

Population: 2,900,000 (United Nations estimate, 1977)

Physical outline

The mainland of Papua New Guinea is approximately 1,250 km long, decreasing in width from 730 km along the border with Indonesia to 50 km at its eastern tip. To the north and north-east lie the island groups of the Bismarck Archipelago, and the North Solomon Islands, with the smaller archipelagos of the Trobriands, d'Entrecasteaux and Louisiades off the eastern end of the mainland (see map 27).

The principal topographical features of the mainland, the Bismarck Archipelago and the North Solomon Islands are the highly dissected mountain ranges which reach 4,500 m in elevation on the mainland and which are punctuated by numerous intra-montane basins. In addition, in the western half of the mainland are the extensive lowland plains and swamps of the Sepik-Ramu and Fly rivers, lying north and south, respectively, of the main mountain ranges.

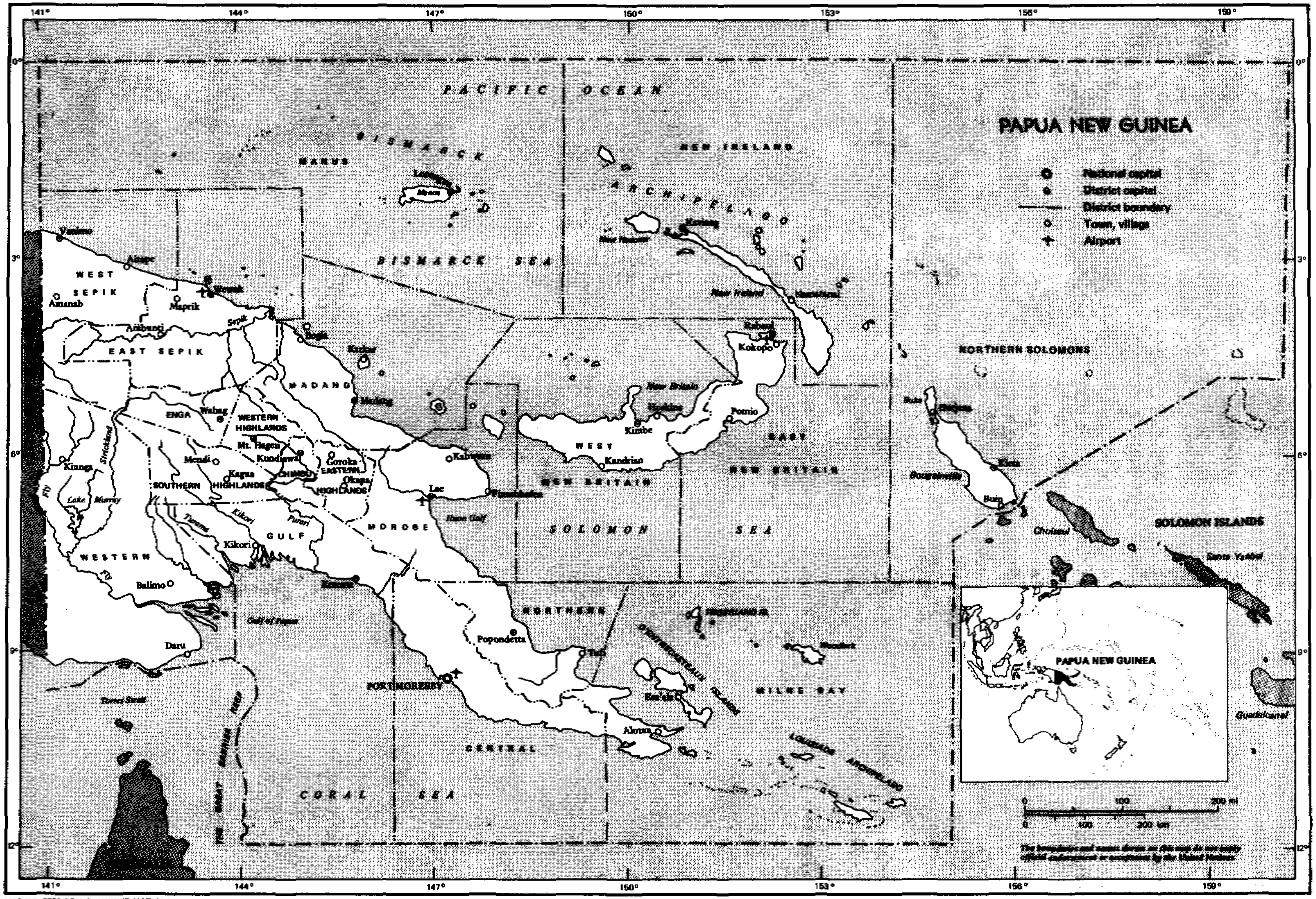
The eastern end of the mainland and many of the island groups are bordered by coral islands, reefs and raised fossil coral terraces.

Highland areas

The highland areas are dominated by massive ridge and valley land-forms. The area may conveniently be classified by two physiographical characteristics: local relief and altitude (see map 28). The northern part forms a belt of uniform mountainous country, extending from the Thurnwald Ranges in the west to the Bismarck Ranges in the east. It includes the highest, most rugged and most remote areas in Papua New Guinea. The central part, extending to the Goroka-Kainantu area in the east, is characterized by relatively low local relief, a succession of intra-montane plains and broad upland valleys, and contains several huge strato-volcanoes. The eastern part of the highlands comprises the Owen Stanley Range and its flanking ranges, running the entire length of east Papua New Guinea. It is similar to the northern part and can, in fact, be regarded as its eastern extension. It is dominated by massive ridge and valley land-forms.

Highland areas are also found in the Papua New Guinea islands, namely, the d'Entrecasteaux, New Britain, New Ireland and Bougainville islands.

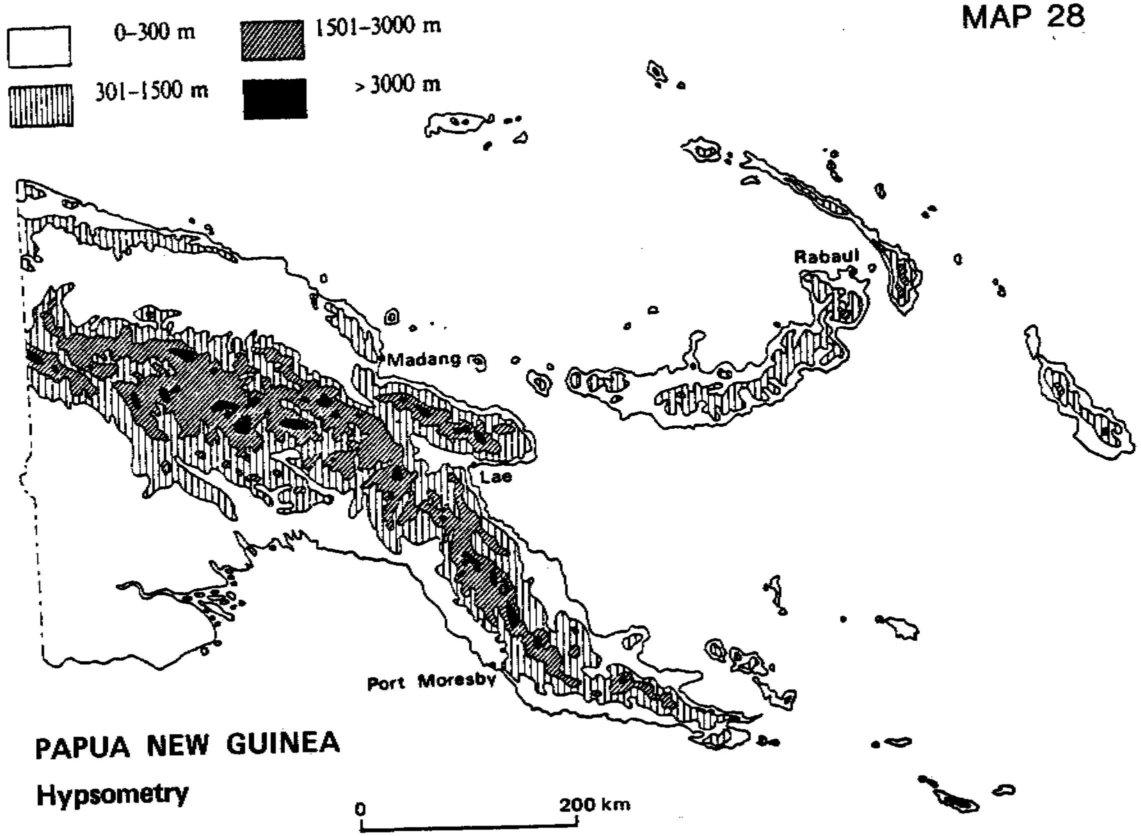
Owing to high slopes in the highland regions a relatively small fraction of the precipitation is usually available for infiltration into the soil. Most of it either evaporates or quickly discharges into streams and rivers as surface run-off. The steep slopes also imply that, where there are potentially aquiferous rocks, the water table is only accessible near rivers where it approaches the surface.



MAP NO. 2208 REV. 5 UNITED NATIONS
FEBRUARY 1983

Map 27. Papua New Guinea

MAP 28



3204.25x

Map 28. Papua New Guinea: Hypsometry

Swamp areas

Large areas of Papua New Guinea are covered with swamps (see map 29). The Papuan Gulf area and the lower part of the Fly river, together with the middle and lower part of the Sepik Valley are the most extensive. Other areas are the lowland parts of the Lakekamu, Kapuri and Biaru rivers, the lower parts of the Vanapa and Laloki rivers, the coastal areas of Table Bay, Mullins Harbour and Katekarua Bay and the Ramu Valley. Swamps are also found in New Britain along the Via river and Riebeck Bay, and may exist in flat valleys in the highland areas, for example, the Wahgi swamps and Lake Kutubu.

The water in these swamps is usually of poor quality, being easily polluted by products of plant decay.

Coastal areas

The major beach sands owe their existence to the great abundance of suspended materials brought down by the rivers and their reworking by wind and current action. The combinations of high precipitation, mountain ranges and intensive erosion are highly favourable to the development of the beaches. They are found mainly along the south coast due to the post-glacial differential rise in sea level. Along the south coast the rise in sea level led to drowning of river inlets, reduction of stream velocities in the lower reaches and formation of embayments which provided ideal loci for deposition. The aquifers are found on beach ridges, beach plains, tidal flats and raised coral reefs (see map 30). The north coast was largely unaffected by the rise in sea level because of its steepness and active uplift. The Sepik plain and Cape Vogel basin were exceptions to the general trend.

Fossil coral reefs are uplifted coral reefs and terraces. They occur in great numbers along the south coast of New Britain, the east coast of New Ireland, the northern part of Bougainville, the Trobriand and Marshall Bennett Islands, and also along the Sialum and Madang coasts. These reefs are ample evidence of the relative movements of land and sea.

Volcanic areas

Papua New Guinea has a great variety of volcanic land-forms. On the mainland, they occur in two irregular clusters (see map 31). The largest is centrally located within and south of the central highlands region. A smaller one occurs in the south-eastern part of the Cape Vogel basins. A third cluster is on the d'Entrecasteaux Islands. In addition, there are two chains of volcanoes in the Bismarck Sea.

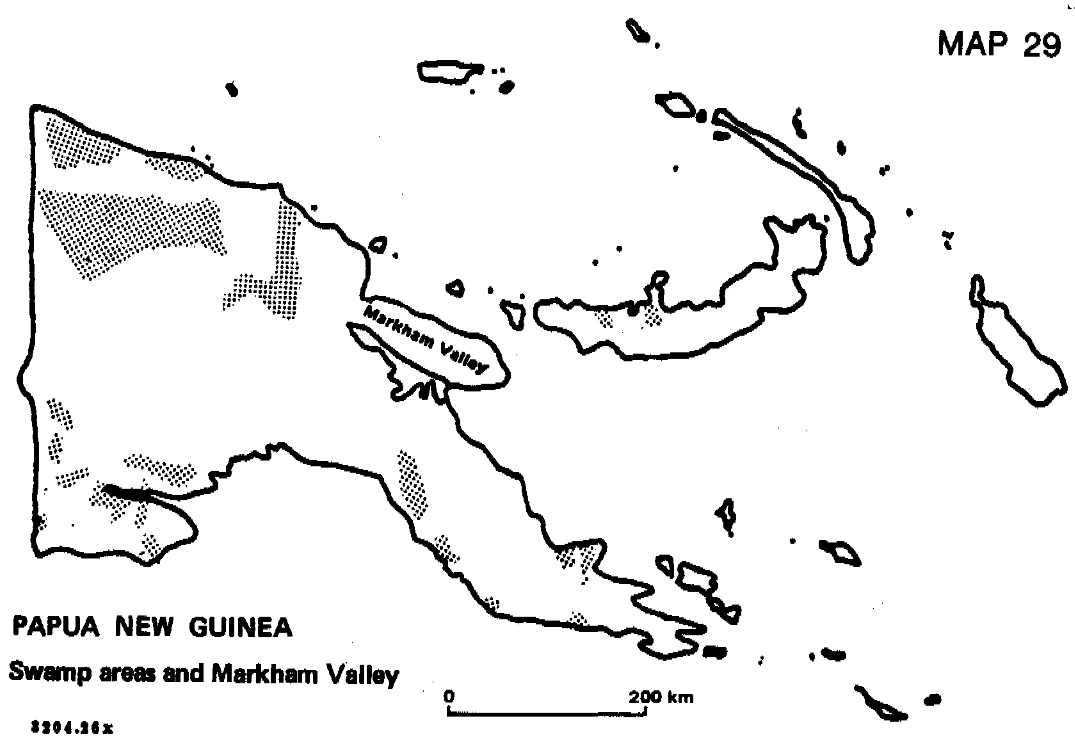
These volcanic areas present special problems for ground-water development. The volcanic ash is extremely permeable, with the result that much of the precipitation infiltrates the soil, rapidly draining the volcanic area.

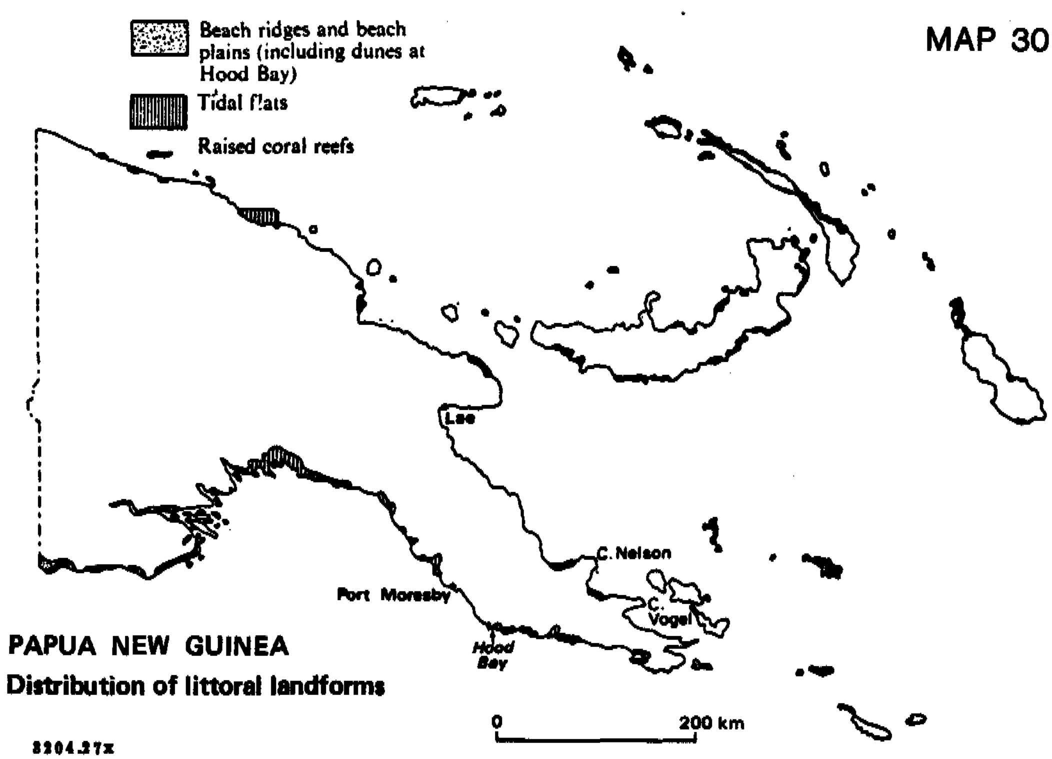
Karst regions

Three areas in Papua New Guinea are dominated by karstic land-forms (see map 32): on the mainland, a belt from the Gulf of Papua in the south-east to the border with Indonesia in the north-west; the western and eastern part of New Britain; and the north-western part of New Ireland. Besides these, several smaller occurrences of karst are found in the highlands, the Saruwaged Range and the westernmost part of the northern coastal ranges.

Map 29. Papua New Guinea: swamp areas and Markham Valley

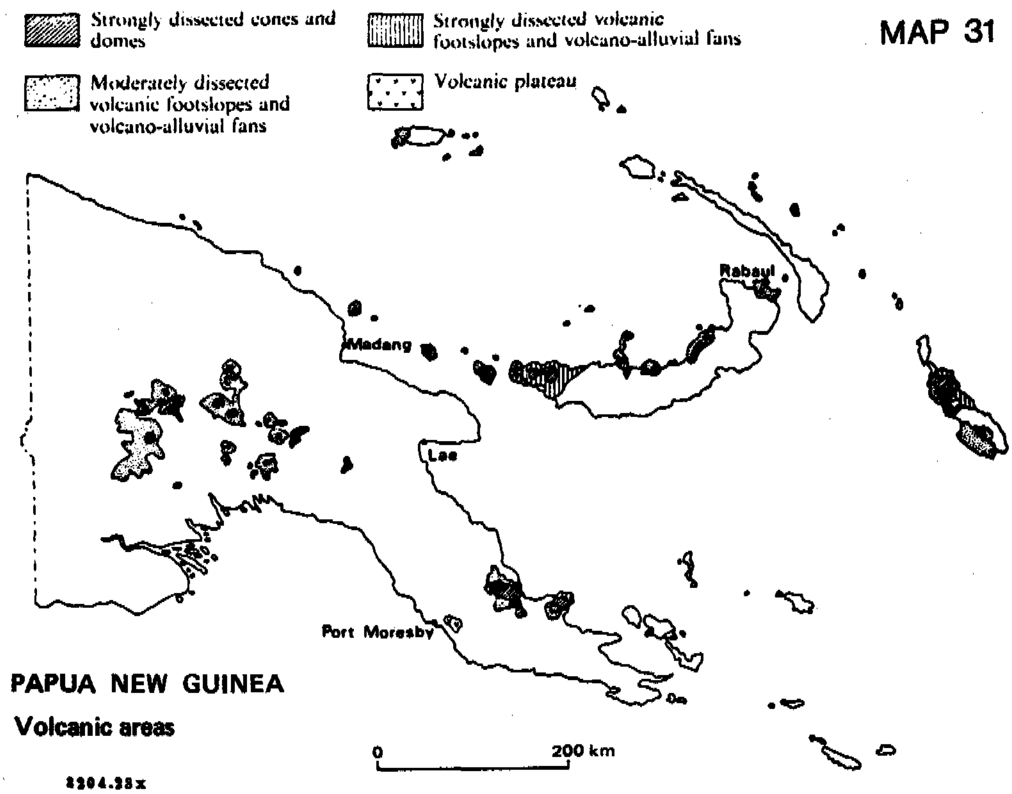
Map 30. Papua New Guinea: distribution of littoral land-forms

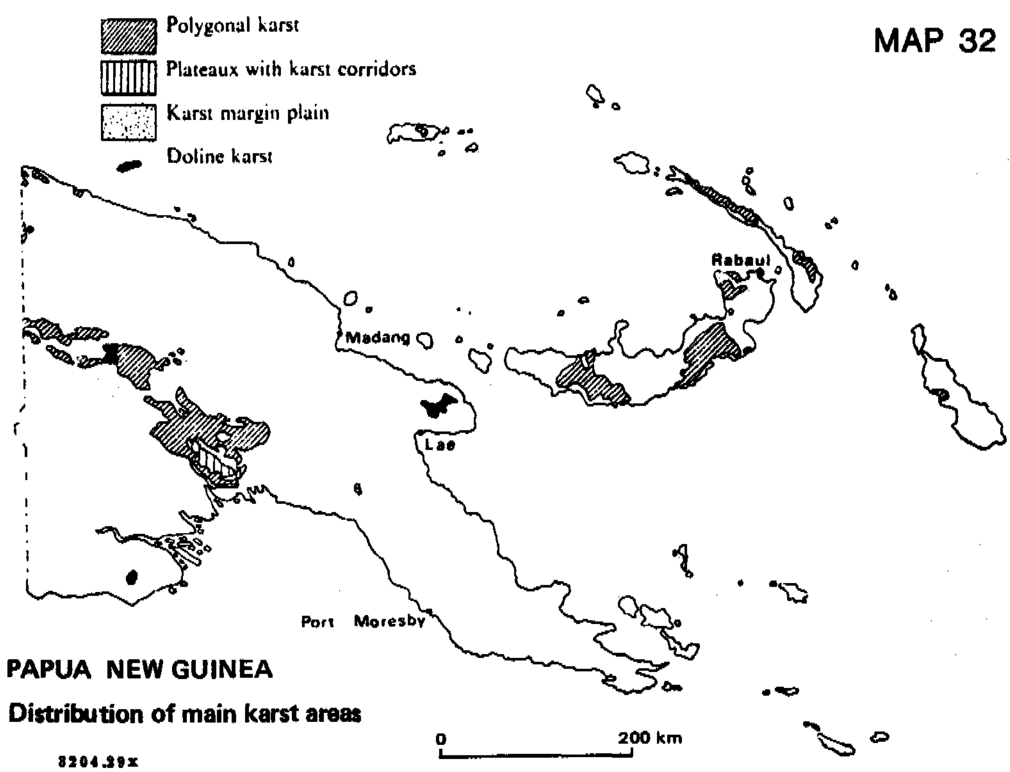




Map 31. Papua New Guinea: volcanic areas

Map 32. Papua New Guinea: distribution of main karst areas





The upper part of Alice River (Ok Tedi) drains an area characterized by limestone. An investigation of this catchment for hydropower potential revealed considerable uncertainties about some of the sub-catchment areas. In the earlier part of that study, it was apparent that the run-off was much greater than the rainfall in some places and less in others. This was ascribed to inaccurate maps, subsurface leakage to or from other catchments, or errors in the estimation of the mean catchment rainfall.

When more accurate maps and more data were available, it became clear that because of the very high rainfall in the area (6,000-8,000 mm/year) and the absence of any lakes, the area drained into the surrounding catchments via sink holes, solution cavities and the like in the underlying limestone.

In a small catchment study, the catchment area had to be reduced to 60 per cent of the apparent area in the hydrological model calibrated. The investigator concluded that this indicated that the loss of water from the catchment occurred at a relatively steady rate throughout the year and was not a function of the variation of the discharge in the streams.

In this region also, the Hindenburg Wall complicates the assessment of the drainage area because of numerous springs that issue from its base and scarp, due to chemical weathering of the limestone area above the Wall.

Markham Valley

Mountain rivers often carry heavy loads of sediment. When these rivers reach the low-lying flood plain of a valley or the coast, the stream velocity is suddenly reduced, leading to the deposition of sediments. The result is the formation of alluvial fans. The rivers will have gradients similar to the fans and flow in highly unstable, wide, braided flood-plains with constantly shifting sandbars and channels. Active fan-building takes place under the present humid tropical rain forest conditions and is widespread in the tectonically most active part of Papua New Guinea.

Extensive fan-building is found in the Markham-Ramu valleys south of the actively rising Saruwaged and Finisterre Ranges (see map 29 above) and along the coastal areas between the Huon Peninsula and Astrolabe Bay to the north of these ranges. Other important fan areas are the Angabunga River, the Fly River and the Sepik River.

Numerous streams from the Saruwaged Range discharge into the valley, forming a series of fans. A significant portion of the river and stream waters is lost by seepage and infiltration into the ground-water reservoir. Since the sediment yielded by these mountains countains a large coarse fraction it makes a good aquifer.

Climate and vegetation

Vegetation

One of the outstanding characteristics of the country is the extensive cover of forest vegetation. Paijmans (1976) recognizes seven major vegetational environments. Four coastal and lowland zones below 1,000 m account for 28 per cent of the vegetation cover and are controlled by drainage conditions, water régime and type of water; three other zones, accounting for 72 per cent of the cover, are controlled principally by climatic changes with increasing altitude.

About 15 to 20 per cent of the total vegetation cover comprises climax and disclimax savanna. Climax savanna is a reflection of seasonal rainfall conditions in the Markham Valley and along parts of the south coast of the mainland, particularly the south-west corner of the Gulf of Papua coast between Kerema and Kwikila. In the highland areas savanna is the result of local climatic and soil conditions.

Disclimax savanna has been created extensively in the central highland areas of the mainland and along coastal stretches of the mainland and islands as a result of human pressure, in particular, the traditional practice of shifting agriculture.

Climate

Since the country lies between latitudes 0° and 12° S, under Koeppen's classification, the climate may be generally described as rainy tropical (Af). Geographical location, altitude and aspect may vary this generalization to give savanna (Aw), temperate (CF) and other more local climatic types.

The seasonal movement of the Intertropical Convergence Zone with its associated tropical air masses control the two principal wind directions which strongly influence the rainfall patterns of the country. From May to October, the south-east trades predominate, whereas from December to March, the prevailing winds are from the north-west. The high mountain barriers across the path of these winds, whose reach covers thousands of kilometres over tropical seas, induces regular heavy orographic convective rainfall on northern and southern slopes in the mountains themselves. Thermal convective rainfall is characteristic of the Fly and Sepik lowlands. Mean rainfall figures on the mainland range from less than 2,000 mm along the coast to more than 8,000 mm in some mountain areas. The island groups to the north and north-east receive between 3,000 and 7,000 mm of rain annually.

Areas receiving less than 2,000 mm of rain a year lie south-west of the Fly river; west of Lae in the Markham Valley, in the rain shadow of the Finnisterre-Saruwaged mountains to the north and the main central ranges to the south; other areas are the south-east parts of the north coast where the coastline runs parallel to south-easterly and north-westerly wind directions and local topography affects wind flow. The least amount of rain, less than 1,000 mm annually, falls in the Port Moresby coastal area. There the coastline runs parallel to the south-east trade winds and lies in the lee of the Owen Stanley range when the prevailing winds are from the north-west.

Seasonal variation in rainfall generally reflect location in relation to the prevailing winds and local topography. In the north coast, the maximum amount of rain tends to fall during the period of the north-west winds and in the south coast the maximum amount falls during the period of the south-east trades.

Evaporation rates range from less than 1,000 mm to more than 2,000 mm annually, depending on temperature and humidity régimes. Areas of highest evaporation rates are coincident with those of lowest rainfall and vice versa.

Annual evaporation rates based on adjusted class A pan values range from 1,250 mm in western highland areas to more than 2,000 mm in the Markham Valley, Goodenough Bay and the Port Moresby region.

Mean daily temparatures range between 21° and 34° C for coastal and lowland locations, and sub-zero values are experienced above 3,000 m. Seasonal variations are small.

Surface water

The coincidence of high and precipitous mountain ranges and abundant rainfall leads to high run-off over most of the country. Rivers are often steep and actively involved in fluvial erosional processes. The young mountain ranges are deeply incised by rapidly down-cutting streams, the sediment load of which is deposited as alluvial fans or in the swamps and deltas of the Sepik, Ramu, Fly, Kikori and Purari rivers and the depositional plains along the south-east coast. Large volumes of surface water are retained in the Sepik and Fly swamps. Extensive limestone and karst areas exist in the Kikori-Lake Kutubu area of the southern fold mountains, the Victor Emmanuel fold belt, the Saruwaged range, New Britain and New Ireland. There is little surface drainage in these areas despite high annual rainfall.

Run-off has been estimated for areas above 900 m elevation at 2,500 mm (Rosenthal, 1953); 800-1,300 mm (Sutton, 1955); and 2,100 mm (Aitken, Ribeny and Brown, 1972). At present there is no generally reliable estimate of run-off for the country as a whole.

Geology

Main geological zones

The Papua New Guinea mainland and its off-shore islands lie in a highly mobile zone of the earth's crust at the boundary of two major tectonic plates: the northward-moving Australian Plate and the westward-moving Pacific Plate. The boundary appears to comprise several smaller fragments of oceanic crust to the north and east. The interaction of these plates gives rise to three main geological zones in the Papua New Guinea region: the Australian Platform; the New Guinea Mobile Belt; and the Melanesian Oceanic Province.

Australian Platform

This zone lies at the south-west side of the country, occurring as a basement of Palaeozoic granitic and metamorphic rocks. Permian granites (240 million years old) are similar in age to the younger granites of the Cape York Peninsula in Queensland, Australia.

The stability of the Platform has permitted the deposition of a thick and uniform sequence of Mesozoic and Tertiary sediments. From the early Jurassic to the Tertiary, shales, siltstone and quartz sandstones were deposited, derived from the weathering and erosion of Australia. The early Tertiary was a dry-land period, but by the Oligocene a marine environment had been re-established. At that time there was little sedimentation from Australia, so that thick limestone and some marls could be deposited. The barrier reef began to form at that time. During the Pliocene, the northern end of the barrier reef and the central ranges of Papua New

Guinea were being uplifted, forming the spectacular folded and overthrust belt along the southern edge of the main range. Subsequent subaerial erosion has resulted in the impressive limestone cliffs of Western, Gulf and Southern Highlands Provinces.

New Guinea Mobile Belt

In contrast to the Australian Platform, continuous earth movements have initiated changes in erosion and deposition along the highland zone. The stratigraphic sequence is consequently complex with a wide variety of sediments interbedded with volcanic rocks from Eraly Jurassic to Late Miocene in age.

Mesozoic and Tertiary intrusive igneous activity created the source of economic copper and gold mineralization in intermediate and acid plutonic rocks (e.g., diorite, granodiorite and gabbro). The principal period of activity occurred during the Middle Miocene in association with a chain of island volcanoes along the Mobile Belt. Relics of this period appear as lavas, agglomerates, volcanic conglomerates and reef limestones capping the mountains of the highlands. To the south these sediments change from volcanically derived sandy sediments to the thick limestones of the Australian Platform. The existence of a trench south of the volcanic belt may have prevented volcanic sediments from reaching the platform.

Metamorphic rocks (including glaucophane schists) occur most extensively in the Owen Stanley Range at the eastern end of the mainland. They were formed along the Owen Stanley fault during the Oligocene by the upthrusting of the Papuan Ultramafic Belt (gabbro, dolerite and submarine lavas of oceanic origin) against the Australian continental plate. Further high pressure metamorphics (glaucophane schists and eclogite) and ultramafic rocks occur to the west along the northern edge of the New Guinea Mobile Belt in the lower Ramu and south Sepik areas.

The Aure Trough, which separates the Owen Stanley Range from the ranges to the west, was created during a continuous period of subsidence from late Oligocene to the end of the Pliocene. Sedimentation was derived from contemporaneous volcanism and the products of erosion. The sequence consists mainly of greywacke, siltstone, conglomerate, reef limestone and marine volcanics.

During the Late Miocene, sedimentation ceased with the start of major uplifting. Some marginal marine sedimentation occurred during the Late Miocene and Pliocene, derived mainly from intermediate and acid volcanic detritus from large sporadic strato-volcanoes. Deep erosion of old volcanoes occurred exposing their cores and, during the Pleistocene, glaciation of the higher volcanoes took place. There is evidence of continuing volcanic activity along the New Guinea Mobile Belt.

Melanesian Oceanic Province

This region comprises mainly sub-aerial and marine volcanoes and reef limestone except north of the Sepik where the mountain areas are metamorphic, possibly of continental coastal origin.

The oldest rocks are basic and intermediate volcanics and their sediments. Complex faulting and folding have occurred with slight metamorphism in places.

Intrusion by small Oligocene acid plutonics has given rise to some volcanically derived sediments lying unconformably on Eocene volcanics.

A brief cessation of volcanic activity during Early to Middle Miocene allowed thick limestones to accumulate on some of the older rocks. Volcanic activity resulting in acid to intermediate rocks began again and has continued from the Late Miocene to the present day. On Bougainville Island intrusive activity in the Pliocene has been exposed by erosion to reveal large porphyry copper mineralization.

Structure

The stable Australian Platform has suffered only minor faulting and warping. The overlying sediments are flat or gently dipping.

Strong deformation of the Platform's sedimentary sequence has occurred only adjacent to the New Guinea Mobile Belt, and appears to be of two different origins. The first has created the Mueller and Kubor Anticlines, near the border with Indonesia, and south of the Wahgi Valley, respectively, where large inliers of older rocks appear in the Tertiary sequences. The second is manifest in the Papuan Fold Belt stretching from the Gulf of Papua to the border with Indonesia. Here the Tertiary sediments have been deformed into long, steep or overturned parallel folds with horizontal axes broken by thrust faults. The basement rocks have remained largely unaffected by this folding.

The rest of the country has been subjected to intense stress since the Early Mesozoic, which has resulted in complex structural changes.

Most of the highlands between the Markham River and the border with Indonesia is broken into a mass of fault wedges by faulting over hundreds of kilometres. Rocks have been broadly folded and steeply dipping blocks have great vertical throws sometimes thousands of metres high, possibly with large horizontal displacement. Small displacements may be indicated by offset rivers.

To the north-east and east the Markham-Ramu fault zone and the Owen Stanley fault delimit the New Guinea Mobile Belt. The Owen Stanley fault runs for more than 400 km and may represent the western edge of the Solomon Oceanic Plate. A recent displacement of 4 km is evidenced by the displacement of river courses near Salamaua but an older displacement of 100 km is indicated by the separation of the northern end of the Papuan Ultramafic Belt.

The Markham-Ramu fault zone separates the Tertiary oceanic rocks of the Huon Peninsula from the Mesozoic and Tertiary rocks of the New Guinea Mobile Belt and is the north-western extension of the New Britain Trench.

The structural trend of the Aure Trough lies at right angles to the main structural trend. Faulting and folding follow the structural grain. Folding is similar to that in the Papuan Fold Belt.

The Sepik basin appears to be a recent down-warping caused by the northward movement of the Australian Plate and it has been suggested that it is a situation analogous to that of the Aure Trough.

Earthquake and volcanic activity

Between 5 per cent and 10 per cent of the world's earthquakes occur in the region. The principal earthquake zones lie along tectonic plate boundaries, the most active being along the northern margin of the Solomon Sea Plate, where the boundaries are defined by the island areas of New Britain, New Ireland and Solomon Islands. The earthquake pattern has typical Benioff zone characteristics. Lesser seismic activity occurs in the north-west of the mainland where the Indian-Australian, Pacific and South Bismarck Sea Plates are interacting in a mountain-building process.

Volcanic activity generally parallels the structural trend of the region. Three major zones of activity exist:

(a) A 900 km arc from Bam near Wewak to Rabaul, east New Britain, parallelling the Markham-Sepik depression and the New Britain Trench;

(b) A 600 km arc parallel to the Solomon Trench from Solomon Islands through the islands off the east coast of New Ireland;

(c) A 300 km arc from Mount Lamington on the eastern mainland through the d'Entrecasteaux Islands.

The Doma peaks and Mount Yelia in the highland provinces are also regarded as volcanically active.

Ground-water investigations

Institutional set-up

Ground-water investigations at a professional level started in the mid 1960s. Since 1974, hydrogeological services have been provided on a regular basis by the Geological Survey of the Ministry of Minerals and Energy. General hydrogeological studies have not been undertaken because of lack of staff. Most work is of an advisory nature, field studies being carried out at the request of public and private developers on an ordinary consulting basis. Investigations provide the developer with information regarding the potential and quality of subsurface waters and aquifers. Wells and well-fields are designed and construction, monitoring and testing of wells is undertaken.

Data on wells and bores are stored in a well archive, and comprise identification of well location and ownership, data on drilling and well capacities. Data on water quality will normally be collected only if such data are needed for ensuring health standards in respect of a public water supply. In the case of small wells, the owner may decide that a chemical analysis is not worth the cost. All wells known to the Geological Survey are registered. But the Survey does not have on record information about all the minor wells drilled by plantations and settlements. At present, about 1,000 wells are registered; and the yearly increase is 30-50 wells.

Continuous data recording from special observation wells is not undertaken, though there are plans to collect such time-series data from a few wells. Because the existing data archive is relatively small, no efforts have been made to store the hydrogeological data in a computer archive.

Between 1976 and 1979 hydrogeological work, amounting to 2.5 man-years annually, was carried out by a hydrogeologist and a technical assistant, as well as by geologists and geophysicists, whose services were utilized on a part-time basis. Between 10 and 20 schemes are investigated each year.

The Geological Survey has at its disposal the following equipment: a Cintrex 2.5 KVA Time Domain IP transmitter; a Cintrex Time Domain IP R8 receiver; various low-power (48-400 V) resistivity transmitters; various receivers sensitive to one microvolt; an SIE 24-channel seismic refraction recorder; a Proton magnetometer; and various gravity meters.

Geophysical techniques are the principal prospecting methods, supplemented by local geological investigations. Electric log methods (self-potential and point resistivity) are commonly used. Resistivity is particularly useful in coastal areas where the high porosity and permeability of coral limestones permit intrusion of saline water. Occasionally refraction seismic sounding may be used (George, 1977).

Main aquifers

Five broad hydrogeological units, described below, may be defined.

Pre-Quaternary bedrock

Metamorphic, intrusive igneous and sedimentary rocks form the basement of most of the axial ranges of Papua New Guinea. They are characterized by generally low primary porosity and permeability. Most available ground water occurs in open joints and fractures, although some sandstone formations may form porous rock aquifers. Since the ground-water potential is relatively low, these rocks are generally avoided during ground-water investigations. Most areas underlain by such rocks are mountainous and sparsely populated, so that the demand for water is small.

Volcanic rock

Andesitic and basaltic lavas and pyroclastics of the Cenozoic volcanic centres comprise this broad hydrogeological unit. The massive lava flows are generally poor aquifers but, where dissected by closely spaced, open joints, are capable of storing and producing large quantities of ground water. The brecciated surface of some lava flows, as well as interbedded pyroclastics reworked pumiceous tuffs and buried alluvium, are potentially good aquifers provided they are not too weathered. Buried soils and fine-grained tuffs form barriers to ground-water movement and may result in perched ground water or act as confining beds.

Although there are widespread areas of volcanic rocks in Papua New Guinea, many of which have good ground-water potential, few bores and wells tap this type of aquifer. The main reason for the lack of development is the relatively low success rate of past drilling in volcanic rocks. For example, at Kuriva resettlement scheme, 40 km north-west of Port Moresby, the success rate is about 45 per cent for bores sunk in weathered, jointed agglomerate. The most intensely developed volcanic aquifer underlies the township of Rabaul, which is located on the floor of a caldera. Much of the volcanic debris underlying the town is reworked pumiceous tuff which forms a good aquifer. Some bores produce about 45 m^3/hour with very little drawdown (Pounder, 1973).

Springs are common in the volcanic areas and constitute a significant proportion of village water supplies on Bougainville, New Ireland and New Britain. During the Second World War, the Japanese developed a number of springs in and around Rabaul, many of which are still utilized. The most common spring locations are at the basal contact of unconsolidated pumiceous tuff overlying massive agglomerate, lava or bedrock, or at the base of open jointed lava flows overlying buried soils or fine-grained tuff horizons. Spring discharges are small, generally less than 2 m^3/hour; most springs are perennial, but some of the smaller ones dry up over extended rainless periods.

Karst limestone

There are extensive areas of limestone throughout Papual New Guinea on which karst features are developed. In most of these areas the limestone has many caves and sink-holes and although the annual rainfall may be greater than 2,500 mm there is very little surface drainage. Ground-water potential is high.

With the exception of areas of poorly developed karst on some of the larger coral islands, for example, Trobriand Islands, there are no known bores or dug wells tapping the karst limestone aquifers. Spring development, however, is common in the Southern Highlands District. Spring discharge in the limestone is variable, but most tapped springs discharge less than 2 m^3/hour. Larger springs with flows of the order of 2.5 m^3/Dsec have been observed in some areas. Since many of the karst limestone areas are sparsely populated, there is little demand for water at present.

Coastal sediments

Coastal sediments in Papua New Guinea include two main lithologies: raised coral limestone, which is generally referred to locally as "karanas" or "coronus", and alluvial and marine detrital sediments, including gravel, sand and mud. This hydrogeological unit is characterized by the risk of salt-water intrusion. Generally, the unit extends no farther than 500 m inland from the coast, where it grades into karst limestone or unconsolidated sediments. The karanas is riddled with solution cavities and is commonly loosely cemented, resulting in high porosity and permeability. On low islands and coastal plains composed of karanas, the water table is usually only a few metres above mean sea level, which means that the fresh-water/salt-water interface may be relatively shallow. For example, at Kavieng, which is located on a raised coral platform about 3 m above mean sea level, the water table is less than 1 m above mean sea level and the fresh-water/salt-water interface (defined by a geoelectric survey) forms an irregular surface 1-12 m below mean sea level (Kidd, 1974).

Because many towns and large villages are located on the coast, there is a considerable demand for supplies of good clean water. Ground water has the potential to meet this demand, but development of the ground-water resource requires close supervision in order to preserve the fresh-water/sea-water balance. Already a number of villages and towns have suffered salt-water contamination of their bores, which in most cases has been caused by drilling the bore too deep.

Unconsolidated sediments

Alluvial, lacustrine and fan deposits make up this broad hydrogeological unit, which is confined to valleys and depressions. The two largest areas are the extensive alluvial plains of the Fly and Sepik-Ramu basins where population is sparse and ground water little developed. In the large basins the alluvium is mainly silt and sand with some gravel, whereas in the smaller mountain-rimmed basins and tectonic depressions, such as the Markham and Wahgi Valleys, coarse gravels or lacustrine muds are abundant. Ground water is generally obtained from clean sand aquifers in the large basins, and clean sand and gravel aquifers in the smaller basins. Both confined and unconfined aquifers are common, but there are few flowing artesian bores.

Most of the water bores so far developed in Papua New Guinea are located in this unit and the rate of successful bores is high. Bores producing 40 m^3/hour with a drawdown of 1-2 m are common and specific capacities are generally high with the exception of some bores in the large basins, such as the Sepik-Ramu basin, where fine sediments predominate. Quantities of ground water withdrawn from this unit vary from less than 1 m^3/day in some small village bores to 8,000 m^3/day from 10 bores in the Lae city water-supply scheme.

The shallow water-table in the lower wetter areas permits the development of sanitary dug wells. On the higher parts of alluvial fans and high river terraces the water-table may be deep, making dug wells impracticable and adding extra depth to drilling.

Gaps in knowledge

Since no regional investigations for ground water have ever been undertaken and investigations to date have been of very localized interest there is clearly a vast area of the country the ground-water potential of which can only be guessed at. Geological mapping by the Geological Survey and run-off investigations by the Bureau of Water Resources give some guidance as to location and discharge of aquifers.

Ground-water investigations are likely to continue on the same basis as previously. There is currently no plan to undertake any regional programme of ground-water research, largely owing to the widespread abundance of surface water.

Ground-water quality

The bacterial quality of most ground water in Papua New Guinea is good. However, shallow dug wells in highly permeable sediments located near latrines or waste disposal sites are susceptible to bacterial contamination.

The chemical quality of the ground water is also generally good. The amount of total dissolved solids varies but is usually below the standard of 1,500 parts per million set by the World Health Organization, with the exception of a few bores near thermal areas and close to the sea, where some excessively high values have been recorded.

Bicarbonate is the dominant anion in ground water obtained from all five hydrogeological units, with chloride becoming dominant in some coastal areas which are subject to salt-water contamination. Calcium and sodium are generally the most common cations.

Some ground-water aquifers near recently active volcanoes and fumarolic areas are warm and have a high fluoride content. For example, the fluoride content of the ground water from the eastern sector of Rabaul township is in excess of (and, in three bores, as much as double) the 1.5 parts per million maximum allowable level for drinking water.

Most ground water in Papua New Guinea is hard to very hard, according to the United States Geological Survey classification.

Ground-water development

The Government, through the Ministry of Minerals and Energy, and two commercial companies are involved in the drilling of wells for water (see table 32).

Table 32. Papua New Guinea: drilling organizations

Organization	Number of drills		Annual Metreage	Number of Drillers	Training
	Rotary	Percussion			
Ministry of Minerals and Energy, Port Moresby		4	1,000	1	In-service
New Guinea Water Drillers, Lae		5	500-5,000	5	Local
United Geophysical Corporation, Madang	1		300	1	Non-National

Since the country has an abundance of surface water and since there are few large-scale consumers, such as heavy industry, ground-water resources have not been extensively developed. However, there is an increasing use of ground water as a source of reliable high-quality water. The high bacterial content of many rivers - caused by village wastes and free-range pigs - has encouraged some development of ground water. A survey of village water supplies conducted in 1974 indicated that 34 per cent of the villages visited relied on ground water from bores, dug wells or springs (Jacobson and Kidd, 1974).

There has been some development of ground water for stock watering and irrigation, particularly in the Markham Valley (Jacobson, 1973) where there are more than 40 boreholes. Recent investigations have been undertaken in the Safia Valley (Northern Province) to determine ground-water potential for a large cattle ranching project (George, 1978).

The Department of Works and Supply is currently submitting proposals for the greatly increased development of ground-water resources in urban areas. Table 33 shows projected yields for ground-water development programmes already in progress (Hayward, 1979).

Table 33. Papua New Guinea: urban ground-water development in progress

Town	Production date	Projected yields (m^3/day)	Status
Lae	1979	3,520	Currently drilling
Madang	1979	1,231	Currently drilling
Vanimo	1979	450	Currently drilling
Rabaul	1979	2,000	Producing
Popendetta	1979	1,000	Trial
	1989	2,000	
Kavieng	1979	1,000	Ready for production
	1989	2,000	
Kimbe	1980	1,000	Ready for production
	1989	2,000	

The Asian Development Bank is currently undertaking a feasibility study of alternative schemes for the long-term development of rural and urban water supplies throughout the country. The adoption of all or part of the recommendations resulting from the study may require the development of high-quality ground-water resources.

The difficult drilling conditions in the country and high costs of casing and transport make the commercial development ground water expensive. An average shallow bore and hand-pump installed by a commercial driller costs more than K1,000 (approximately $1,404 in 1979) while bores in areas of deep aquifers (deeper than 30 m) may cost more than K2,500 (approximately $3,510). These are high costs for a local government council budget, in which it is very likely that water supply will have low priority. Costs to the local authority can be reduced by as much as 50 per cent if drilling is undertaken by rigs of the Mines Division under the direction of the Geological Survey, provided that the drilling programme is sufficient to warrant the expense of transporting equipment into the area. A sanitary dug well or spring development may cost less than K300 (approximately $421), complete with hand pump, and thus is preferred to drilling wherever possible (Jacobson and Kidd, 1974). Funding for ground-water development may become available if the recommendations made by the Asian Development Bank are adopted.

The abundant surface water is likely to satisfy most rural requirements in most areas for the foreseeable future.

Bibliography and references

Only one collation of bibliographical material has been compiled in the country. Published by the Geological Survey, it provides information on published and unpublished material issued between 1961 and 1973. Its 59 entries include unpublished reports of the Geological Survey of Papua New Guinea (Note on Investigation Series) and the Bureau of Minerals Resources (Record Series). Most of the references cover specific site investigations and omit other aspects of ground water, such as thermal springs, karst hydrology and ground-water problems in engineering construction. More than 30 reports and papers have since been published, the majority being site investigations by the Geological Survey. No regional studies have been undertaken.

Details of bores and wells are on record at the Geological Survey.

Hydrological maps are confined to the localities of site investigations.

Selected references are as follows:

Aitken, A. P., F. M. J. Ribeny and J. A. H. Brown. The estimation of mean rainfall and run-off over the Territory of Papua New Guinea. Civil Eng. Trans., vol. CE14, No. 1, April, 1972, Australian Institute of Engineers.

Beca, Carter, Hollins and Ferner (Papua New Guinea) Pty. Ltd., Consulting Engineers. 1976. Water supply schemes for Lae, Mt. Hagen, Wewak, Madang.

Bielefeld, R. J. 1977. Kavieng water supply. Geological Survey of Papua New Guinea, Report No. 77/11.

Bureau of Water Resources and United Nations Development Programme. 1979. Brief Survey on Groundwater resources in Papua New Guinea. Bureau of Water Resources, Papua New Guinea, Report No. 5/79.

Denham, D., and G. A. M. Taylor. 1974. Earthquakes and volcanoes. Papua New Guinea Resources Atlas, E. Ford, ed., pp. 6 and 7.

Dow, D. B. 1974. Geology. Papua New Guinea Resources Atlas, E. Ford, ed., pp. 4 and 5.

Ford, E. 1974. Climate. Papua New Guinea Resources Atlas, E. Ford, ed., pp. 8 and 9.

George, E. 1977. Hydrological investigations. Geological Survey of Papua New Guinea, Report No. 77/10.

__________. 1977. The drilling and testing of an interim production bore at Beon, Madang. Geological Survey of Papua New Guinea, Report No. 77/20.

__________. 1977. Exploratory drilling for groundwater at Madang. Geological Survey of Papua New Guinea, Report No. 77/21.

__________. 1978. A manual for groundwater exploitation in Papua New Guinea. Geological Survey of Papua New Guinea, Report No. 78/13.

Gough, J. A., and C. H. Kidd. 1976. Karst in the Upper Purari and Kikori River basins. Geological Survey of Papua New Guinea, Report No. 76/7.

Gough, J. A., and W. Guthrie. 1976. Village water supply survey Chimbu Province. Geological Survey of Papua New Guinea, Report No. 76/17.

Hayward, R., Principal Engineer, Department of Works and Supply, Port Moresby. Personal communication, 1979.

Jacobson, G. 1973. Bibliography of groundwater investigations in Papua New Guinea. Geological Survey of Papua New Guinea, Report No. 73/24.

Jacobson, G., and C. H. Kidd. 1974. Groundwater in Papua New Guinea. Geological Survey of Papua New Guinea, Report No. 74/16.

Kidd, C. H. 1974. Kavieng groundwater system. Preliminary study. Geological Survey of Papua New Guinea, Report No. 74/22.

__________. 1975. Village water supply, Chimbu District. Geological Survey of Papua New Guinea, Report No. 75/9.

Loeffler, E. 1977. Geomorphology in Papua New Guinea. Australian National University Press. Canberra.

McAlpine, J. R., G. King and K. Short. Climatic tables for Papua New Guinea. Division of Land Use, Technical Paper, No. 37. Commonwealth Scientific and Industrial Research Organization (CSIRO), Canberra.

National Weather Service. Monthly returns of climatic data (unpublished). Port Moresby.

Paijmans, K. 1976. New Guinea vegetation. CSIRO/Australian National University, Canberra.

Pounder, G. M. 1973. Summary of groundwater bore data, Rabaul, East New Britain District. Geological Survey of Papua New Guinea, Note on Investigation, No. 72-019.

Robbins, R. 1974. Vegetation. Papua New Guinea Resources Atlas, E. Ford, ed., pp. 12-14.

Rosenthal, C. C. 1953. Hydroelectric potential - Eastern New Guinea. Proc. Eng. Conference, Australian Institute of Engineers, Melbourne, pp. 96-102.

Snowy Mountains Engineering Corp. 1974. Papua New Guinea Water Resources, vols. 1 and 2. Office of Minerals and Energy, Port Moresby.

Sutton, A. A. 1955. Hydroelectric development in Papua New Guinea. Paper presented to the New Guinea Scientific Society, 27 June 1955. See "The assessment of the water resources of the Territory of Papua New Guinea", University of New South Wales, Water Research Laboratory Report No. 74, appendix X.

Area: 300,000 km^2

Population: 45 million (United Nations estimate, 1977)

General

Geographical conditions

The Philippine archipelago lies within latitudes 4.5° N and 21° N and longitudes 117° E and 127° E. The country consists of about 7,000 islands and islets. The two largest islands, Luzon and Mindanao account for two thirds of the area. The remaining groups of larger islands, composed mostly of the Visayas, are situated between Luzon and Mindanao (see map 33).

With a growth rate of 2.5 per cent to 3.2 per cent a year, the population is expected to increase to 83 million by the year 2000. About 80 per cent of the population lives in the rural areas.

Topography varies considerably - from the lowest marshland, plains and hills to mountain peaks and ranges, 1,000-2,000 m high (see map 34). Agriculture flourishes on the many plains which are recharged by rain water from the nearby mountain ranges. The plains are areas of high ground-water potential. Among the significant plains in the country are the central Luzon plain and the Cagayan Valley in Luzon island, and the Cotabato and Agusan plains in Mindanao.

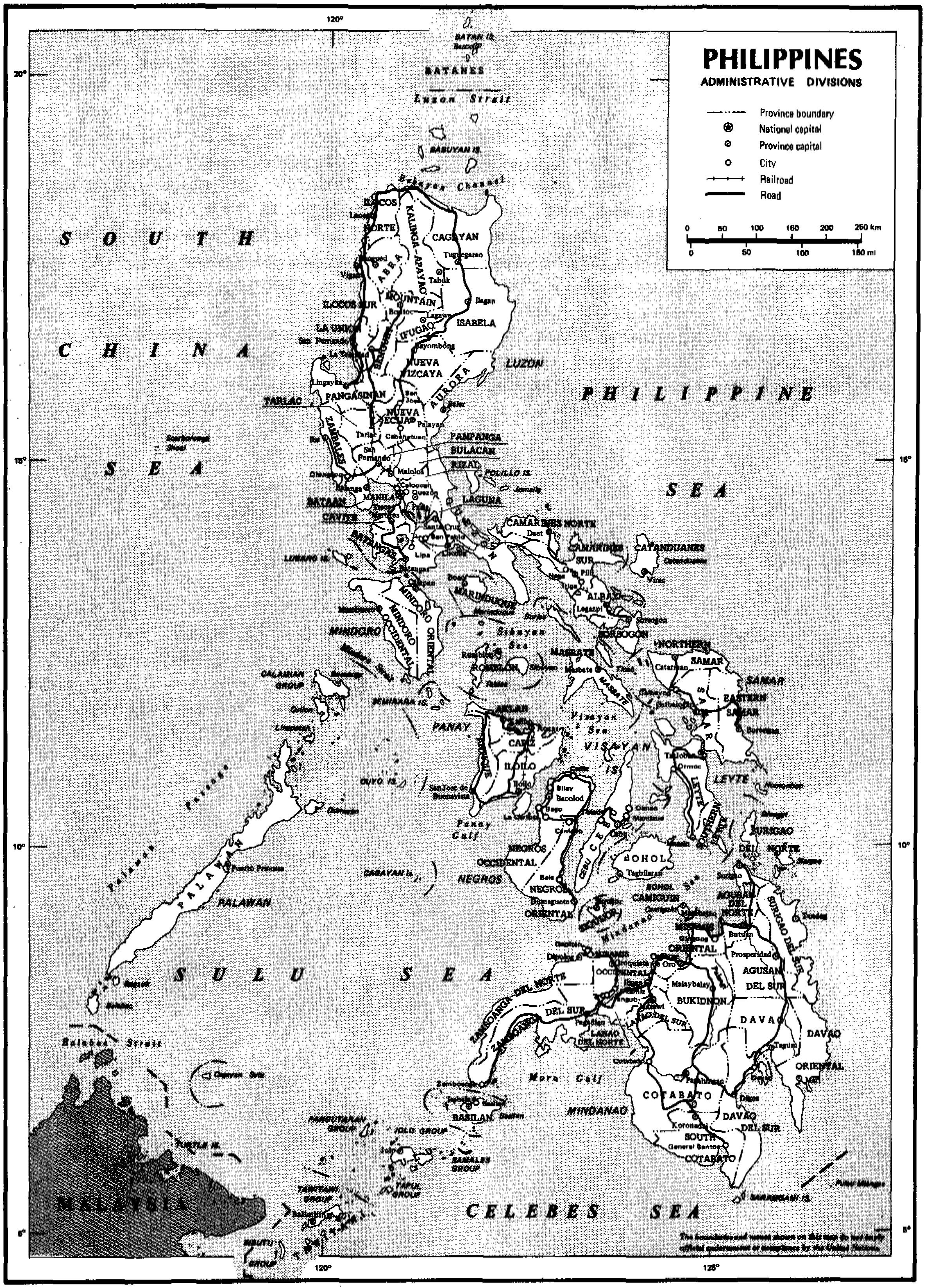
The rugged mountainous terrain in some parts of the country is rich in valuable minerals, metals and other important elements. These areas also catch more rainfall to replenish ground and surface reservoirs, both artificial and natural. The Cordillera Ranges that run along the boundary of the Ilocos and the Cagayan Valley regions (regions I and II), the Zambales Range - west of the central Luzon plain (region III), the Sierra Madre Ranges that run from north to south along the eastern Philippines, and the Caraballo Mountains that connect the Cordillera to Sierra Madre (boundary of regions II and III) are among the distinctive features of the country.

Climate

The country is situated in the tropical typhoon zone. An average of 19.7 tropical typhoons reach the country annually, on the one hand causing considerable destruction to property but, on the other hand, bringing rain and cooling the country's tropical atmosphere. Approximately 2,256 mm/year of rain falls in the Philippines. The average temperature is 26.2° C.

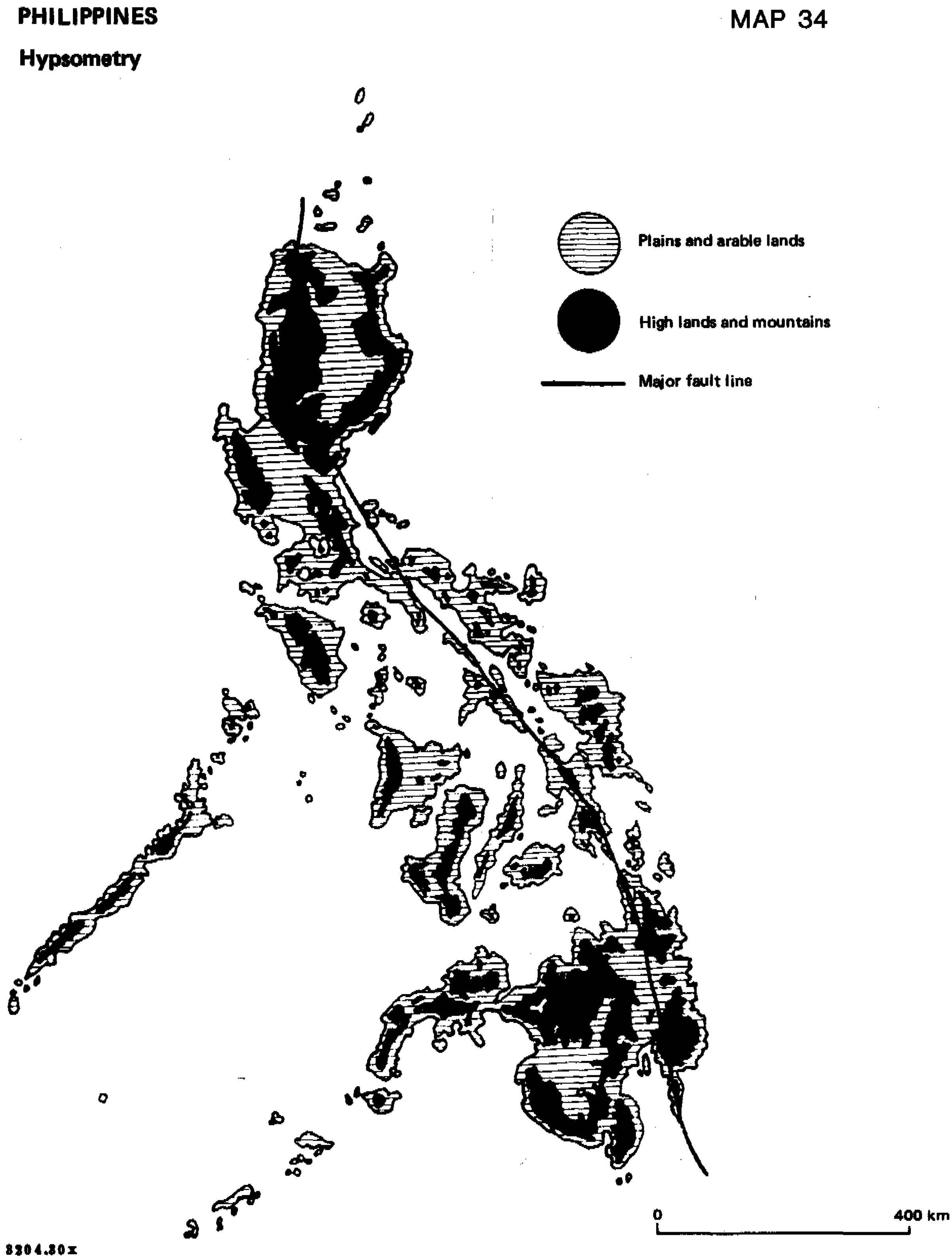
Map 33 [Philippines]

MAP 33



MAP NO. 3111 UNITED NATIONS
AUGUST 1980

[Map 34. Philippines: hypsometry]



The amount of rain that reaches ground-water reservoir systems through infiltration ranges from 5 per cent to 30 per cent. Part of this discharges through numerous springs and finds its way to the river systems as base flows. Another part, which percolates into the deep aquifer, goes directly to the sea. It should be noted that the Philippines, being composed of many islands, has a coastline of considerable length, about 16,000 km. Four types of climate have been described as follows (see map 35):

1st type: Two pronounced seasons: dry from November to April and wet during the rest of the year;

2nd type: No dry season with very pronounced maximum rainfall from November to January;

3rd type: Seasons not very pronounced; relatively dry from November to April and wet during the rest of the year;

4th type: Rainfall more or less evenly distributed throughout the year.

Surface-water resources

The Philippines has about 421 principal rivers, 59 lakes and numerous individual streams.

Figure V shows the availability of surface water. It may be noted that the total amount of surface water, available 90 per cent of the time, is sufficient to meet the water requirements of the country until or even after the year 2000. In this connection, it should be pointed out that the amount of available water referred to in figure V includes the shallow ground water that discharges through springs and/or river systems. In this situation, there is still a need to exploit ground water. Moreover, since surface water is not always available near the area where it is needed, its development may not be justifiable financially. In the case of ground water, the source can be made near the user, and generally no water purification systems are required, since ground water is usually suitable for direct domestic consumption.

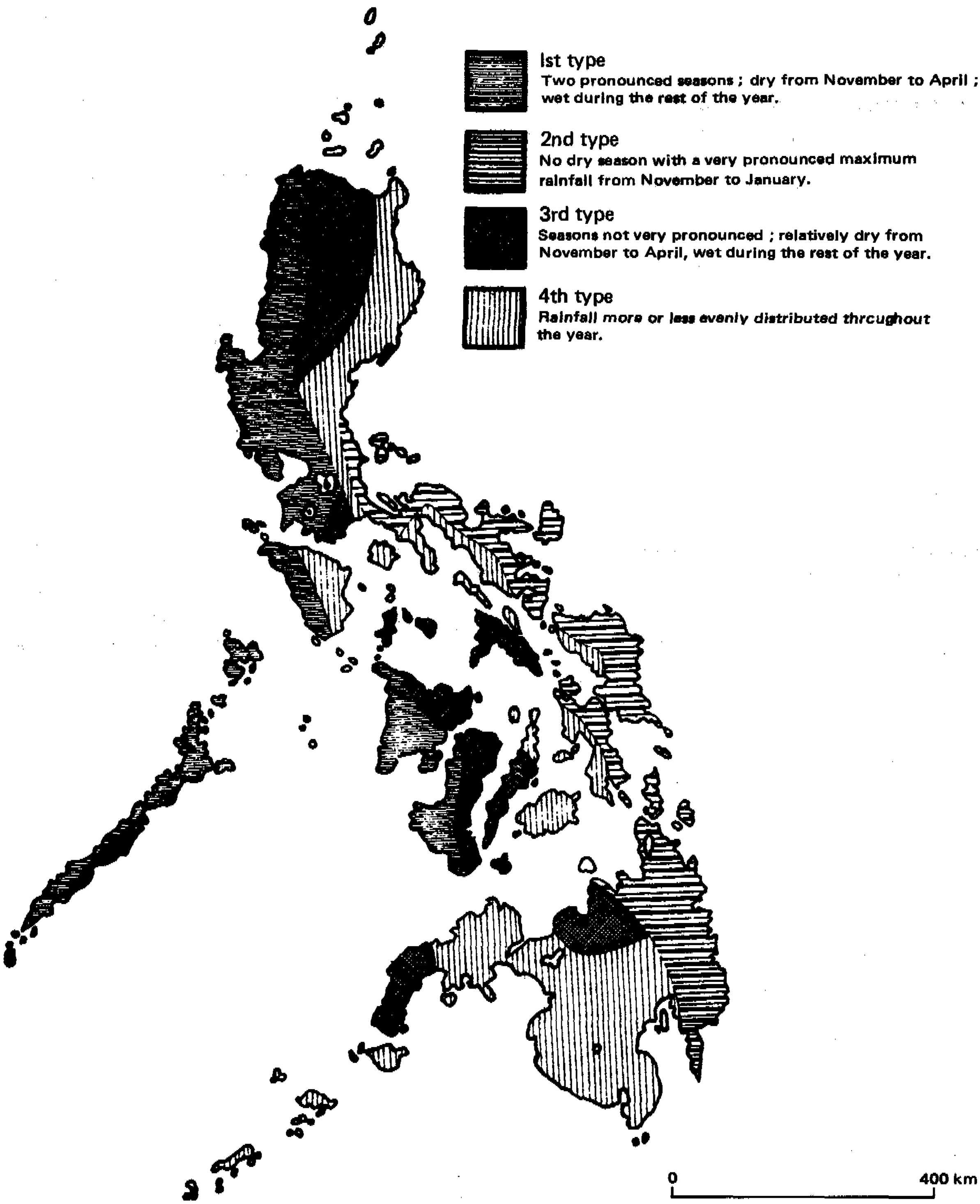
In order to have comprehensible units, the entire country has been divided into 12 water resources regions, as follows (see map 36):

1. Region I: Ilocos
2. Region II: Cagayan Valley
3. Region III: Central Luzon
4. Region IV: Southern Tagalog
5. Region V: Bicol
6. Region VI: Western Visayas
7. Region VII: Central Visayas
8. Region VIII: Eastern Visayas
9. Region IX: South-western Mindanao
10. Region X: Northern Mindanao
11. Region XI: South-eastern Mindanao
12. Region XII: Southern Mindanao

[Map 35. Philippines: climate]

PHILIPPINES
Climate

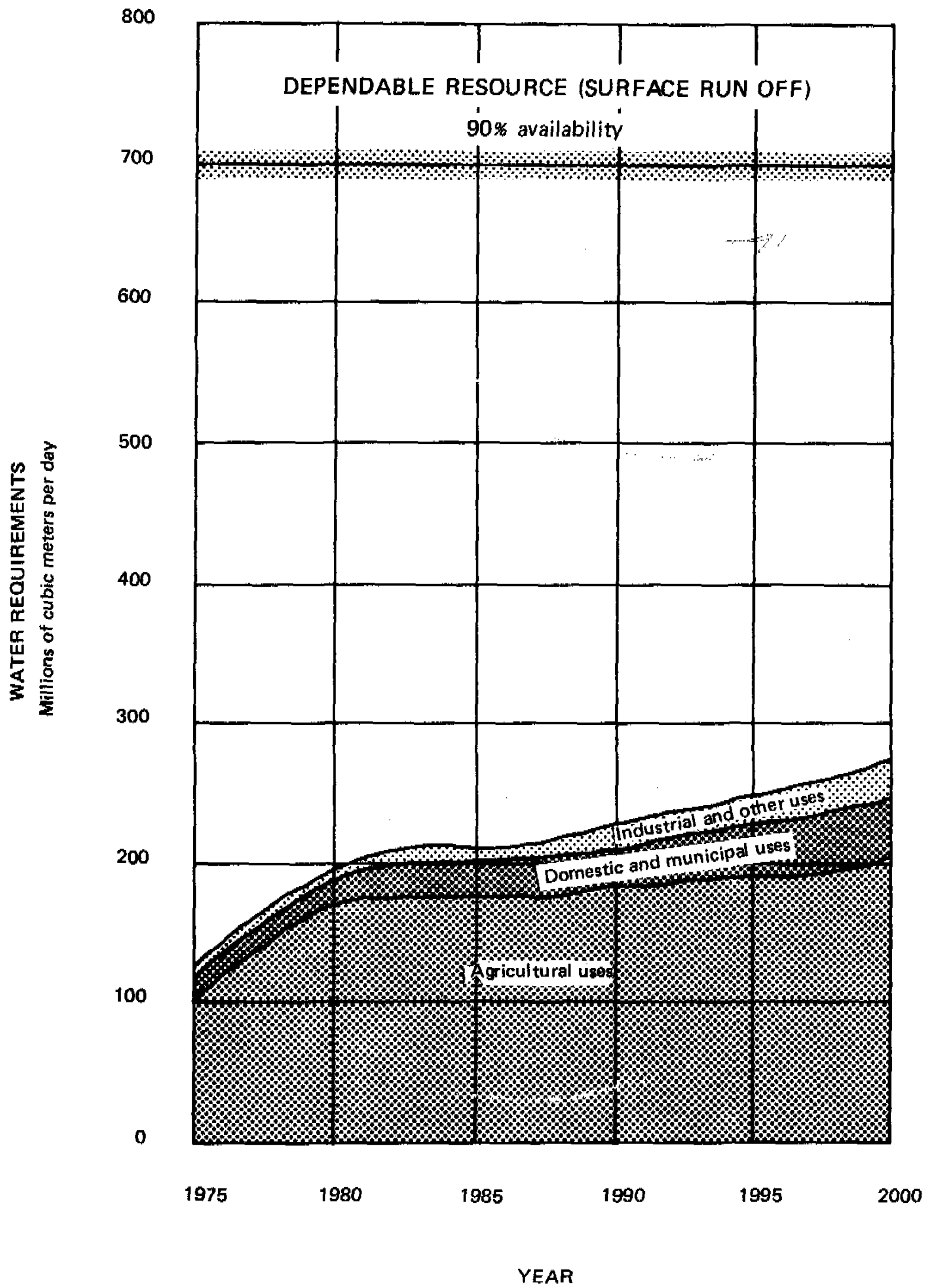
MAP 35



8204.8lx

[Figure V. Philippines: water requirements, 1975-2000]

Figure V. Philippines: water requirements, 1975-2000

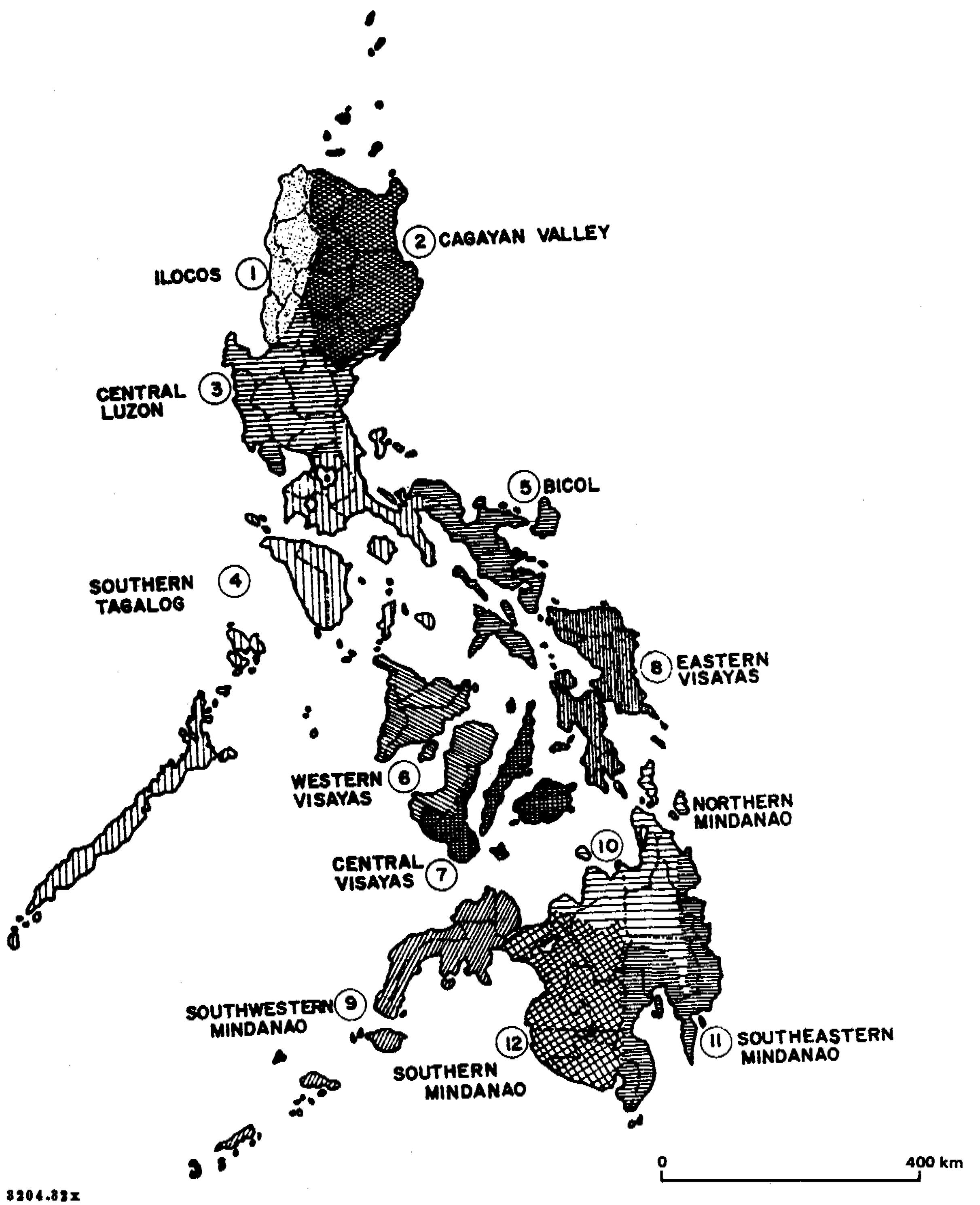


[Map 36: Philippines: water resources regions]

PHILIPPINES

Water resources regions

MAP 36



Geology

The country is located along the earth's volcanic belt. According to the records of the Commission on Volcanology, a total of 44 volcanoes have been registered, 13 of which are active. In this setting, the Philippines has considerable areas of volcanic formations, the younger portions of which yield a considerable amount of ground water.

A major geological fault line traverses from north to south, passing through regions I, V, VIII, X and XI (see map 34).

Generally, the country's geology is highly complex. The Bureau of Mines has made three general classifications, namely, sedimentary and metamorphic areas; volcanic areas; and igneous areas. The first classification consists of approximately 176,000 km^2; the second, 87,566 km^2; and the third, 36,434 km^2.

Sedimentary and metamorphic areas are classified into 10 categories. Volcanic and igneous are divided into nine and four time periods, respectively.

The structure of the sub-surface is generally made up of Tertiary and Quaternary sedimentary rocks which are composed of fine to coarse elastic materials. They originated in a marine and continental environment, particularly a fluvial one. In some basins, these geological formations are mostly unconsolidated, the thickness easily exceeding 50 m; for example, in Central Luzon. Pyroclastic Tertiary and Quaternary rocks (volcanic) very commonly are interbedded with the above-mentioned clastic sediments. On the other hand, Mesozoic sedimentary rocks are predominant in the sub-structure of some areas.

Ground-water resources

Ground water is found in all types of rocks. However, significant amounts of water exist within the unconsolidated rocks of both sedimentary and volcanic formations. Ground-water occurrence in clastic sediments, as well as in limestone and volcanic rocks, depends mainly upon the secondary permeability of the rocks, which varies with the existence, distribution and frequency of fissures, fractures, faults, cavities in karstified limestone etc. Some ground-water-related features are shown in table 34.

If ground-water development and ground-water exploration are two separate exercises, ground-water development in the Philippines precedes exploration. According to records, ground water was utilized during the Spanish régime (1521-1898). However, the level of exploitation during that time was confined to shallow hand-dug wells.

The drilling of deep wells was started by the Bureau of Public Works (BPW) in 1904 and continued during the American occupation. Hand-operated drilling outfits were used in the vicinity of Manila. In 1912, deep wells were drilled by mechanical means, particularly the Columbia steam-drilling machine.

BPW, through the Wells and Spring Section, is responsible for drilling wells. Diesel or hand-operated outfits are used, depending upon the geological conditions of the area. The Wells and Spring Section has on record a total of 30,000 wells.

Table 34. Philippines: main ground-water-related features

Region a/	Length of shoreline (km) Sea	Large natural lakes	Area (km²)	Mean annual temperature (° C)	Average annual rainfall (mm)
1	329		14,400	26	2,878
2	538		34,500	23.6-26	2,083
3	648		23,600	27	3,045
4	3,851	344	46,500	27	1,250
5	1,954	38	17,600	27	2,347
6	1,150		20,200	27.5	2,500
7	1,296		14,900	27	1,500
8	2,005		20,400	27	2,300
9	2,628		20,600	25	1,750
10	937	46	24,300	26.7	2,389
11	1,170		24,900	27.5	2,300
12	405	106	31,900	23.6	2,032
Total	16,937	534	293,000	26.22 (average)	2,256 (average)

a/ See map 36 above.

BPW initiated the establishment of ground-water observation networks. At present, there are about 739 observation wells, mostly concentrated in Central Luzon, the Cagayan Valley, and the Agusan and Cotabato Basins. They were constructed by the Water Resources Survey of BPW, which also operates them. Unfortunately, data collection from these observation wells ceased in 1972.

The National Irrigation Administration (NIA), entrusted with a major task in the country's food production programme, has constructed several observation wells in various pilot areas, for example, Laguna, Nueva Ecija, Tarlac and Pangasinan. In many cases, the exploratory wells of NIA are so designed and located that they can be used for production purposes.

Entrusted with the responsibility of co-ordinating the exploitation of the country's water resources, the National Water Resources Council (NWRC) is spearheading a resistivity survey to determine variations in ground-water potential in the country. The same agency also registers both surface-and ground-water users and, at the same time, gathers available data on ground-water wells.

There are no uniform standards and/or systems for the collection of data on ground water in the Philippines (NWRC has recently developed a manual on data standards). For these reasons, collection of ground-water data is still far from adequate. Each agency and/or each well owner or driller collects the data necessary to meet specific project needs.

From the output of this unco-ordinated data collection system, NWRC is at present assembling and synthesizing information in order to gain some idea of the very complex ground-water situation of the Philippines. The assessment of ground water, presented below, is based on that data.

The total amount of ground-water storage is estimated at 260,000 million m^3 and the rate of net ground-water inflow at 33,000 million m^3/year. An equal amount of that inflow is assumed to be unusable, since it is believed to flush salt water. It may be interesting to note that, on the basis of those estimates, ground-water storage is numerically 4-10 times the net inflow. This means that if ground water is "mined" (i.e., more is withdrawn than flows in) replenishment of the empty aquifers may take only 4-10 years. Furthermore, the possibility of aquifer destruction or land subsidence is slight because most of the areas are hard-rock formations. Thus, in the Philippines, "ground-water mining" may be considered justifiable.

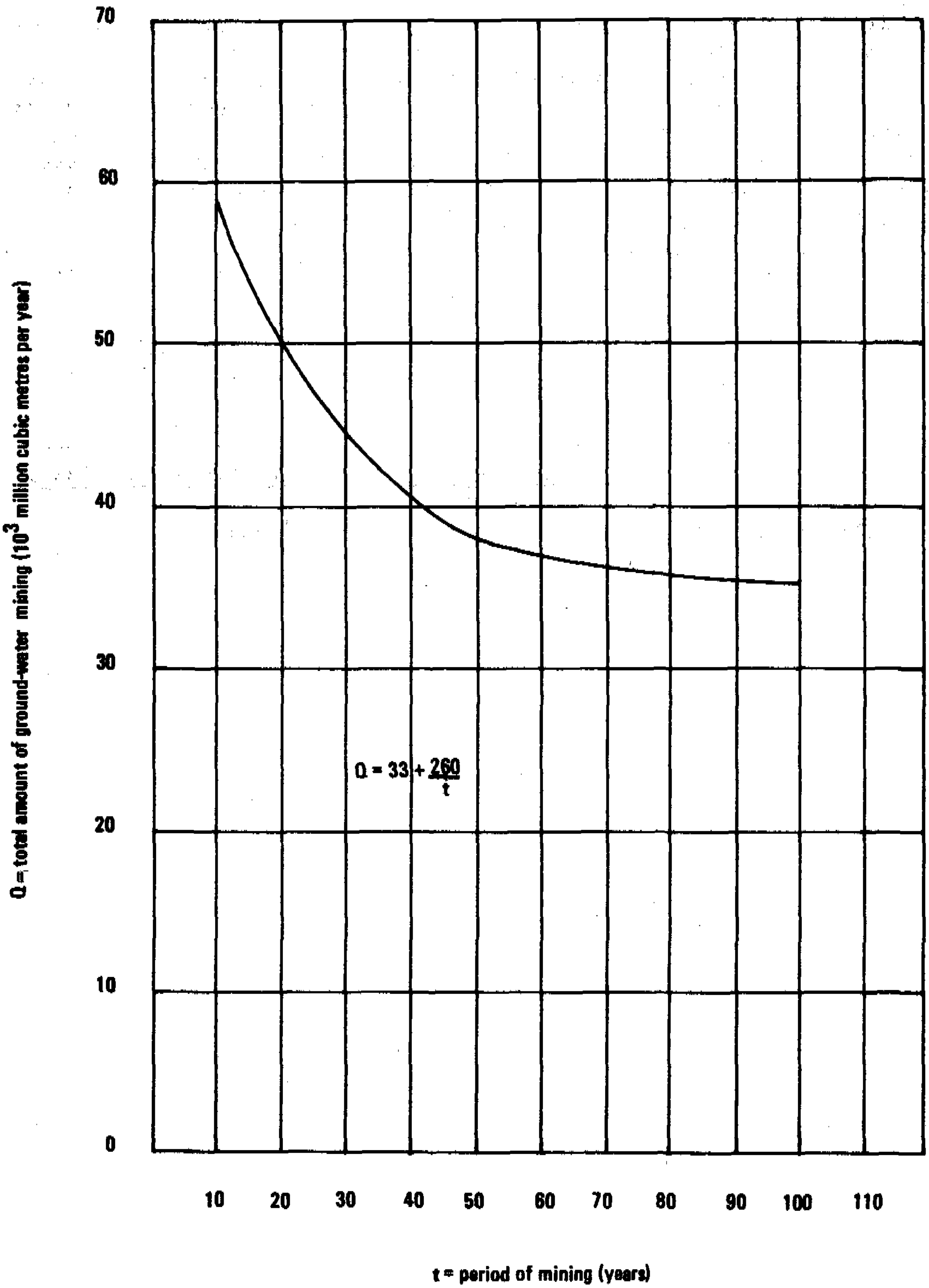
Some idea of the country's ground-water storage and inflow and its mining characteristics are shown in table 35 and figure VI.

Table 35. Philippines: ground-water macro-picture

Region	Estimated storage (Millions of m^3)	Estimated inflow (10 per cent of rainfall) a/	
		Gross	Net
		(millions of m^3/year)	
1	4,620	4,144	2,072
2	11,850	7,186	3,593
3	54,700	7,186	3,593
4	37,000	8,137	4,068
5	8,625	4,130	2,065
6	55,242	5,050	2,525
7	2,053	2,235	1,111
8	8,400	5,712	2,856
9	14,700	3,605	1,802
10	15,950	5,805	2,902
11	12,635	6,525	3,262
12	36,000	6,482	3,241
Total	261,775	66,197	33,090

a/ Fifty per cent of the estimated inflow is assumed to mix with or flush salt water.

Figure VI. Philippines: ground-water mining characteristics



Other parameters, such as ranges of depth, static water level, transmissivity and storage coefficient are indicated in tables 36 and 37.

Table 36. Philippines: statistics of ground-water level

Region	Number of wells considered	Number of wells with static water level at a depth of		
		0-3 m	3-6 m	6 m and over
1	1,407	538 (38)	463 (33)	416 (30)
2	1,558	220 (14)	358 (23)	980 (63)
3	4,173	2,262 (54)	988 (24)	923 (22)
4	3,726	1,287 (35)	509 (14)	1,930 (51)
5	1,607	897 (56)	426 (27)	284 (17)
6	1,886	958 (51)	616 (33)	312 (16)
7	1,633	297 (18)	370 (23)	966 (59)
8	1,498	599 (40)	378 (25)	222 (15)
9	821	331 (41)	224 (27)	266 (32)
10	1,667	784 (47)	357 (22)	526 (31)
11	952	339 (36)	189 (20)	424 (44)
12	118	40 (34)	15 (13)	63 (53)
Total	21,046	8,552 (41)	4,893 (24)	7,312 (35)

Note: Figures in parentheses are percentages.

Table 37. Philippines: regional ground-water parameters

Region	Geological formations: Sedimentary and metamorphic: Recent (km²)	Others (km²)	Volcanic (km²)	Igneous (km²)	Number of wells considered: Observation	Production a/	Depth of wells (m): min.	max.	av.	Depth to static water level (m): min.	max.	av.	Transmissivity (m²/day): min.	max.	av.	Storage coefficient: av.	Specific capacity (1/sec/m): min.	max.	av.	Specific conductance of ground water (micro-mhos): min.	max.	av.	Temperature of ground water (°C): min.	max.	av.
1	2 685	6 878	2 792	1 540	106	6 552	0.7	154.2	33.8	0.3	107.6	15.67	2	1 100	200	0.04	0.015	2	0.75	102.7	2 370	654.8	25	32	26.06
2	5 577	21 079	7 323	1 985	103	1 712	1.8	153.9	35.1	0.61	62.5	15.7	0.5	2 000	240	0.05	0.02	9	1.5	190	6 890	641	25	31	25.6
3	10 272	7 389	5 684	4 250	223	2 210	2.4	269	111.2	0.304	48.17	8.85	0.1	2 500	500	0.03	0.02	15	2.8	306	2 110	682.6	30	82	47.2
4	5 626	22 981	7 117	3 484	18	2 218	157	456	199.5	0.90	40.14	6.72	170	4 500	800	...	0.05	7	3	352	1 360	526.2	...	...	...
5	1 623	6 919	14 588	247	79	1 724	28.9	153.4	143.3	0.30	46.95	11.2	...	...	...	...	0.3	7	2	...	...	...	...	...	...
6	4 448	6 606	6 375	634		2 449	3.0	255	48.9	...	...	...	...	...	...	...	0.3	20	5	...	...	...	...	...	...
7	552	9 448	2 521	157		2 020	5.0	230	44.4	0.30	84.45	22.7	...	...	...	...	0.02	3.5	7.5	...	...	...	...	...	...
8	2 671	7 067	3 665	741		1 708	3.6	112.8	28.4	0.3	216.46	28.7	...	...	...	...	0.05	14	2.5	...	...	...	...	...	...
9	1 557	6 215	11 861	1 820		1 147	3.6	164	45.2	0.3	134.2	23.2	...	...	...	...	0.02	5	2	...	...	...	...	...	...
10	2 232	2 627	6 730	1 886	55	1 667	0.7	167.6	30.6	0.91	20.43	4.6	...	...	...	...	0.004	3.5	1	129.2	490.2	294.3	33	33	33
11	8 443	16 845	5 568	1 054		252	3.2	225	49.3	...	...	...	...	...	...	...	0.015	12	3	...	...	...	...	...	...
12	6 672	9 860	13 344	99	77	118	1.0	167.6	78.5	...	...	...	...	...	...	...	...	7	3	107.5	14.50	472.9	25	29	25

a/ Data refer to wells owned by the Government. No data are available on privately owned wells.

Owing to lack of data on ground water, it is not at present possible to make a detailed analysis in respect of the aquifer system's complexity. Also, it may be observed that the collection of data on water quality has not been seriously considered.

To help solve the problem of lack of data, NWRC is collecting, on a continuous basis, ground-water data from water permit applicants (both government and private) all over the country.

Apart from this, there is still a need to establish and maintain ground-water observation wells, which may be classified as follows:

Class A: Purely ground-water level and quality observation wells;

Class B: Conjunctive wells (partly for ground-water observation and partly for community water supply);

Class C: Ground-water level and quality observation wells with earthquake prediction capabilities.

Class A wells may be established by rehabilitating existing but non-operational stations and by the construction of new ones in some areas.

Since Class B observation wells are suitable for rural areas, more of this type is necessary. Their existence is easily justifiable because they may serve a very important purpose, namely, community water supply.

Only a few Class C observation wells may be constructed along the country's major fault line and near areas of potential volcanic activity. This type, as well as promoting water-resources development and management, may also save numerous lives and property by anticipating the occurrence of earthquakes.

Ground-water development and management

Seven government agencies are involved in ground-water development and management: NWRC, BPW, the Bureau of Mines, NIA, the Metropolitan Waterworks and Sewerage System, the Local Water Utilities Administration and the Army Corps of Engineers.

NWRC is mainly responsible for co-ordinating the exploitation of water resources, especially ground water. For instance, it is responsible for granting permits to drill and permits to extract water; it also sets standards for ground-water development and data collection and undertakes special studies, for example, with respect to surface resistivity surveys for ground water and new concepts of rural water supply.

NWRC has a technical staff of 10, all of whom have post-graduate backgrounds in water-resources development and management, and a sufficient number of deputies and technical and administrative support staff.

BPW has two activities related to ground water. The first, implemented by the Bureau's Water Survey Section, is exploratory in nature. The second, implemented by the Wells and Spring Section, is primarily geared to providing a supply of drinkable water to the rural population. The Water Survey Section has three exploratory drilling rigs and the Wells and Spring Section has about 50 rigs for medium-sized boreholes.

The Bureau of Mines handles ground water through its Geological Survey Division. It has two staff members with post-graduate preparation in ground water and a number of experienced geologists with a working knowledge of the ground water of the country. Although the Bureau has a sufficient number of geo-physical instruments, they are not primarily used for ground-water investigation.

NIA works with ground-water development through its Water Resources Division. It has a sufficient number of hydrogeologists, engineers, support staff, drillers, among others, capable of undertaking detailed basin-wide hydrogeological studies. The agency has at least three sets of resistivity equipment.

The Metropolitan Waterworks and Sewerage System (MWSS) exploits ground water for the supply of Metropolitan Manila and the Local Water Utilities Administration (LWUA), operating through its Water Districts, exploits ground water for the provincial urban areas.

The Phillipine Army, through its Corps of Engineers, drills wells for civilian purposes and maintains about 14 drilling rigs.

There are seven major drilling organizations in the country (see table 38). They have a total drilling capability of 2,510 wells a year, equivalent to 197,200 m.

Water-supply facilities in the country, which rely mainly on ground water, are generally categorized according to three levels:

Level I: Point source: artesian well or developed spring;

Level II: Communal faucet systems;

Level III: Individual faucet systems.

Level I systems are implemented by the Wells and Spring Section of BPW, the Task Force on Rural Water Supply of NWRC, and the Bureau of Community Development of the Ministry of Local Government and Community Development (MLGCD). The Wells and Spring Section has drilled about 30,000 rural water-supply wells, each well yielding approximately 0.6 to 1.2 l/sec by hand pumping. The Task Force on Rural Water Supply of NWRC is experimenting with the application of low-cost wells, in conjunction with the Bagong Lipunan Communal Water Program. The Task Force, which is still in the early stages of its work, is aiming at constructing and/or rehabilitating 10,000 shallow wells this year. The Bureau of Community Development of MLGCD usually assists in the development of springs, particularly those developed by the barangay (the basic political element of the Philippines, formerly known as the barrio).

Table 38. Philippines: estimated capabilities of water-well drillers

Name	Number of rigs		Number of drillers a/	Wells drilled annually			
	Percussion	Rotary		Number	Average (m)	Total (m)	Diameter of wells (inches)
Well Drillers Association of the Philippines	90	38	750	250	300	75,000	...
Wells and Spring Section, BPW	40		320	1,500	40	60,000	4-5
Water Survey Section, BPW	3		9	9	100	900	...
Army Corps of Engineers	7		21	21	50	1,000	...
National Irrigation Administration	14		112	112	300	33,600	8-10 (large wells)
Other private drillers	200		600	600	40	24,000	...
Bureau of Mines	15		15	18	150	2,700	...
Total, in the range of	250	40	2,000	2,510		197,200	

a/ In all cases, the drillers are high school graduates, with at least five years' experience.

Level II is still at the pilot stage. The NWRC Task Force on Rural Water Supply, the National Electrification Administration Power Use Directorate and Tanglaw Project and the Barangay Water Program of MLGCD are jointly undertaking this type of water-supply service. About a hundred level II systems are at present in operation in the country. Each system needs about 0.6 to 1.8 l/sec of water, assuming a pumping period of 12-16 hours.

Level III is under the supervision of MWSS, LWUA and BPW. Although MWSS concentrates on the Metropolitan Manila area, it still covers about 79 provincial systems (remains of the defunct National Waterworks and Sewerage System). In addition, BPW claims to have been instrumental in the construction of 800 water systems of this type in some municipal poblaciones and large barangay centres at present managed by local government (provincial, municipal or barangay). Of the systems supervised by MWSS and BPW, about 70 per cent are supplied by deep wells and the remainder by springs and surface water.

Meanwhile, LWUA is in the process of bringing up to date the water-supply systems of the provincial urban areas whose constituents believe in the formation of water districts. A recent count registers about 50 cities and large municipal poblaciones that were converted into water districts and are therefore under the co-ordination of LWUA. The total withdrawal by these water districts as of 1978 is computed at 100 million m^3/year (including losses).

Most of the industries in Metropolitan Manila and other major cities obtain water from under ground. Present data available at NWRC are not enough to estimate this use more accurately.

For agriculture, NIA and the Farm Service Development Corporation have some irrigation projects that are partly supplied by ground water. NIA has major ground-water-related projects in the Central Luzon Basin (Tarlac, Guimba, Pangasinan and Nueva Ecija) and in the periphery of Laguna de Bay, particularly the area of Santa Rosa-Binan, Laguna.

The need for ground water for domestic and industrial supplies will continue to grow as a direct function of population. With the increase in capital cost of surface-water supply and with rainfall unevenly distributed throughout the year, the demand for water for agriculture may also rise, although not at such a high rate as that for water for domestic and industrial uses. The use of ground water for irrigation may not be continuous, since it may be required only during the dry part of the year.

In the exploitation of ground water, salt-water intrusion is the most likely problem to arise. Since most coastal areas are composed of consolidated rocks, there is little probability that land subsidence will occur. Withdrawal of ground water does not generally consolidate the rock formations, so that the possibility of salt water replacing pumped fresh water is very high. Moreover, the country has an unusual length of shoreline (estimated at 16,000 km).

To minimize salt-water intrusion and other problems, artificial recharge may be applied, which sounds reasonable since a sufficient amount of excess surface water is available at certain times of the year. Efficient management schemes must be carefully studied before implementation of artificial recharge projects.

Conclusion

Ground water in the Philippines has been used primarily for domestic water supply, about 28 per cent of the total population being served with domestic and municipal water withdrawn from wells and springs. For this use, total ground-water withdrawal is estimated at 2 x 10^3 million m^3/year. Assuming a unit cost of ₱0.50/m^3 the economic value of ground-water withdrawal will be ₱1,000 million or $133 million a year. The consumer cost of water in Metropolitan Manila is ₱1.00/m^3. For provincial urban areas (water districts), the average cost is ₱0.85/m^3.

Another sector in which ground water is utilized is industry, which needs approximately 2 x 10^3 million m^3/year. Assuming that 50 per cent of this need is satisfied by ground water, the economic value of the volume withdrawn would be ₱500 million or $66.5 million a year.

The projected need for water for domestic, municipal and industrial uses for the year 2000 is 28 x 10^3 million m^3/year. It may be noted that the total net ground-water inflow is 33 x 10^3/million m^3/year. Therefore, the safe yield of ground water may be enough to satisfy domestic, municipal and industrial requirements.

However, this might not be true in areas in which people and industry are densely concentrated. In this case, ground-water mining may be considered.

In some degree, the agricultural sector also makes use of ground water, but the amount used has not yet been determined.

If the power requirement only is considered, ground water in the Philippines costs about ₱0.05 to ₱0.20/m^3. Domestic wells (drilled) cost about ₱3,000 to ₱30,000 ($399 to $3,990), depending upon the geological location, the materials used and the method of construction. Larger industrial and/or irrigation wells cost about ₱100,000 to ₱300,000 ($13,300 to $39,900), excluding the pump and its appurtenances.

The main trend of ground-water use is towards the domestic and industrial sectors, while surface waters are tapped for agricultural and other uses. The future may see the need for controlling the exploitation of ground water by industry in favour of domestic users.

In the four major basins in the country (Central Luzon, Cagayan, Cotabato and Agusan), ground-water exploration activities have been undertaken in order to optimize ground-water development and management. In most coastal aquifer areas, there is also a need to define aquifer boundaries, the salt-water/fresh-water lens etc., in order to have appropriate well design and construction. This activity can probably be carried out by means of the surface resistivity method.

Selected references

National Water Resources Council. 1979. Philippine Water Resources, First National Assessment, Report No. 19.

Bureau of Mines, Geological Maps of the Philippines (Scales 1:1,000,000 and 1:50,000).

PPDO, the Ministry of Public Works, Transportation and Communication and Tahal Consulting Engineers. April 1976. Pampanga Delta/Candaba Swamp Area Development Project.

Open files of the Bureau of Public Works (Water Survey and Wells and Spring Sections); the National Irrigation Administration; the National Water Resources Council; the Metropolitan Waterworks and Sewerage System; the Local Water Utilities Administration; the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAG-ASA); and the Commission on Volcanology (COMVOL).

SAMOA

Area: 2,849 km^2

Population: 153,000 (United Nations estimate, 1977)

General

Geography

Samoa lies in the south-west Pacific between latitudes 13° 25' S and 14° 05' S and longitudes 171° 23' W and 172° 48' W. It comprises two large islands, Savai'i and Upolu, two smaller inhabited islands, Manono and Apolima, and a number of smaller uninhabited off-shore islands, islets and rocks (see map 37). It is a part of the 500 km-long Samoan archipelago, the other main islands (which are part of American Samoa) being Tutuila, Ofu, Olosega, Tau and Rose.

The islands are covered with a moderately dense tropical forest away from the cultivated coastal strip. However, as a result of the growing population, the pressure on land is increasing, and development of land is moving further inland.

Upolu's crestal ridge of volcanic cones rises to 1,100 m; Savai'i has many more and younger volcanic cones, the highest (Maugasilisili) rising to 1,858 m. Although most slopes are gentle (generally up to 10-15 degrees), there are a few areas of canyons more than 300 m deep, principally in central Savai'i. Areas of steep hills are more common, particularly in eastern Upolu. Small areas of steep hills also occur in north-east Savai'i and south-west Upolu.

Climate

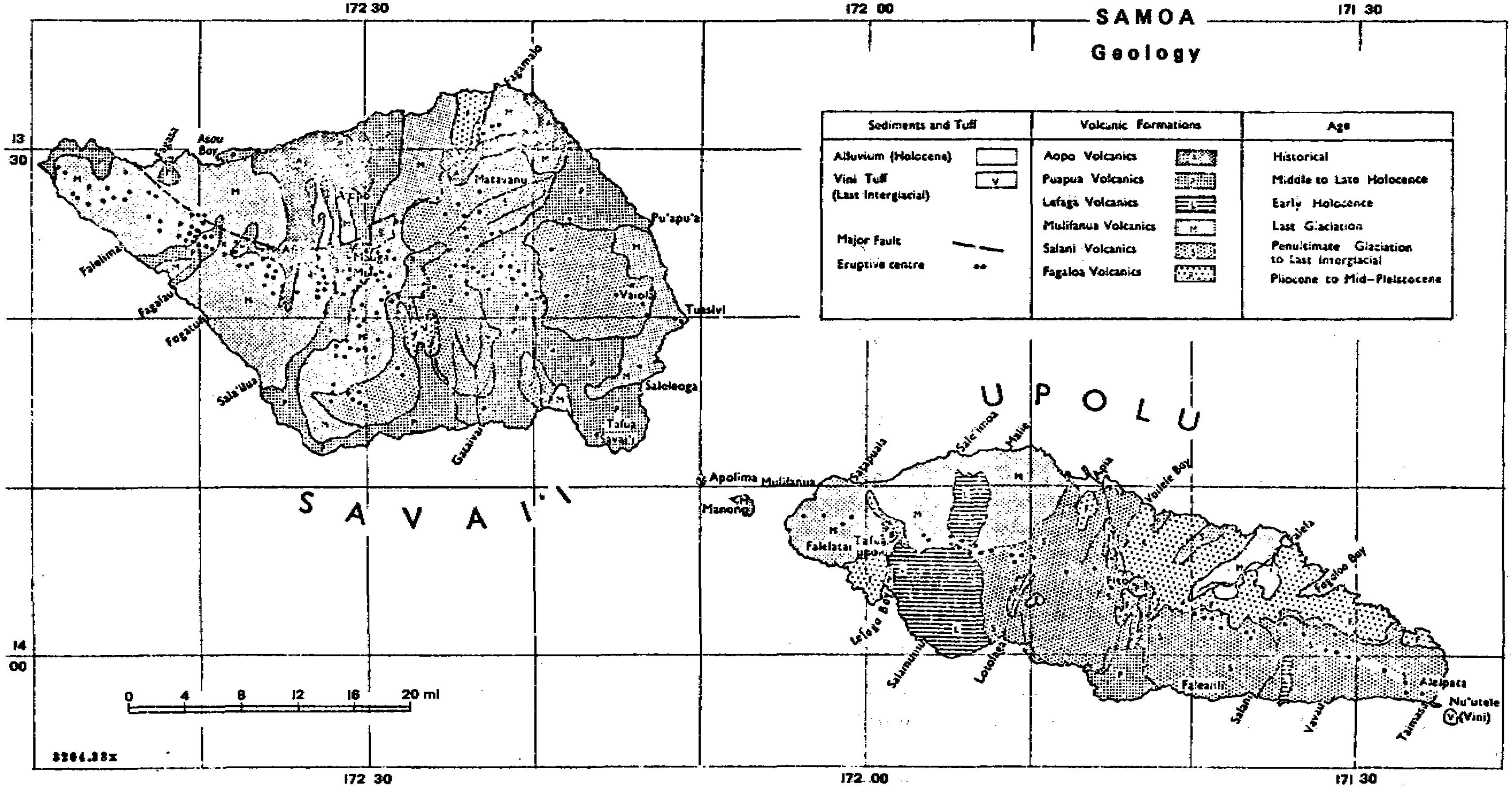
The islands of Samoa are isolated high volcanic land masses against which sea winds drop their moisture in an orographic pattern. The main sea winds are south-east trades. These trade winds, blowing approximately 50 per cent of the time (at more than 3 knots), can be ascribed to the effect of a low pressure area that persists in equatorial latitudes north of Samoa and a relatively high pressure area to the south-west of Samoa. Air pressures in Samoa are relatively stable, despite slight diurnal and seasonal fluctuations. The climate is in general hot and wet (tropical rain forest climate).

Temperature

Temperatures vary but little from the average annual value of 26.5° C in coastal areas, with a decrease from the coast inland, especially as the land rises (see table 39).

Although the station network is very incomplete and records have been kept for short periods only, there appears to be a good correlation between temperature and altitude. The temperature gradient derived from the various stations is 0.64° C per 100 m, which compares favourably with temperature gradients in other countries with similar climatic conditions.

MAP 37



SAMOA
Geology
Sediments and Tuff
Alluvium (Holocene)
Vini Tuff (Last Interglacial)
Major Fault
Eruptive centre
Volcanic Formations
Aopo Volcanics
Puapua Volcanics
Lefaga Volcanics
Mulifanua Volcanics
Salani Volcanics
Fagaloa Volcanics
Age
Historical
Middle to Late Holocene
Early Holocene
Last Glaciation
Penultimate Glaciation to Last Interglacial
Pliocene to Mid-Pleistocene
SAVAI'I
UPOLU
172 30
172 00
171 30
13 30
14 00
0 4 8 12 16 20 ml
Asau Bay
Matavanu
Pu'apu'a
Vaiola
Tuasivi
Saleleoga
Falelima
Fagafau
Fogatuli
Sala'ilua
Gataivai
Apolima
Manono
Mulifanua
Falelatai
Lefaga Bay
Salamumu
Lotofaga
Sale'imoa
Apia
Vailele Bay
Saleia
Fagaloa Bay
Falealili
Salani
Vavau
Aleipata
Nu'utele
(Vini)
Taimasa

Table 39. Samoa: mean monthly temperatures at Apia and Afiamalu

Station	Temperature	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
Apia (3 in above mean sea level)	Maximum	30.1	30.1	30.2	30.4	30.2	29.8	29.3	29.3	29.6	29.7	29.9	29.9	29.9
	Minimum	23.6	23.6	23.7	23.7	23.3	23.0	22.7	22.6	22.8	23.1	23.3	23.5	23.2
	Mean	26.9	26.9	27.0	27.1	26.8	26.4	26.0	26.0	26.2	26.4	26.7	26.7	26.6
Afiamalu (705 in above mean sea level)	Maximum	25.3	25.1	25.6	25.7	25.5	25.2	24.6	24.8	24.8	25.0	25.2	25.4	25.2
	Minimum	19.1	19.1	19.1	18.9	18.5	18.1	17.8	17.6	17.6	18.6	18.4	18.9	18.5
	Mean	22.1	22.1	22.4	22.3	22.0	21.7	21.2	21.2	21.2	21.8	21.8	22.2	21.8

Rainfall

Rainfall varies from 2,200 mm/year in the north-westerly parts of the main islands to more than 6,000 mm/year in the highlands of Upolu (see table 40). With the exception of areas near the coast and areas near the crests of the islands, there appears to be a near linear relationship between annual rainfall and altitude on the north and south slopes of central Upolu. The gradient is of the order of 295 mm/100 m.

Table 40. Samoa: rainfall at Apia and Afiamalu

(Millimetres)

Station	Rainfall a/	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Apia (3 in above mean sea level)	Long-term mean	432	362	353	248	178	138	105	107	144	209	268	385	2 929
	Maximum	1 518	765	1 297	529	594	342	279	395	466	579	847	858	4 387
	Minimum	84	90	85	46	10	17	3	2	7	31	25	77	1 765
Afiamalu (705 in above mean sea level)	Long-term mean	733	688	524	395	307	218	211	180	196	330	485	652	4 937
	Maximum	1 691	1 300	1 598	914	461	668	852	425	618	751	1 279	1 509	6 838
	Minimum	244	215	229	256	82	44	63	23	85	64	247	199	3 413

a/ The figures for Apia are based on data collected over a 75-year period; those for Afiamalu are based on data collected over a 27-year period.

Evaporation

The potential evaporation (ET) and the evapotranspiration (ET) has been estimated using the Penman combination method (see table 41).

Table 41. Samoa: estimated long-term means for potential evaporation (Eo) and evapotranspiration (ET) at Apia and Afiamalu

(Millimetres)

Station	Evaporation	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Apia	Eo	179	155	166	150	141	131	143	163	177	180	178	174	1 936
	ET	165	148	154	139	131	123	133	152	164	168	164	161	1 797
Afiamalu	Eo	118	97	108	100	94	86	93	106	113	125	112	118	1 270
	ET	107	87	99	90	84	77	83	95	101	112	101	107	1 143

Surface water

The three main factors affecting the surface hydrology of Samoa are geology, rainfall and topography. The depth of weathering of the volcanic rocks forming the islands increases with age, thereby decreasing their infiltration capacity. The eastern part of Upolu is composed of the oldest rocks, the Fagaloa volcanics, which are largely overlain by the generally more permeable Salani volcanics in the south-eastern and central parts of the islands. On Savai'i, Fagaloa and Salani formations are mainly restricted to the central northern and southern portions of the island.

The relatively low permeability of the Fagaloa rocks and, in certain areas, of the Salani volcanics, particularly where valley floors are formed by underlying Fagaloa, generally results in high water tables, and thus perennial streamflows. Other areas with younger Salani volcanics as the surface formation have intermittent streams, for example, large portions of south-east Upolu and eastern Savai'i. On the younger parts of the islands, that is, west Upolu and the western half of Savai'i, where surface formations consist of Mulifanua or younger rocks, the high permeability results in rapid infiltration and dispersion of direct recharge through ground-water discharge to the sea. Streams in these areas are rare to non-existent and generally only flow after heavy rainfall (see map 38).

The highly variable spatial permeability of the rocks forming the catchments of perennial streams and rivers makes run-off régimes difficult to predict. The characteristically complex rainfall/run-off relationship in these volcanic areas is controlled very largely by this variability and by temporal variations in the elevation and configuration of the ground-water table. There is abundant evidence of flow loss and gain, in influent and effluent reaches of streams, which tend to produce a poor correlation between catchment size and run-off volume. Stream-flow recording stations have kept records for varying lengths of time (two to six years). These records indicate that run-off coefficients of the corresponding catchment areas range from less than 0.3 to more than 0.6, despite a certain similarity in geology and topography. Mean annual discharges from these areas are generally of the order of 0.04 to 0.08 $m^3/sec/km^2$, but can be considerably higher or lower, depending on the geology and the annual rainfall on the catchment (see table 42).

Peak floods characterize the run-off patterns seasonally, depending on rainfall intensities and run-off coefficients. When the natural vegetation in the upper catchment areas is disturbed by bush clearing for agricultural purposes, the direct run-off component increases, causing higher peak floods and lower base flows. Under these conditions large amounts of debris, silt and sand are transported, particularly during the wet season.

Map 38. Samoa: water resources

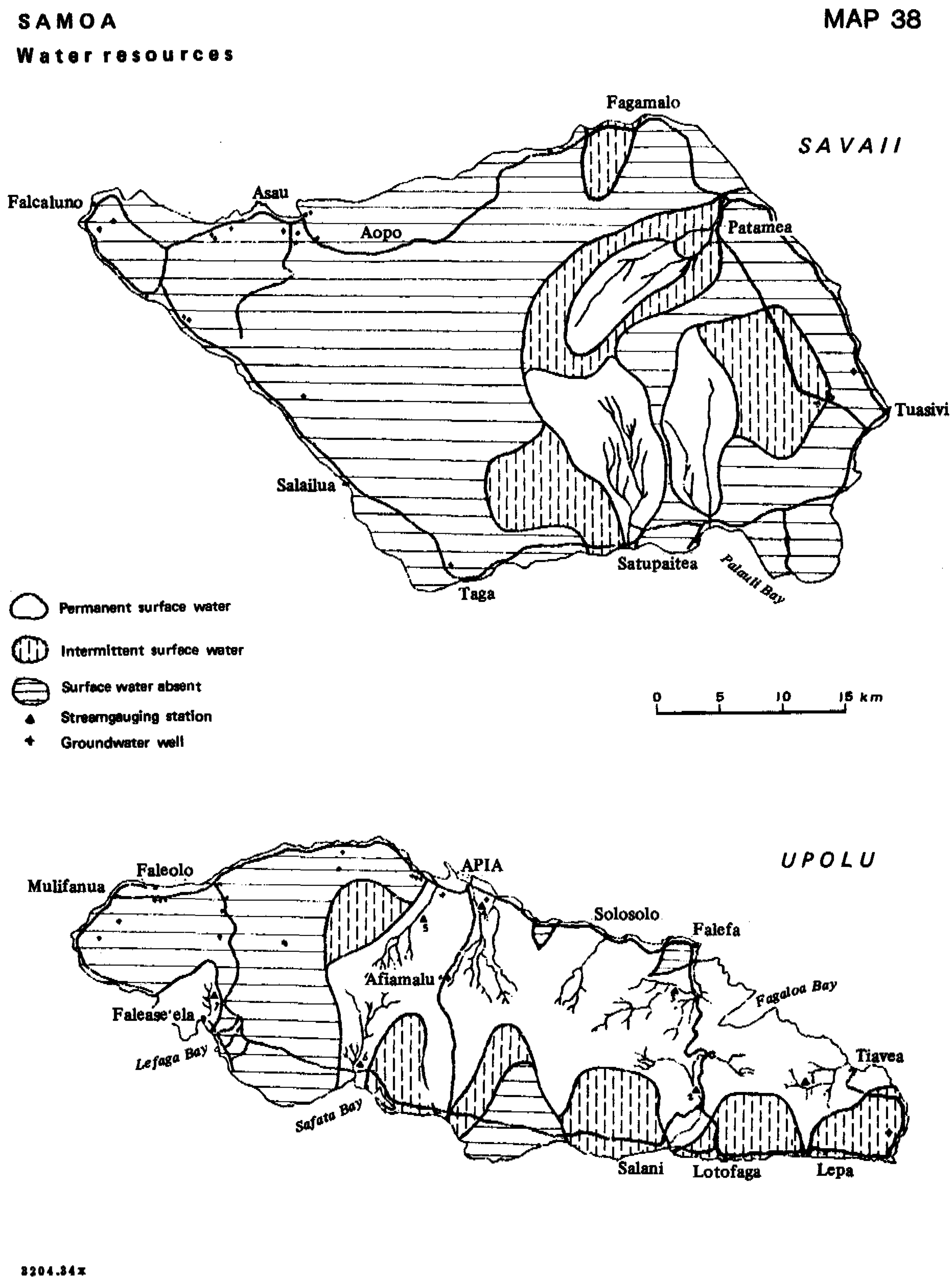


Table 42. Samoa: mean monthly run-off data at stream gauging stations (m^3/sec)

Basin a/	Area (km^2)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Average
Mulivai	10.8	0.68	0.62	0.35	0.53	0.90	0.34	0.56	0.21	0.17	0.33	0.41	0.66	0.49
Salani	37.6	5.22	4.36	2.01	2.99	3.66	2.46	2.45	1.15	1.59	3.54	5.34	5.58	3.24
Falefa	35.7	2.20	2.25	2.14	1.17	2.21	1.15	1.81	0.83	0.41	1.15	2.39	2.05	1.64
Vaisigano	16.5	3.25	4.53	2.95	2.03	1.91	1.25	1.06	0.91	0.66	0.96	1.81	2.32	1.98
Fuluasou	6.7	0.94	1.44	1.03	0.76	0.77	0.45	0.32	0.25	0.21	0.23	0.50	0.77	0.64
Leafe	19.3	1.65	2.35	1.89	1.46	1.78	1.06	1.17	0.76	0.49	1.25	1.89	1.57	1.42
Faleseela	10.1	0.71	0.87	0.57	0.65	0.50	0.30	0.26	0.22	0.14	0.19	0.31	0.60	0.43

a/ See map 38.

Geology

General

The islands of Samoa are almost wholly composed of basic volcanic rocks (olivine basalt, picrite basalt and olivine dolerite of the alkali basalt suite have all been identified). According to Kear and Wood (1959) these basalts can be divided into six formations on the basis of weathering and erosion criteria. All include blocky (aa) and massive ropey (pahoehoe) lava types ejected from steep cinder cones. More than 40 such cones form the crestal ridge of Upolu and very many more form the highland ridges of Savai'i.

The 110° alignment of Upolu, and to a lesser extent of Savai'i, is almost certainly associated with a major fracture in the floor of the Pacific. Other similar faults have been identified and are essentially minor collapse features within the volcanic pile, along which eruptions occurred.

Except where cliffs are steep, or where very young lavas have flowed into and filled the lagoon, coral reefs exist along nearly half the coastline. Coral sand occurs along much of the coastline, up to 5 m above sea level. Alluvium is not common, but is important locally, particularly around Apia, and where lava flows have dammed valleys. Some of the offshore islands are composed of marine volcanic tuff. Kear and Wood (1959) have prepared a geological map of Samoa (map 37) and have summarized, in tabular form, the characteristics of the above formations (see table 43). A summary of the main volcanic formations described by Kear and Wood (1959) is given below.

Main volcanic formations

Fagaloa volcanics

Fagaloa volcanics, the oldest formation in Samoa, generally consist of interbedded lava flows and pyroclastic deposits with thicknesses ranging from 0.3 to 30 m. Typically, the lava flows are soft to medium-hard, slightly to highly weathered grey olivine basalts, with closely to widely spaced discontinuities. The pyroclastic deposits can be partly lithified to form tuffaceous agglomerates. In certain areas the rocks are deeply weathered to depths of, say, 75 m with deep leached clayey soils. Volcanic cones or centres are not obvious; steep valleys with permanent streams are common. Ground-water levels are generally high.

Salani volcanics

The formation consists of interbedded lava flows and pyroclastic deposits, of a thickness similar to that of the Fagaloa. The rocks can be weathered to depths of, say, 30 m and generally have soils developed over depths ranging from 0.5 to 5 m, with rounded residual weathered boulders at the surface. The degree of weathering is generally less than that of the Fagaloa rocks. Discontinuities can be partly filled in with weathered material, causing the formations to be of moderate to low permeability by Samoan standards. Basal ground-water levels are generally low, but perched ground-water bodies do occur. Water, flowing either permanently or intermittently in many river valleys, has cut deep gorges in certain areas, sometimes down to the underlying Fagaloa rocks.

Table 43. Samoa: rock formations

Formation	Cover of vegetation	Weathering zone and soil	Present reef	Boulders on uneven land	Alterations to cone form	Surface water	Olivine nodules	Age
Aopo volcanics	None or poor	None	None	Very common	None	None	Rare	Historical
Tafagamanu sand	Sedimentary formations approximately contemporaneous with Puapua volcanics							Post-glacial, 5 ft above sea level
Nu'utele sand								Post-glacial, 15 ft above sea level
Lalomauga high-level alluvium								Post-Mulifanua
Puapua volcanics	Normal	Very thin	None	Very common	None	Virtually none	Rare	Middle to Late Holocene
Lefaga volcanics	Normal	Intermediate	Close inshore	Very common	Little	Virtually none	Rare	Early Holocene
Mulifanua volcanics	Normal	Intermediate	Far offshore	Common, weathered, angular	Crater filling	Rare	Uncommon	Last glaciation
		Erosional unconformity with canyon formation						
Salani volcanics	Normal	Thick (over 12" soil	Far offshore	Very weathered, rounded	Gorges cut in flanks	Sometimes	Present	Penultimate glaciation of last interglacial period to early last glaciation
Vini tuff	Marine tuff rings, definitely pre-Lefaga post-Fagaloa, and probably early Salani							Last interglacial period (about 30 ft above sea level)
		Great erosional unconformity beneath younger volcanics						
Fagaloa volcanics	Can be poor (leaching)	Very thick	None or close inshore	Rare	Up to complete destruction, dykes exposed	Always	Common	Pre-penultimate glaciation possibly late Pliocene

Mulifanua volcanics

This formation consists of moderately hard to hard unweathered or slightly weathered vasicular olivine basalts. The thickness of surface weathering is generally not greater than 10 m, and soil depths normally do not exceed 1.5 m. The Mulifanua volcanics are generally areas with only temporary or no surface drainage. Undoubtedly this results partly from less weathering, but also from the more open contraction/subsidence cracks and even the presence of lava tunnels. Overall permeability is high and consequently ground-water tables are low.

Lefaga volcanics

The only large outcrop of Lefaga volcanics, which covers approximately 10 per cent of Upolu, is mapped in the south-western part of the island. The rocks are mainly hard to very hard, fresh to slightly weathered olivine basalts with closely to widely spaced, highly permeable discontinuities. The surfaces, which show only thin weathering (up to 4 m), are unmodified by erosion; surface streams are very rare to non-existent.

Puapua volcanics

Young Puapua volcanics cover 3 per cent of Upolu and 18 per cent of Savai'i. Some lava flows were confined to river valleys or gorges, their solidified flows forming part of the valley floor. Where lava flows have filled in lagoons, cliff coasts with no offshore reef occur. The Puapua rocks are fresh to slightly weathered, have very thin soil covers and are highly permeable. Ground-water levels are very low.

Aopo volcanics

Aopo volcanics are the result of eruptions which occurred in the years 1760, 1902 and during the period 1905-1911. Vegetation is beginning to re-establish itself.

Ground-water resources

Review of investigations

In the western parts of both Upolu and Savai'i which are covered with very permeable young volcanics, rivers and streams do not exist at all, or only for a few hours during torrential rain. Remote from surface-water supplies, villages have relied solely on coastal springs for water or, in a few cases, on impermanent piped supplies from distant streams. Water cartage and shortage have therefore been characteristic features of the life styles of many villages.

The Public Works Department, which is responsible for the construction of water reticulation systems throughout the country, indicated at an early stage that, without a detailed inventory of all surface-water and ground-water resources, no systematic progress could be expected in water supply.

In this light, the Hydrological Services Project was established in 1971 with financial and manpower support from the United Nations Development Programme (UNDP). The Project has since been responsible for the establishment of a hydrological-climatological station network to permit the systematic investigation of all water resources for industrial, agricultural and domestic purposes. Apart from conducting water-balance studies for the assessment of hydropower potential in selected basins, the Project has participated extensively in the scientific supervision of various drilling programmes for ground-water exploration.

The first hydrogeological data that became available was from the several water wells that had been dug in the early part of the century when the islands were a German colony. In 1956, after a detailed survey had been undertaken, it was concluded that ground water should be plentiful in many parts of the islands (Kear and Wood, 1959). That conclusion was confirmed when a series of boreholes were drilled in the Asau area to supply the new timber industry with water. On the basis of those findings, an experimental drilling programme to assess the ground-water potential in different areas in Samoa was envisaged. The initial programme was funded by UNDP and the Food and Agriculture Organization of the United Nations (FAO) (1971-1972). It proved successful because the five sites, which were deliberately so selected, proved to be in very different geological environments from each other, so that important inferences could be drawn. A secondary objective of the programme was the provision of water to critical agricultural and rural areas, thereby increasing interest in ground-water usage. Four out of five holes yielded adequate flows.

Though significant information became available from the bores, the limited number drilled made extrapolation of the hydrogeological data to other areas unreliable if not impossible. It was therefore proposed (Kear and Kammer, 1974) to implement a second experimental drilling programme to be funded again by UNDP and FAO. At the same time, the Government of New Zealand showed interest in supporting a production drilling programme. Although the UNDP-funded programme was cancelled eventually, the New Zealand Bilateral Aid Project was fortunately expanded to include both experimental and production bores. Through that programme, 15 holes were drilled during the period 1976-1977. Of these, 11 were very successful, two produced water that will probably be used and two remained dry, but all provided further basic hydrogeological data (data on all existing wells are listed in table 44).

Prospecting methods

The well-known Ghyben-Herzberg principle of a fresh-water lens floating on salt water beneath islands of permeable rocks has been found relevant to Samoa. Inevitable difficulties of interpretation and application arise, however, because (a) zones of mixing are present which have uncertain salinities; (b) tidal effects even well inland are greater than the theoretical height of the fresh-water surface above sea level; and (c) the ground water in coastal wells has been found to vary markedly in salinity between high and low tides. Although the principle of the fresh-water lens had no practical application in respect of detailed planning for water supplies for villages near the coast, it was valuable as general background theory.

Systematic listing of exact location and altitude, bore depth, diameter, casing and screen setting, static water-table elevation, tidal fluctuation, discharge, drawdown, specific capacity, aquifer transmissivity and water quality formed, therefore, the basis on which ground-water prospecting in other areas was carried out. Advanced prospecting methods, such as geophysical, geoelectrical and infrared surveys, have not yet been applied on a systematic basis because of the assumed limited value under the local hydrogeological circumstances. It may be, however, that an experimental geoelectrical survey will be carried out in future at selected locations where interference in the data by the inhomogeneous geological characteristics is thought to be minimal.

Table 44. Samoa: ground-water wells

Well	Inld (m)	GL (m)	Depth (m)	WL (m)	Tide (m)	Flow (l/sec)	D/D (m)	S Cap (l/sec/m)	Chl- (ppm)	Formation
(1978 wells) a/										
Vaitele 1	600	16.0	30.5	0.5	0.02	6.3	8	0.79	5	M
Vaitele 2	600	16.7	21.6	0.5	0.04	22.2	0.14	158.7	5	M
Vaitele 3	600	16.9	21.8	0.5	0.04	22.2	0.14	158.7	5	M
Alafua	3 000	28.6	33.5	3.7	...	18.8	0.20	90.9	10	S
Tuanai	1 300	15.0	20.0	6.0	...	16.4	2.5	6.6	10	M
Vaivase	1 500	25.3	30.5	6.1	...	18.8	3.2	5.9	25	S/F
(1976-77 wells)										
Afiamalu	9 600	761.9	62.2	7.55	...	0.4	45.0	...	...	S/F
Aleipata, Satitoa	1 760	80.1	85.3	2.74	0.04	11.8	0.14	84.3	10	S
Aleisa East	7 500	250.0	108.0	...	...	...	...	...	...	M
Asau 12	1 300	43.1	55.5	0.43	0.21	17.0	0.12	141.7	300	M
Auala	1 920	62.2	67.9	0.70	0.31	11.8	0.01	118.0	200	M
Faleolo 1	500	14.2	21.3	0.45	0.06	18.2	0.04	455.0	50	M
Faleolo 2	500	14.2	21.3	0.45	0.06	18.2	0.03	606.6	50	M
Faleolo 3	500	14.2	21.3	0.45	0.06	18.2	0.03	606.6	35	M
Fogasavai'i	1 200	82.9	90.8	0.33	0.33	10.4	0.07	148.6	145	M
Leulumoega 2	1 300	37.3	43.0	0.60	0.03	18.2	0.64	28.4	5	M
Malae, Faga	2 250	35.2	41.8	1.00	0.15	18.2	0.67	27.2	5	S
Mulifanua, Tausagi	2 400	44.5	60.9	0.36	0.02	10.1	2.56	3.9	1 750	M
Sataua 1	800	24.9	29.6	0.15	0.39	18.0	0.23	78.3	400	M
Sataua 2	900	34.1	40.2	0.00	0.40	18.2	0.12	151.7	280	M
Vaiola 2	8 000	213.0	76.2	...	...	...	...	...	...	M
(Earlier wells)										
Afia (dug)	2 000	39.6	39.5	0.5	0.04	2.3	0.0	282.2	20	M
Asau 2	2 000	...	11.7	...	0.51	1.5	...	...	470	M*
Asau 3	1 600	23.4	24.7	0.4	0.20	3.0	...	...	±400	M*
Asau 4	800	22.0	26.2	0.2	0.10	3.0	...	...	±700	M*
Asau 8	180	20.0	...	...	...	0.2	...	...	±600	M*
Craddick 1 and 2	1 000	24.5	...	...	...	...	...	...	...	M
Falealupo (UN)	800	18.5	23.2	0.0	0.30	6.3	...	...	±1 000	L
Falelima 1 (dug)	800	5.5	6.4	0.2	0.53	2.5	0.1	40.9	±1 200	P
Falelima 2 (dug)	800	6.0	6.4	0.2	0.53	2.5	0.0	250.0	±1 200	P
Faleolo Airport 1	425	7.3	9.9	0.23	Yes	1.5	...	...	54	M
Faleolo Airport 2	400	7.3	9.5	0.4	...	2.5	0.0	500.0	20	M

Table 44 (continued)

Well	Inld (m)	GL (m)	Depth (m)	WL (m)	Tide (m)	Flow (l/sec)	D/D (m)	S Cap (l/sec/m)	Chl^{-} (ppm)	Formation
Leulumoega (dug)	400	7.0	8.4	0.3	0.3	4.5	...	...	Low	M
Leulumoega 1 (UN)	2 100	70.0	91.4	10.4	0.00	9.5	25.9	0.4	13	M/F
Mauga (dug)	1 600	30.0	30.0	Low	...	...	...	...	Low	M
Neiafu (dug)	800	7.6	9.3	...	...	3.4	...	...	±1 300	P
Potlatch 5	1 300	18.6	20.4	0.6	...	3.2	...	...	±500	M*
Potlatch 6	3 200	23.1	29.3	0.9	...	3.8	...	...	±400	M*
Potlatch 7, 9, 10	350	17.5	18.5	...	...	190.0	-	...	960	M*
Taga	1 200	28.2	33.5	0.5	...	3.3	...	...	450	M
Tanumalala (UN)	7 000	310.0	77.7	289	0.00	0.5	23.8	...	...	M/F
Tuana'i (UN)	3 200	56.0	57.9	27.4	0.00	12.6	1.37	9.2	...	M/S
Tufutafoe	2 400	27.6	29.7	0.5	0.15	2.5	1.4	1.8	±1 000	L
Vaiola 1 (UN)	5 600	14.5	61.6	92.0	0.00	2.1	...	...	10	M

Inld: Distance inland from coast (metres)

GL: Ground level (metres above mean sea level)

Depth: Completed well depth (metres)

WL: Static water level (metres above mean sea level)

Tide: Tidal fluctuation of static water level (metres)

Flow: Discharge rate (litres/second) up to maximum of pump capacity

D/D: Drawdown corresponding to discharge rate

S Cap: Specific capacity (litres/second/metre of drawdown)

Chl^{-}: Salinity (chloridity) (ppm of chloride ion)

Formation: F. Fagaloa; L. Lefaga; M. Mulifanua; M*, younger Mulifanua in coastal areas; P, Puapua; M/F, Mulifanua over Fagaloa; M/S, Mulifanua over Salani; S/F, Salani over Fagaloa

(UN) GWS/UNDP/FAO programme borehole

---

a/ Work carried out under the New Zealand Bilateral Aid Programme.

Overall assessment of ground-water resources

The results of drilling for ground-water in various regions of Samoa differ significantly according to two factors: (a) the formation involved; and (b) its geographical location relative to the coast. These two factors also influence the need for seeking ground water in the first place, because they also combine to determine whether there are streams, rivers and inland springs in a region, and the amount of water in each in the dry season.

In the evaluation of the drilling results, therefore, from the point of view of the occurrence of ground water, a subdivision by groups of formations has been made, as follows:

(a) Aopo, Puapua and Lefaga volcanics

All young; unweathered; no surface water; no off-shore lagoon;

(b) Mulifanua and Salani volcanics

Different in weathering characteristics and appearance in drill logs, but common in intermediate age and weathering; some surface water and springs; wide off-shore lagoon;

(c) Fagaloa volcanics

Old formations; steep terrain; deep weathering; abundance of surface water; fringing reef.

Data collected are as follows:

(a) Aopo, Puapua and Lefaga volcanics

Near coastal areas (800-2,400 m inland)

Number of wells:	5
Well depths:	5-28 m
Water levels:	0.1-0.4 m above mean sea level
Water level fluctuations:	0.3-0.5 m
Specific capacities:	Greater than 100 l/sec/m
Salinity:	Higher than 1,000 parts per million of chloride
Conclusion:	Wells in these young rocks will be high producers, with water levels close to sea level and subject to tidal fluctuations. The key problem will be salinity, which will be liable to exceed the WHO maximum of 600 parts per million of chloride, unless the wells are sited inland from the coastline that existed before the extension of these rocks, with a minimum total distance of 1 km from the present coast.

Inland areas

No boreholes have been drilled in inland areas of these rocks, but it can be inferred that their water levels would be close to sea level for several kilometres inland and that salinity would remain the major problem for a greater distance inland than with other formations.

(b) Mulifanua and Salani volcanics

(i) Mulifanua volcanics

Near coastal areas (300-1,000 m inland)

Number of wells:	17
Well depths:	8-35 m
Water levels:	0.1-0.5 m above mean sea level
Water-level fluctuations:	0.2-0.4 m
Specific capacities:	More than 500 l/sec/m
Salinity:	500-700 parts per million of chloride
Conclusion:	Shallow wells drilled or dug in near coastal Mulifanua volcanics yield large quantities of water, but salinity values may exceed the acceptable level. In two cases, however, shallow wells are known to yield large quantities of good quality water.

Inland areas (1,000-3,000 m inland)

Number of wells:	10
Well depths:	30-90 m
Water levels:	0.5-6.0 m above mean sea level
Water-level fluctuations:	0.1-0.2 m
Specific capacities:	100-200 l/sec/m
Salinity:	50-200 parts per million of chloride
Conclusion:	Wells located more than 1,000 m inland from the coastline show a decreasing specific capacity, but water quality increases significantly.

(ii) Salani volcanics

Number of wells:	5
Well depths:	50-85 m

Water levels:	2-20 m above mean sea level
Water-level fluctuations:	None
Specific capacities:	10-100 l/sec/m
Salinity:	0-10 parts per million of chloride
Conclusion:	Useful quantities of very good quality water have been found in Salani volcanics as long as basal ground water was reached. Perched aquifers do exist, but water from them is limited in quantity.

(c) Fagaloa volcanics

Number of wells:	3
Well depths:	65-100 m
Water levels:	Levels of perched aquifers related to impermeable horizons
Water-level fluctuations:	None
Specific capacities:	Less than 1 l/sec/m
Salinity:	None
Conclusion:	Wells drilled in inland Fagaloa volcanics are capable of producing small quantities of good quality water.

Overall conclusion

In total, 46 wells have been drilled or dug in Samoa so far. The majority of them are located in coastal and near coastal areas (500-3,000 m inland), with a maximum site altitude of 80 m above mean sea level. They penetrate the basal ground-water body and, apart from a few exceptions, they are able to produce large quantities of water.

Saline-water intrusion is a general problem where wells are located too close to the coastline, particularly in the youngest volcanic formations. However, some shallow near-coastal wells are known to produce large quantities of fresh water. It is assumed that these bores were fortuitously located above converging subsurface fresh water conduits or where an occasional impermeable layer separates the fresh-water lens from the basal salt-water body.

The salinity values of water from wells near the coast generally decrease with increasing distance from the coast. Further inland, however, construction and operation costs of water wells increase considerably, because of their necessarily greater depth to reach the basal ground-water body. Favourable locations of low altitude (lower than, say, 35 m) and sufficient distance from the coast (more than, say, 2,000 m) are hard to find in Samoa.

Five bores were drilled in the higher inland areas (the highest at 705 m above mean sea level) to locate possible perched aquifers. Three of these were successful in providing small quantities of water.

Ground-water development

Though extremely diverse, most Samoan water-supply schemes are reticulated by gravity and fed from inland streams and springs. The capacity of the reticulation systems, as well as the dry-weather flows at the source, are frequently inadequate. Water quality is often poor, particularly during the wet season when streams carry a considerable load of debris from, in some cases, unprotected catchment areas. Other populated areas in the western part of Upolu and Savai'i, where inland springs and streams do not exist, had until recently no water supply at all.

The extension of the urban areas and the development of rural areas, coupled with a rapid population growth, require considerable additional quantities of water. Schemes for tapping additional surface water and upgrading existing reticulation systems are going ahead. Large-scale artificial catchment areas for rain-water harvesting in the higher inland areas will be constructed in the near future, but the majority of the additional water-supply schemes will draw on ground-water resources, in particular in areas near the coast.

The experimental stage of ground-water exploration was finalized on completion of the 1976-1977 drilling programme. On the basis of the hydrogeological data derived from the bore logs and pumping tests, it is possible for most areas to predict with reasonable accuracy where ground water of useful quantity and quality will be found.

Though at the end of 1977 the water-well network (23 producers with a potential total discharge of 240 l/sec) established under the experimental programmes would contribute significantly to the water requirements on both Upolu and Savai'i, it was emphasized that an extension of the network would be desirable, especially in areas where present requirements are only marginally met by existing water sources and do not allow for future increase in demand. A follow-up drilling programme was therefore formulated, in order to further develop the ground-water resources already located.

Earlier drilling programmes were mainly carried out by overseas contractors and all costs involved were covered by development aid sources, since the Government of Samoa lacked the funds, equipment and manpower to implement the desired programmes out of government resources. On completion of the 1976-1977 programme, however, a suitable drilling rig (Sanderson Cyclone 36-R truck-mounted rotary drill, with a maximum drilling depth of 200 m at 22.5 cm bore diameter) was donated to Samoa under the New Zealand Bilateral Aid Programme. To operate this machinery, a Geological Services Section was established, responsible for all drilling and technical aspects of future programmes. The Government of New Zealand would cover part of the costs involved for spare parts, consumables and additional equipment during the running-in period of two years. During that period, two national driller foremen and four driller assistants were to be trained under the supervision of an overseas drilling instructor.

It was envisaged that 16 to 18 additional wells would be drilled in a first-stage ground-water development programme. At present, six have been successfully completed in the Apia town area. They will in total supply 100 l/sec, in addition to the approximately 300 l/sec drawn from inland streams. About seven new wells will be drilled on Savai'i, four of which are to be located near existing surface-water reticulation systems in order to establish integrated surface-water/ground-water schemes. In the wet season, when the surface-water supply from streams and springs in eastern Savai'i is adequate, pumping hours will be restricted. The other three wells are to be drilled in the dry western part of Savai'i, which is totally dependent on ground-water. Finally, three to four additional wells will be drilled in the higher inland areas of Upolu, after which the contribution of the water-well network to the water-supply requirements in Samoa will be reviewed and a possible follow-up programme will be formulated.

Progress in ground-water development, however, is not without problems. Young volcanics are very hard to drill through by any standards throughout the world. Extremely hard basaltic formations, alternating with very loose unstable cindery layers, causes drilling to be a slow (less than 0.5 m/h on the average) and expensive (about $200/m) process. Difficult access to the bore site, very poor drilling water supply, collapsed holes, down-hole tool jams and lengthy mechanical breakdowns have characterized the drilling programmes so far. Poor maintenance and repair facilities for pumps and engines installed at existing water wells have frequently caused the majority of the ground-water supply schemes to be out of operation.

Overpumping of a few water wells with water tables very close to sea level has caused salinity values to increase gradually beyond acceptable levels. In this respect, extreme care should be taken in future since increasing salinity of a well is a process that is hard to reverse when fresh water recharge is limited.

Conclusion

The assumption that ground water should be plentiful in many parts of the islands of Samoa (Kear and Wood, 1959) has been confirmed by the results of the water-well drilling programmes that have been undertaken. Large areas, previously without any reliable water source will in future be supplied with good quality ground water in adequate quantities.

In contrast with surface-water supplies, which give rise to very limited costs as far as operation and maintenance are concerned, ground-water supplies are expensive. A broad cost estimate of ground water amounts to $\$0.04/m^3$, including costs of well construction, pump and engine, and operation and maintenance, but excluding costs related to storage and the reticulation system. Because of its isolated location, Samoa has very poor access to the services of overseas manufacturers of pumps, pipes, engines and spare parts which, combined with limited local repair and maintenance facilities, causes ground-water development schemes to run behind schedule. Only 35 per cent of the existing water wells on both Upolu and Savai'i are in production at present. Once these problems, which are mainly of an organizational nature, have been overcome, ground water will form a reliable source of water of increasing importance for industrial, agricultural and domestic purposes.

Selected references

Kammer, D. 1978. The hydrology and climate of Western Samoa. Internal report. United Nations Development Programme project SAM-74-006. 101 pp.

Kear, D. 1971. Hydrogeology and water supply for agricultural development. Technical report. United Nations Special Fund project, Western Samoa. 101 pp., 3 figs.

Kear, D., and D. Kammer. 1974. Hydrology, hydrogeology and water supply for agricultural and other development. Unpublished report. 147 pp., 4 figs.

Kear, D., D. Kammer and C. D. L. Brands. 1978. The hydrogeology and water supply of Western Samoa. Internal report. UNDP project SAM-74-006. 73 pp.

__________. The hydrogeology of Western Samoa. Pacific Island Water Resources, W. R. Dale, ed. (Wellington, New Zealand, Department of Scientific and Industrial Research (DSIR), 1981), pp. 75-86.

Kear, D., and B. L. Wood. 1959. "The geology and hydrology of Western Samoa". Bulletin of the New Zealand Geological Survey, No. 63.

Risk, G. F. Resistivity prospecting for groundwater in Western Samoa. Pacific Island Water Resources, W. R. Dale, ed. (Wellington, New Zealand, DISR, 1981), pp. 117-120.

Various borehole reports. 1971-1978. Hydrological Services, Apia Observatory.

SOLOMON ISLANDS

Area: 28,446 km^2

Population: 214,000 (1979)

General

The location of Solomon Islands is shown in map 39.

Island formation may have begun in the middle and late Tertiary. Volcanism, tectonic dislocation and uplifting played a significant role in shaping the present land forms.

The geography of the islands can be described in the context of Cook's classification of islands as high or low islands. The main islands fall under the high island category. The high islands are mountainous and often have sharp ridges with steep-sided valleys in between. In some of the islands, mountains are high in proportion to their width, sometimes exceeding 900 m. The highest mountain is 2,330 m above sea level. Flat land is restricted to coasts and is of limited extent except in the north-central part of Guadalcanal, referred to as the Guadalcanal Plains. These plains are the largest in the country, extending from Lungga to Aola and covering an area of approximately 1,219 km^2. Their width varies from 2 to 13 km. They are the result of the coalescing of the deltas of the rivers draining the area. Rivers tend to be short and are rarely navigable. The longest river course (Mbokakimbo in Guadalcanal) is 92 km and drains an area of 365 km^2. Flash flooding is common in the larger rivers. The low islands are made of upraised sand cays and limestone; streams tend to be rare.

Solomon Islands has a tropical climate, hot and humid with an oceanic modification. During the day, a sea breeze blows and at night a cool breeze blows from the mountain areas. Temperatures vary between 22° C and 29° C. Inland areas sometimes experience temperatures as low as 16° C at night. The wet season begins late in October and ends in April. The dry season begins in April and may extend into November. Cyclones are sometimes experienced during the wet season. Mean precipitation in most land areas is between 3,000 and 5,000 mm.

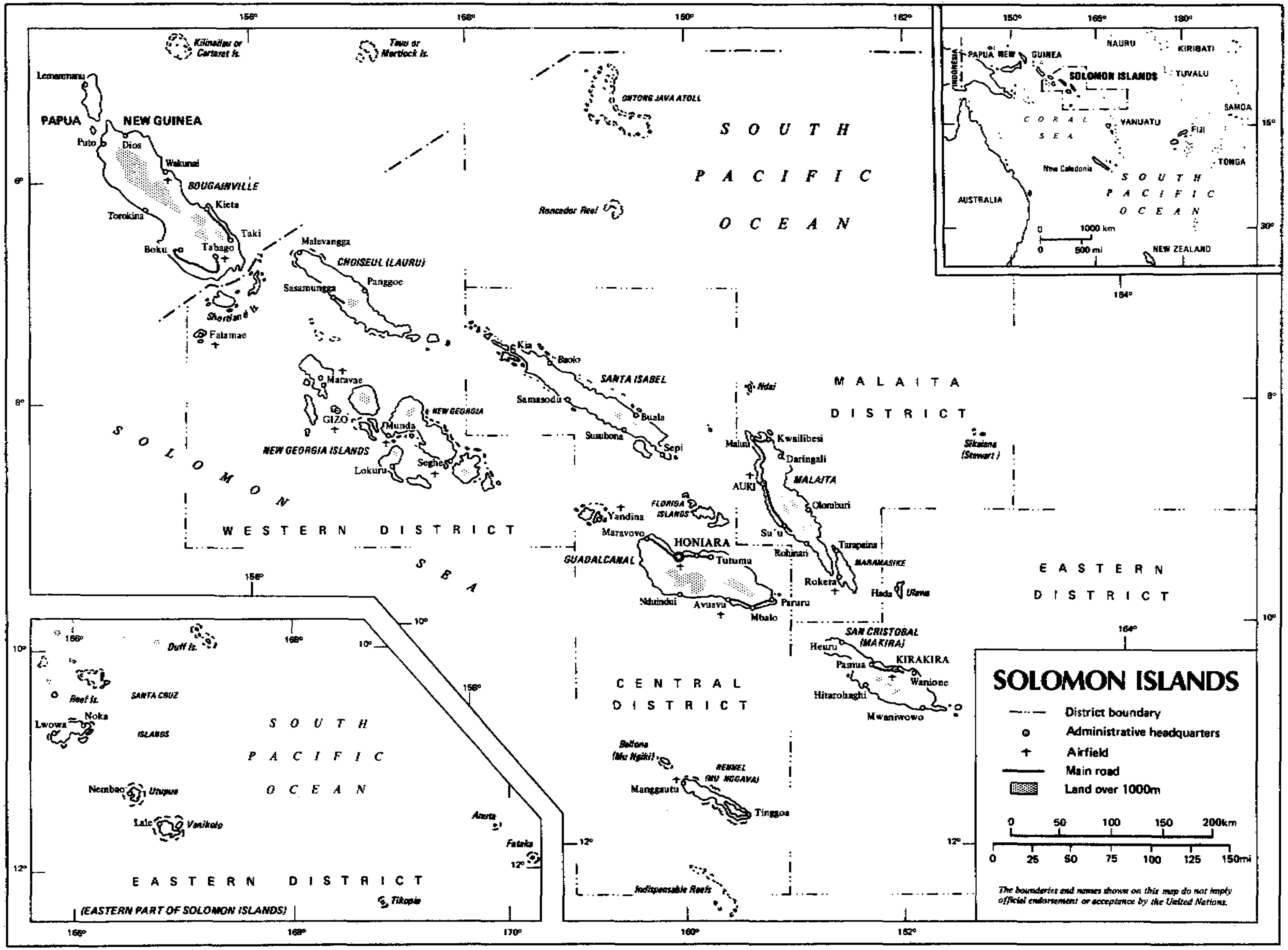
Surface water, though abundant, is not evenly distributed. The major rivers have permanent flows, but during long droughts the water level may drop. Streams, however, dry up. There are a few lakes in the country the largest being Lake Tenggano on Rennell Island.

Geology

From geological information available, Coleman (1965) divided Solomon Islands into five geological provinces, namely, the Central, Pacific, Volcanic, Oceanic Volcanic and Atoll Provinces.

The Central Province is characterized by intensely faulted cores of pre-Miocene basic lavas which in part have been regionally metamorphosed. Overlying these is a sedimentary cover with variable thickness in different islands with an age range from Lower Miocene to Holocene.

MAP 39



MAP NO. 2960 REV. 1 UNITED NATIONS
DECEMBER 1982

The Pacific Province has a basic core similar to that of the Central Province and is overlain by pelagic sediments. The core and the sediments have been faulted and folded. An age range from Cretaceous to Recent has been assigned to the sediments.

The Volcanic Province which includes the whole of the New Georgia group and extends into north-west Guadalcanal comprises cores and lava piles of basaltic and andesitic composition surrounded by clastic sediments and fringing reef material.

The Oceanic Volcanic Province consists of the Santa Cruz group and is of volcanic origin with a sedimentary cover.

The Atoll Province includes a large number of outlying islands made essentially of reefs and upraised sand cays.

Ground-water resources

Hydrogeological investigations in Solomon Islands probably date back to the Second World War, at the time of the American occupation of some of the islands. There are no records of these investigations. Boreholes were drilled for water; some are still being used today (e.g., on Munda, Noro and Tetere). Systematic investigations of ground water in the country have yet to be undertaken. Only when surface water is insufficient to meet rising demand is ground water considered as a supplement.

Investigations have been mostly confined to Honiara (capital of Solomon Islands) and the areas east and west of it. Most of these were aimed at locating water for human and industrial consumption. None of the boreholes was electrically logged and siting was a matter of trial and error.

Another area that has been, and still is, under investigation is Noro in the New Georgia group where urban and industrial development is under consideration. At present, an old well, dating from the Second World War, supplies water for the existing facilities. Nine drill holes have been sunk, three for observations and the rest for pumping tests. Electrical logging was undertaken, probably for the first time on Solomon Islands.

From the available information, aquifers can be divided into two types, alluvial and limestone. All the holes drilled near the coast and in areas east of Honiara in general ecountered alluvium.

Aquifers are confined to sandy clay, sand and gravel. The depth of the aquifers varies in different areas. Another type of aquifer occurs in limestones (e.g., on Noro and Bellona).

Most of the production wells have potable water. During drilling, water samples are collected and submitted for chemical analysis. The results obtained are compared with the standards set by the World Health Organization and if they fall within permissible limits it is recommended that the wells should be exploited. Those drilled for agricultural and industrial purposes do not undergo the same scrutiny. At present the Geochemical Laboratory of the Ministry of Natural Resources carries out all the analyses.

Despite the large number of boreholes drilled in some of the islands, knowledge of the ground-water resource is still limited, since there has not been any hydrogeologist employed by the Government to plan and co-ordinate ground-water investigations.

All the ground-water investigations are carried out under the auspices of the Ministry of Works and Public Utilities Drilling Section, though personnel from the Geological Division are often called upon to site boreholes. The Drilling Section is at present concentrating on Noro. An Australian consultant has won a contract to carry out detailed pumping tests and reappraise the ground-water potential of Noro. It is envisaged that some more boreholes will be drilled in the area early in 1981.

Ground-water development

Since 1976, three ministries have been involved in ground-water development: the Ministry of Works and Public Utilities, the Ministry of Health and Medical Services and the Ministry of Natural Resources. Their activities are co-ordinated by the Water Resources Committee. The Committee formulates policies on surface-water and ground-water development. The three ministries involved are represented on the Committee.

Before 1976, drilling was done by the then Geological Surveys Department. The drilling rigs and personnel have since been transferred to the Ministry of Works and Public Utilities. Two Pilcan rigs of 2 1/2 and 6 1/2 tons, respectively, are used. Some of the drilling personnel have undergone training overseas.

The number of metres drilled yearly varies, depending on the demand for ground water and the availability of serviceable drilling equipment. Almost all the boreholes drilled are for water, but the Drilling Section sometimes sinks drill holes for foundation investigation.

Problems related to ground-water development, other than those of finance and expertise, can be categorized into two depending on the types of aquifers: aquifers found in alluvium are subject to subsidence if overdrawn and if there is quicksand above or below the aquifer; shallower wells may be contaminated from the surface; aquifers found in limestone face the problem of overdraught and saline intrusion (e.g., on Noro and Bellona).

Conclusion

Since the population is growing and economic activity is increasing, and since surface water is unevenly distributed, ground water will become more significant as a natural resource from the economic and social point of view. The ground-water resources of the country have not been fully explored and assessed. Exploration and development are hampered by lack of expertise and the fact that they are very costly processes. Only those with financial means can afford to have wells more than 10 m deep. The Government of Solomon Islands charges $SI 197/day (US$ 246/day) for every borehole drilled. It does not charge on the basis of the number of metres drilled. No data are available on the cost of ground water at the well.

Selected References

Buckley, D. K. 1980. Noro Water Supply Investigation, February-May 1980. Applied Geophysical Unit, Inst. Geol. Sci. WD/OS/80/11.

Coleman, P. J. 1965. Stratigraphical and structural notes on the British Solomon Islands with reference to the First Geological Map, 1962. Br. Solomon Isl. Geol. Rec., vol. 2 (1959-1962), pp. 17-31.

Grover, J. C. 1957. Some geographical aspects of the British Solomon Islands in the Western Pacific. The Geog. Journ., vol.CXXIII, Part 3, pp. 297-317.

Hackman, B. D. 1980. The geology of Guadalcanal, Solomon Islands. Overseas Mem. Inst. Geol. Sci., No. 6, pp. 10-16.

Statistics Office, Ministry of Finance, Honiara, Solomon Islands. 1979. Statistical Year Book and Bulletin, No. 24/79.

Wall, J. R. D., and J. R. F. Hansell. 1972. Soils of some Quaternary marine terraces in the British Solomon Islands Protectorate and some problems in their agricultural use. New Zealand Journ. Agri. Res., 16, pp. 271-286.

TOKELAU

(Territory administered by New Zealand)

Area: 10 km^2

Popoulation: 2,000 (United Nations estimate, 1977)

General

The Tokelau Islands lie between latitudes 8° S and 10° S and longitudes 171° W and 173° W. They consist of 110 islets arranged in three low-lying coral atolls: Fakaofo, Nukunonu and Atafu (see map 40).

The islets, which surround a relatively shallow lagoon, vary in size from less than 100 m to 7 km in length and up to 300 m in width. In most cases, the highest point is the beach-head on the ocean side, which generally does not exceed 5 m above mean sea level.

The climate is of the maritime equatorial type. Average annual rainfall is about 2,900 mm, the highest rainfall occurring from December to February and the lowest from April to September. The average temperature is 28° C, with diurnal variations of less than 5.5° C, and the average relative humidity is 85 per cent. Evapotranspiration is estimated at 1,600 mm.

Geology

The islets are built up of coral sand and fragments, generally resting on old reefs of coral-limestock rock. Because of the high permeability of the unconsolidated material there is virtually no surface run-off. Excess precipitation percolates down and recharges the fresh-water body (the lens) floating on the underlying saline water.

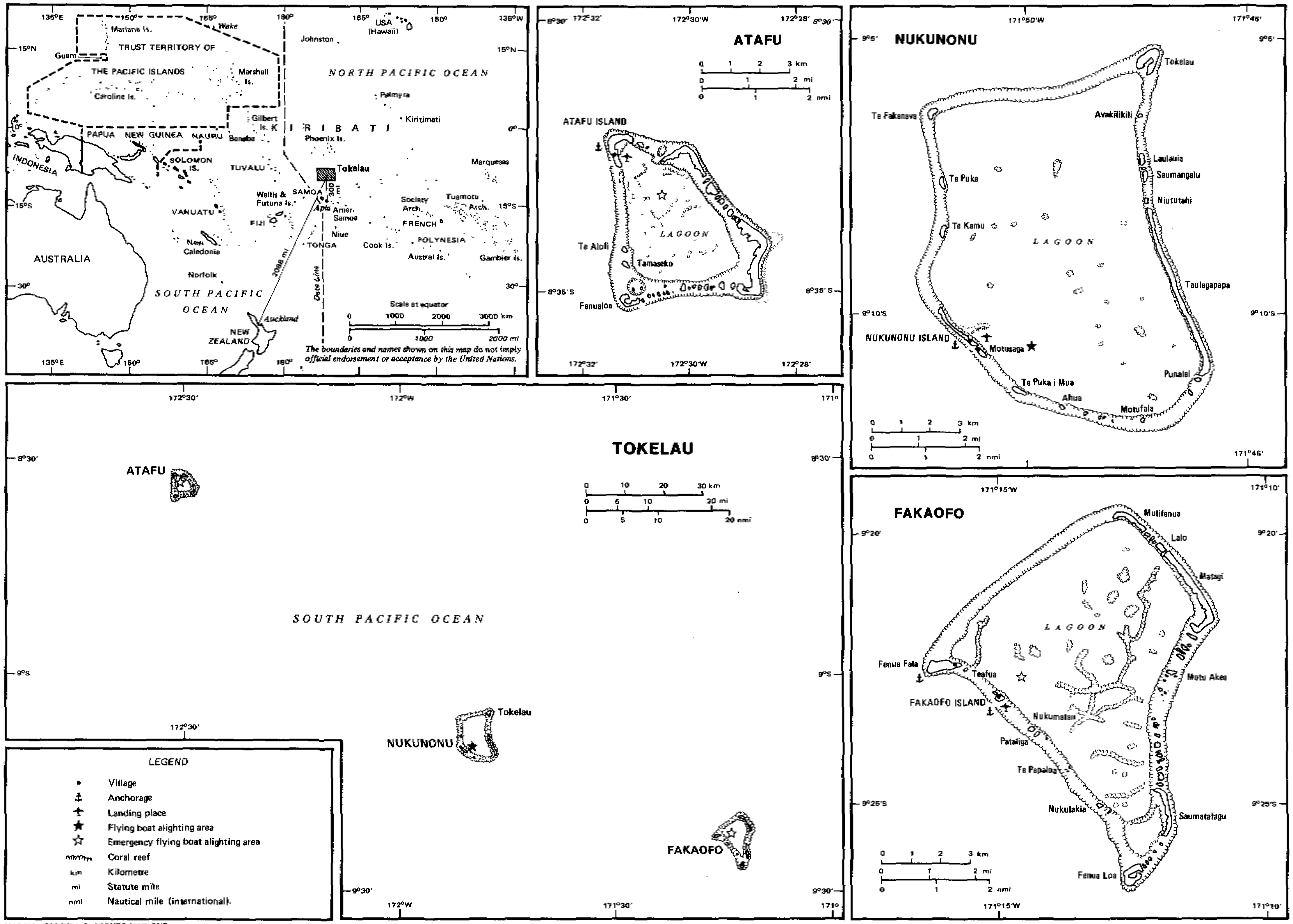
Ground water

To date, no systematical hydrogeological investigations have been carried out in Tokelau and very little is known about the thickness and extent of the fresh-water lenses on the majority of the islets or their sustainable yields.

Observations at a number of hand-dug wells on the inhabited islets indicate that lenses are generally very thin. The quality of the ground water is poor as a result of the mixing of fresh and saline water and bacteriological contamination. Some islets seem to have slightly raised water-tables (up to 0.6 m above sea level), but sustainable yields are low due to low permeability and salt-water intrusion.

Ground water in Tokelau will have limited economic and social value. The inhabitants will continue to depend on the collection and storage of rain water for their domestic supply. On only a few islets can ground water of an acceptable chemical quality be developed to supplement the rain water supply, but its use will have to be restricted to purposes other than cooking and drinking.

MAP 40



MAP NO.2898 REV. 3 UNITED NATIONS
DECEMBER 1982

Selected references

Kammer, D. The hydrogeology of Tokelau. Pacific Island Water Resources, W. R. Dale, ed. (Wellington, New Zealand, Department of Scientific and Industrial Research, 1981), pp. 91 and 92.

Richard, C., D. Kammer and E. Burk. October 1975. Report on a visit to the Tokelau Islands. Unpublished report in the files of the United Nations Development Programme, Samoa.

TONGA

Area: 699 km^2

Population: 90,000

Conditions of ground-water occurrence

Geography and physiography

Tonga, located in the south-western Pacific Ocean between latitudes 15° S and 22° S and longitudes 173° W and 175° W, is divided into four main groups comprising more than 50 islands, 36 of which are inhabited (see map 41). The economy is based predominantly on agriculture with export crops principally of coconut products and bananas.

The most southerly and principal group consists of Tongatapu and a number of small islands, including Eua and Ata to the south. Tongatapu, about 30 km long and 14 km at its widest part, is some 260 km^2 in area, and is the largest island in the country. Mostly flat, it slopes gently from south to north and reaches a maximum elevation of 65 m above sea level in the east. The capital and seat of Government is Nuku'alofa, where most of the group's population of 48,000 reside.

The central Ha'apai Group and Nomuka Group form a scattered archipelago of small islands with a total population of some 10,600 people resident mainly around the main village of Lifuka, about 160 km from Nuku'alofa.

The most northerly islands, the Vava'u Group, support a population of some 13,500 on the main island of Vava'u (elevation 201 m) and surrounding islands. The chief village, Neiafu, is 273 km from Nuku'alofa.

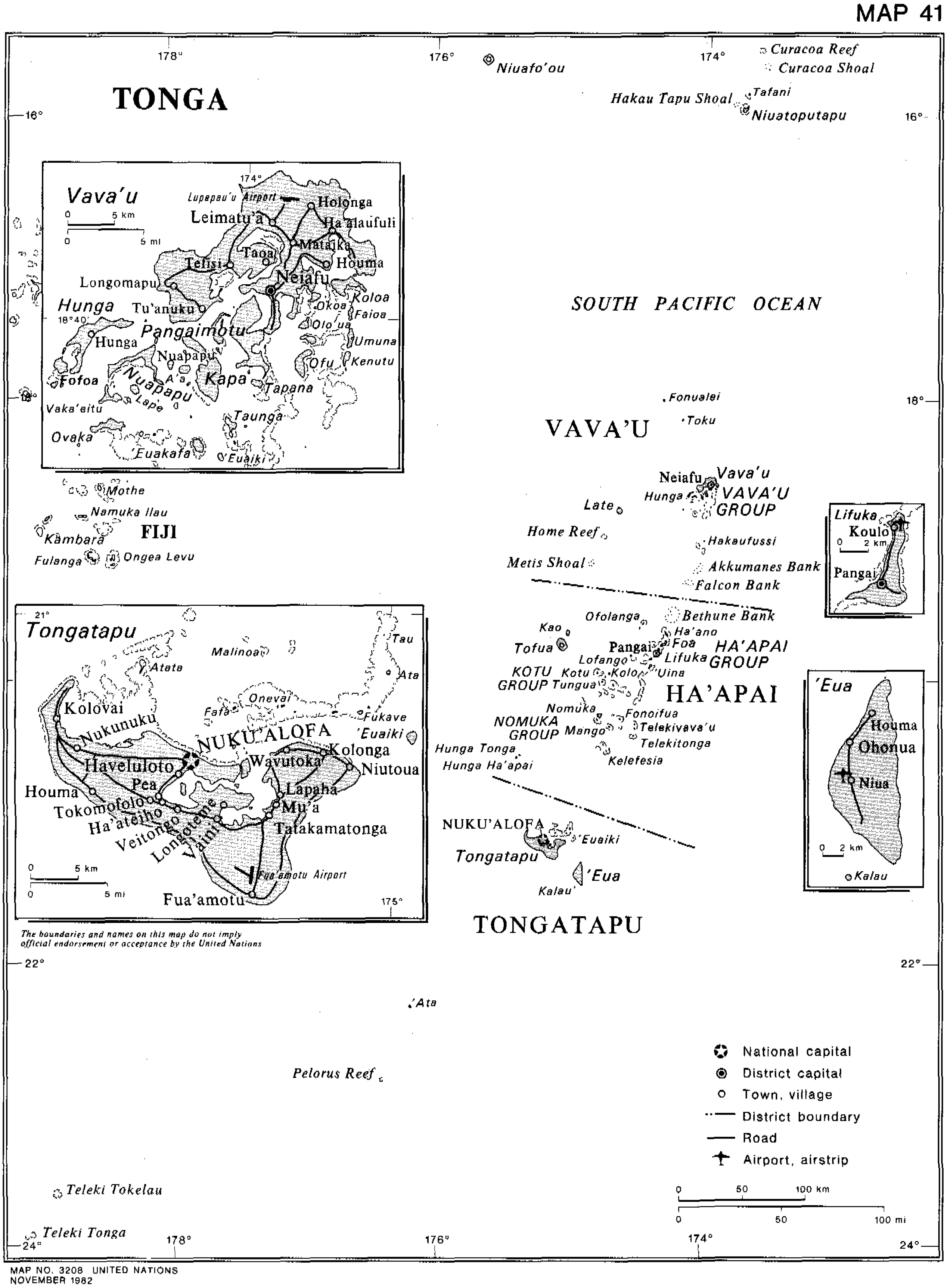
Climate

The climate is semi-tropical with moderate rainfall and high humidity during the wet season which extends from December to April. Meteorological records from Nuku'alofa show temperatures ranging from 10.6° C to 32.5° C (mean average, 23.5° C) and humidity from 44.5 per cent to 100 per cent (mean average, 76.9 per cent). Mean annual rainfall from records kept between 1949 and 1970, amounted to 1,801 mm at Nuku'alofa and to 2,236 mm on Vava'u.

Geology

The Tonga Ridge is a young volcanic island arc uplifted between the Tonga Trench to the east and the Lau Basin to the west. The ridge originated in the Eocene and is formed of mildly metamorphosed basic-intermediate lavanas, gabbros and tuffs, overlain by thick Eocene limestone, Miocene carbonates, slope breccia and volcaniclastics, and Pliocene to Holocene coralline limestone.

All the islands on the eastern side of the ridge are limestone covered. On Tongatapu, oil drillholes penetrated through 137 m of reef limestone and alternating coarse and fine detrital sediments rich in volcanic lithoclastics to a total depth of 1,685 m. On Vava'u Quaternary tilted terraces were cut in coral limestone, underlain by massively bedded detrital limestone, soft chalky limestone and thin packstone.


MAP 41
TONGA
Niuafo'ou
Curacoa Reef
Curacoa Shoal
Hakau Tapu Shoal
Tafani
Niuatoputapu
SOUTH PACIFIC OCEAN
Vava'u
Leimatu'a
Holonga
Ha'alaufuli
Neiafu
Hunga
Pangaimotu
Kapa
Fofoa
Ovaka
Fonualei
Toku
VAVA'U
VAVA'U GROUP
Late
Home Reef
Metis Shoal
Hakaufussi
Akkumanes Bank
Falcon Bank
FIJI
Lifuka
Koulo
Pangai
Ofolanga
Bethune Bank
Kao
Tofua
HA'APAI GROUP
KOTU GROUP
HA'APAI
NOMUKA GROUP
Nomuka
Mango
Hunga Tonga
Hunga Ha'apai
Kelefesia
Tongatapu
NUKU'ALOFA
Kolovai
Houma
Kolonga
Niutoua
Fua'amotu
Fua'amotu Airport
The boundaries and names on this map do not imply official endorsement or acceptance by the United Nations
'Eua
Ohonua
Niua
Kalau
TONGATAPU
'Ata
Pelorus Reef
Teleki Tokelau
Teleki Tonga
National capital
District capital
Town, village
District boundary
Road
Airport, airstrip
MAP NO. 3208 UNITED NATIONS
NOVEMBER 1982

In the west, volcanic islands form a chain along the western margin of the Tonga Ridge close to the Lau Basin. During the past 200 years, more than 35 eruptions have been recorded from these islands, which represent the summits of structures rising between 1,500 m and 2,500 m from the sea floor. They are named Hunga Ha'apai, Hunga Tonga, Tofua, Kao, Late, Niuatoputapu and Tafahi and are composed predominantly of basaltic andesite and andesite, with abundant scoria, lapilli, ash and spatter material. In 1846-1847, 1939 and 1943, Fonulei erupted dacitic lava, pumice and ash. Metis Shoal, in frequent rhyolitic eruptions between 1851 and 1968, is recorded as building up to 24 m above sea level before erosion reduced it again to wave level.

It is considered that a wide area of the Tonga platform is covered by thick sediments ranging from Lower Miocene to Lower Pliocene age and that these are at least 1,500 m thick beneath Tongatapu. The area was probably dotted with intermittently active volcanoes, between which sediments were deposited in shallow to deep water environments. The sediments are mainly coarse to fine grained volcaniclastics, but reef, bioclastic, and foraminiferal limestones are also present.

Ground-water resources

Regional availability

There are no large surface-water supplies in Tonga and the source of domestic, agricultural and industrial water is either roof catchment or hand-dug or drilled wells tapping a lens of fresh water floating on denser sea water.

Little is known about ground water on the volcanic islands, but more than 50 dug or drilled wells from a few metres to 62.5 m deep are recorded in coral limestone on Tongatapu. The logs are all broadly similar and record hard and soft coral limestone beneath weathered surficial clay. The softer limestone, open textured and composed mainly of comminuted coral fragments, transmits water rapidly. It is estimated that between 25 and 30 per cent of the average annual rainfall penetrates to the water table, and that permeability may reach 1,300 in/day. The contours of the water table in Tongatapu are shown in map 42.

At the Mataki'eva Water Reserve the surface of the fresh-water lens is from 50 to 75 cm above sea level. The lens does not occur at the coast and reaches a total thickness of about 20 m in the interior. Transmissivity is calculated at 1,200 m^2/day. Draught from the fresh-water lens on Tongatapu amounts to about 300 m^3/day (1978).

Quality

On Tongatapu, chloride content ranges from 997 mg/l near the coast in the west to about 20 mg/l at Fua'amotu Airport in the east. Chloride concentrations are largely the result of chloride ions dispersing upwards through the salt-water/ fresh-water interface and may be decreased by reducing abstraction rates, or possibly by artificial recharge of the ground water.

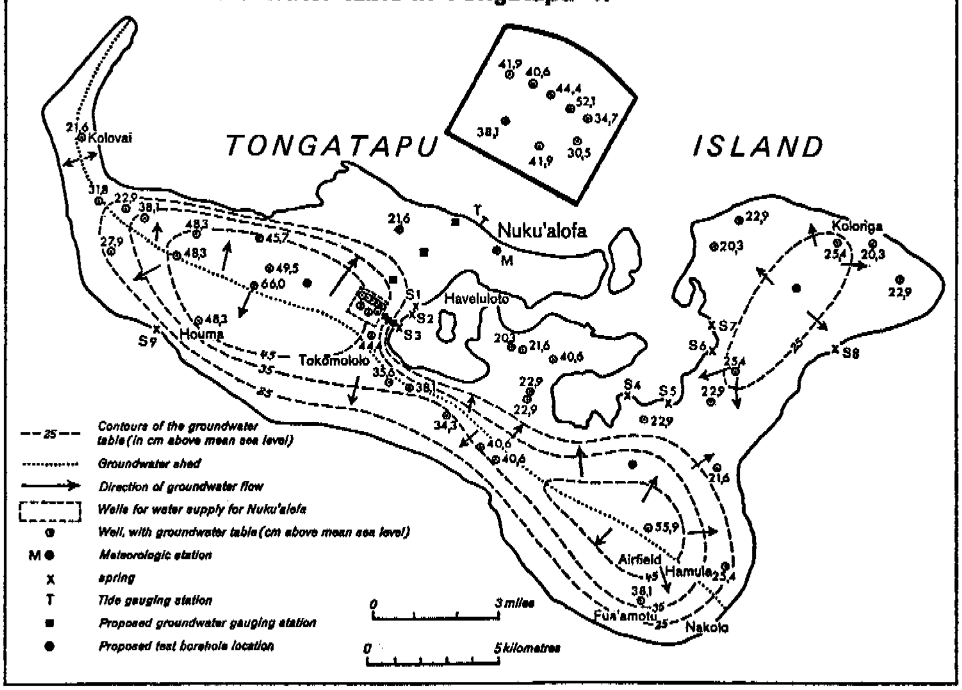
Ground-water administration and servicing

The water resources are administered by the Tonga Water Board under the direction of a manager who is responsible for development and reticulation of all water, but principally for the ground water from a Water Reserve area at Mataki'eva, near Nuku'alofa.

Map 42. Tonga: ground-water table in Tongatapu Island

MAP 42

TONGA • Groundwater table in Tongatapu I.



8204.86x

Drilling organizations

Initially holes were hand dug or drilled with a Southern Cross percussion rig. In the mid-1970s, however, under the auspices of a Bilateral Aid Programme funded by New Zealand, a Sullivan 37 drilling rig was donated to the Government of Tonga and during the years that followed local workers were recruited and trained in its use.

Selected references

Ewart, A., R. N. Brothers and A. Mateen. 1977. An outline of the geology and geochemistry, and the possible petrogenic evolution of the volcanic rocks of the Tonga-Kermadec-New Zealand Island Arc. Journal of Volcanology and Geothermal Research (2), pp. 205-250.

Hunt, B. H. 1978. An analysis of the Groundwater Resources of Tongatapu Island. Civil Engineering Research Report No. 78-15. University of Canterbury, Christchurch, New Zealand, 20 pp.

Katz, H. R. 1976. Sediments and the tectonic history of the Tonga Ridge, and the problem of the Lau Basin. Technical Bulletin No. 2. International Decade of Ocean Exploration (IDOE) Workshop, Suva, Fiji, September 1975, jointly sponsored by the International Oceangraphic Commission and the Committee for Co-ordination of Joint Prospecting for Mineral Resources in the South Pacific Offshore Areas (CCOP/SOPAC) of the Economic and Social Commission for Asia and the Pacific, pp. 153-165.

Pacific Islands Business and Trade Directory, 1978. 23rd edition. Universal Business Directories, Auckland, pp. 449-461.

Pfeiffer, D. I. 1971. Outline of the hydrogeology of the Island of Tongatapu (Kingdom of Tonga, South Pacific). Advisory Services Report, United Nations Economic Commission for Asia and the Far East, 16 pp.

Waterhouse, B. C. 1974. Tongatapu Island Water Supply, Kingdom of Tonga. New Zealand Geological Survey Report, Otara, 8 pp.

__________. 1976. Nuku'alofa Water Supply. New Zealand Geological Survey Report, Otara, 7 pp.

__________. The hydrogeology of the Southern Cook Islands, Niue and Tonga. Pacific Island Water Resources, W. R. Dale ed. (Wellington, New Zealand, Department of Scientific and Industrial Research, 1981), pp. 57-74.

TRUST TERRITORY OF THE PACIFIC ISLANDS

Area: 1,779 km^2

Population: 126,000 (United Nations estimate, 1977)

Overview

The Trust Territory of the Pacific Islands lies within the area known as Micronesia. It consists of more than 2,000 islands and atolls spread over 7.8 million km^2 of the west central Pacific Ocean between the equator and latitude 20° N and from longitudes 130° E to 180° E (see map 43). The Trust is administered by the United States of America for the United Nations, but this political arrangement is in the process of dissolution as the various districts of the Territory assume a greater measure of self-government.

In the vast ocean expanse of the Trust Territory, only 1,779 km^2 of land area occurs, distributed among 2,141 islands about 130 of which are inhabited. The largest single island is Babelthuap in the Palau group with an area of 334 km^2. Many atoll islands of less than 1 km^2 are inhabited. The highest point, an elevation of 964 m, is on the island of Agrihan (area 47.4 km^2) in the Mariana chain.

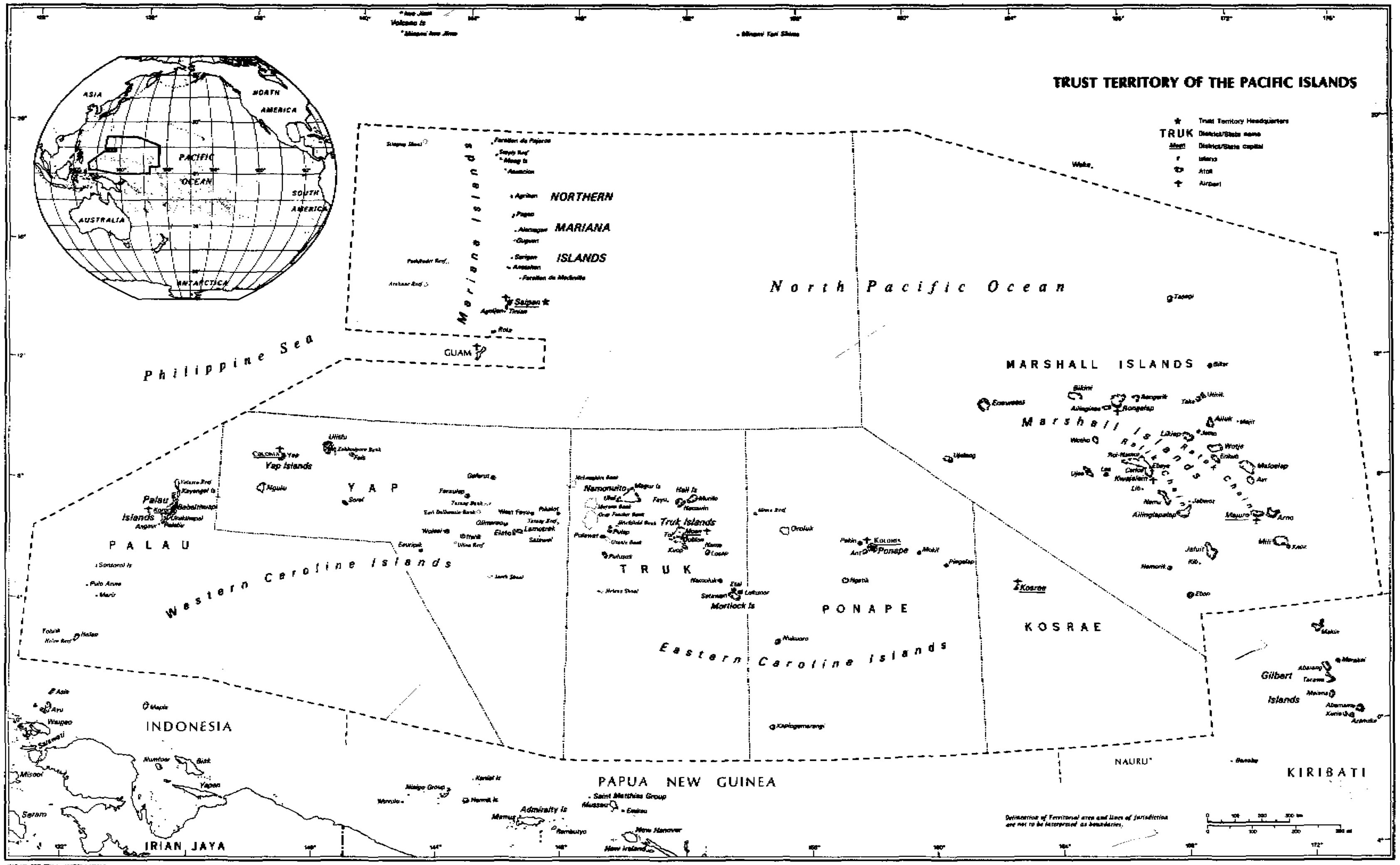
The traditional geographical names given by the Europeans to the islands of Micronesia are: the Western Caroline Islands, which include the Palau and Yap groups; the Eastern Caroline Islands, consisting of the Truk and Ponape groups; the Mariana Islands; and the Marshall Islands. Guam is the largest of the Mariana Islands but has been a Territory of the United States since 1898 and was not included in the Trust.

As the Trust Territory, the islands were divided into administrative districts named the Palau, Yap, Truk, Ponape, Marshall and Mariana districts. The first group to negotiate its political status was the Mariana District, which has become a part of the United States of America as the Commonwealth of the Northern Mariana Islands. Upon satisfactory termination of the Trusteeship Agreement, but in some sort of association with the United States, the Marshall and Palau districts will form separate self-governing entities; and Yap, Truk, Ponape and Kosrae districts have become the Federated States of Micronesia.

Climate

Throughout the Micronesian sector of the Pacific Ocean the climate is generally similar, notably in being warm and humid. The annual average temperature at sea level is 27.2° C, although it may be a degree cooler in the northern part of the Mariana chain and half a degree warmer near the equator. The average seasonal range in temperature is less than 2° C and the daily range is less than 7° C. The minimum recorded temperature is about 20° C and the maximum about 35° C. The relative humidity normally ranges from 60 to 100 per cent, the average being 80 per cent. Rainfall is plentiful, varying at the coast from a low annual average of 2,160 mm in the Marianas to 4,900 mm on Ponape. Probably the highest rainfall occurs in the mountainous interior of Ponape where the annual average is of the order of 10,000 mm. Throughout the entire region the wettest months are July to

MAP 43



Map 43. Trust Territory of the Pacific Islands

the end of November and the driest, January to the end of April. During the drier season the trade winds are dominant; in summer and autumn the doldrums often oppress the islands and powerful storms (typhoons) may afflict the Caroline and, especially, the Mariana groups.

Geology

The islands of Micronesia fall into two major geological provinces of the central and western Pacific Ocean, one province lying immediately west of the great trenches into which the Pacific tectonic plate is being subducted and the other on the plate itself. The trenches are coincident with what has been called the andesite line, to the west of which the islands lie along arcs parallel to the trenches and are presumed to have continental affinities. This province may be more properly called the andesitic province because of the nature of its typical volcanism. To the east lies the oceanic province, whose volcanoes are characteristically dominated by basaltic rocks rather than the andesitic pyroclastics typical of the arc islands. In both provinces basic igneous rocks occur as lavas and pyroclastics over the range from basalt to trachyte. In the andesitic province submarine pyroclastics predominate; in the oceanic province most exposed volcanic deposition has been subaerial.

The volcanic rocks of the andesitic province are as old as early Tertiary (Paleocene-Eocene) and on most of the major islands are no younger than Oligocene. Several volcanoes in the Northern Marianas are still active, however. In the oceanic province the exposed volcanics are younger, primarily of Pliocene age and later. None is known to have been historically active.

The regional geophysical phenomenon that differentiates the islands of the two provinces is the emergence-submergence behaviour of the initial volcanic masses with respect to sea level. Except for eustatic changes in sea level, which are small compared with total changes in elevation, islands of the andesitic province rise and those of the oceanic province subside. The directions of movement are likely to be monotomic, exclusive of the relative movements of up to 30 m above and 100 m below present sea level owing to the melting and forming of the Pleistocene glaciers.

Hydrogeological conditions

Whether an island rises or subsides profoundly affects its hydrogeology. After the cessation of volcanic activity, limestones in the form of coral reef associations were deposited on the arc islands whose surfaces lay below sea level, and also along the coasts of oceanic islands and those arc islands whose surfaces reached above sea level. As arc islands rise, the coral reef associations become exposed and new reefs grow along the expanded margin of the island. Some arc islands are entirely covered with limestone, their surfaces reaching to hundreds of metres above sea level; other islands embrace both raised limestone and exposed volcanics. The coral reef growth around the margin of the oceanic islands, on the other hand, subsides with the volcanic mass while new growth attempts to keep pace with the subsidence. Fossil reefs generated during eustatic high sea levels may rim oceanic islands but do not dominate the insular hydrogeology as limestones so often do in the arc islands. The ultimate fate of a subsiding island is an atoll, as Darwin postulated more than a century ago.

In Micronesia the only significantly exploitable aquifers are composed of limestones of the fossil reef facies, the thicknesses of which are usually less than 200 m. Volcanic rocks in both the andesitic and oceanic provinces are poorly permeable and rarely act as worthy aquifers. This is in sharp contrast with the oceanic islands to the east of Micronesia, such as the Hawaiian islands, Samoa, and the Society Islands, where basalts are the premier aquifers. The inhabitants of the high oceanic and limestone-free arc islands of Micronesia are reduced to exploiting the weathered zone of volcanic rocks for ground water.

Thus, the nature of the hydrogeology of an island in Micronesia depends, first of all, on whether the island is in the andesitic or oceanic province. If it is an andesite island, hydrogeology further depends on the extent and thickness of raised limestones. If it is a high oceanic island, hydrogeology is dominated by low permeability volcanics and their somewhat more favourable weathered zone. If it is oceanic but an atoll, the only available formation is limestone lying a few metres above sea level.

Micronesia is fairly well divided between the andesitic and oceanic provinces. More individual islands are oceanic, but the andesite islands account for about 60 per cent of the total land area. Included in the andesitic province are the main Yap islands, the main Palau islands and the Mariana Islands; atolls that are administratively part of the Palau and Yap districts are actually on the oceanic side of the deep trenches. The oceanic province embraces the Truk Islands and atolls, the Ponape Islands and atolls and the Marshall Islands, all of which are atolls.

References

There is extensive literature covering the hydrology and geology of much, but not all, of Micronesia. This literature is most readily available at the Micronesian Area Research Center at the University of Guam, the Pacific Collection at the University of Hawaii, the United States Geological Survey offices at Honolulu and in Guam, and the United States Geological Survey Library at Reston, Virginia. Publications that give an overview of elements of hydrology of Micronesia are as follows:

Mink, J. F. 1970. Ground-water development in the Trust Territory. Report to the Trust Territory Administration (not widely circulated).

United States Department of the Army. 1971. Pacific Islands and Trust Territories. DA Pamphlet 550-10.

United States Geological Survey. (Annual). Water Resources Data for Hawaii and Other Pacific Areas. Water Data Report HI-[year]-2 series, United States Department of the Interior.

Palau Islands

General

The Palau Islands, forming a chain 160 km long north-west of the island of New Guinea and south-east of the Philippines, are the westernmost district of Micronesia. The group comprises more than 200 islands with a total land area of

464 km^2, but fewer than 10 of them exceed 1 km^2 in area. The largest island, Babelthuap, has an area of 334 km^2; no other island of the group exceeds 50 km^2. Only eight of the islands are regularly inhabited. The estimated total population is 15,000.

The principal islands lie west of the Palau trench. Babelthuap consists almost entirely of volcanic rock, as do the smaller islands of Arakabesan and Malakal, while Koror, Peleliu, Angaur and Urukthapel are partially or completely capped with raised limestone. All of the islands lie below an elevation of 230 m. On Babelthuap about 80 per cent of the coast is rimmed with mangrove. On some islands raised limestones form a sharp shoreline. Six atolls lying to the east of the Palau trench are included in the administrative district.

Climate

On Koror, the capital island of the group, the average annual rainfall is 3,810 mm. On none of the major islands does the average fall below 3,225 mm. Perennial streams occur on the volcanic terrain of Babelthuap, but not in the limestone caps of other islands where run-off is transient and drainage primarily internal. About 55 per cent of Babelthuap's rainfall flows to the sea in streams, yet during the drier months even the largest streams yield less than 10 l/sec. A small lake, about 50,000 m^2 in area, is found in the upper drainage of Babelthuap's Ngardok River, the largest stream in the Palau group.

Geology

The volcanic rocks of the major islands are predominantly composed of andesitic pyroclastics, much of it originally deposited below water, but include flows and breccia of basalt, andesite and dacite. The earliest rocks, the Babelthuap and Aimeliik formations, erupted in the early Tertiary (Paleocene-Eocene) and were followed by the Ngeremlengui formation of Oligocene time. Each of these formations is more than 600 m thick. Volcanism ceased, followed by genesis of the Airai clay during the Miocene-Pliocene period. The limestone series (Peleliu and Palau formations) formed during Pliocene to Pleistocene times. The Palau limestone is of the order of 215 metres thick and the Peleliu about 30 m thick. The vocanic rocks are disturbed by small-scale folding and faulting.

Ground water

Throughout their history, the people of Palau have relied on a variety of sources for a water supply. Rain catchment, stream flow, seepages and dug wells were, and still are, utilized by the native population. During Japan's administration a few small stream catchments were built, numerous dug wells excavated, and a limestone spring on Koror was developed. Immediately following American occupation about 40 wells were dug in the limestone on Peleliu and nine on Angaur, many of them yielding brackish water. At present surface water is the chief source of supply for the major population areas of Koror and Babelthuap.

The essential geology and hydrology of the Palau Islands have been studied by the United States Geological Survey which continues to operate a data collection programme on the major islands. Through these investigations, it has been concluded that the ground-water resources of the volcanic rocks are not capable of extensive exploitation, while the limestones of Peleliu and Angaur are moderately good aquifers. However, the population centre of Koror is remote from any sizeable limestone aquifer.

On Angaur and Peleliu ground water occurs as a basal lens with a head of less than 0.5 m. Wells are shallow and rates of extraction low to avoid sea-water intrusion. On the volcanic island of Arakabesan two shallow wells were drilled in the weathered zone: one was a failure and the other yielded less than 1 l/sec. Dug wells exploit the weathered zone on all the volcanic islands but rarely yield as much as 1 l/sec. Wells have not yet been drilled deep into the volcanic formations.

While Palau was a district within the Trust Territory, the central water system serving the administration centre on Koror was operated by the Government. A similar arrangement will continue under the new political status. However, elsewhere village and individual water systems serve the people. The population of 6,000 or so on Koror is supplied by surface-water catchments on Babelthuap and from a small limestone spring on Koror. Surface water will be further developed to serve the growing population. Ground water is not expected to play a major role in either Koror or Babelthuap.

The small populations of the atoll islands and of Angaur and Peleliu must depend on dug wells to supplement rain catch. There are no firm plans to enhance ground-water development and production in any of the Palau Islands.

References

No published work deals specifically with the ground-water resources of Palau. The only extensive investigation of the geology and hydrology of the islands was completed by the United States Geological Survey, but few copies of the report were printed. Numerous engineering consulting reports on water supply have been written but their distribution has been even more limited than that of the United States Geological Survey report. Data records for five stream gauges on Babelthuap are published yearly by the United States Geological Survey. The principal reference for hydrology and geology is as follows:

Mason, A. C., and others. 1956. Military Geology of Palau Islands, Caroline Islands. United States Geological Survey for the United States Army.

Yap Islands

General

The Yap Islands, like Palau, are part of the Western Caroline Islands. The group contains four major islands - Yap, Tomil, Rumung, and Map - and more than 20 atolls and smaller islands. The total area is 120 km^2 of which the largest island, Yap, accounts for 56 km^2. Ulithi, the largest atoll, includes 40 islets with a total land area of 5 km^2. The total population of the group is about 8,000 people, about 40 per cent of whom live on Yap. Ulithi has a population of 600 to 700.

Climate

At Colonia, the administration centre, the annual average rainfall is 3,025 mm. About 57 per cent of the total rain is discharged by streams, none of which drain an area larger than 3 km^2. Some are weakly perennial during the dry season, providing, at most, about 1 l/sec.

Geology

The major islands lie west of the Yap trench and are volcanic with no limestone except near sea level. The atolls lie in the oceanic province to the east of the trench. The volcanic islands are formed of low hills below a maximum elevation of 172 m and of small plateaux. The hills plunge into the sea, leaving little space for coastal flats. Mangrove is common along the coast.

Yap is unique in Micronesia in that basement metamorphic rocks are exposed. This basement consists of green amphibolite schist (Yap formation) of an age much older than the Miocene when andesitic volcanism was active. The volcanics (Tomil formation) were preceded by deposition of breccias and gravels of the Yap formation, which was laid down in Eocene-Oligocene time and in places is more than 75 m thick. The Tomil formation consists of pyroclastics and lava, all deeply weathered. The only limestone on the major islands are spotty exposures at low elevention, the product of eustatic changes of sea level in the Pleistocene. Alluvium covers the lower reaches of streams and serves as the substrate for coastal mangrove. The atolls, of course, are composed only of low-lying limestone.

Ground-water resources

The United States Geological Survey made fundamental geological and hydrological studies of the major islands 20 years ago and since then numerous engineering consulting reports on water supply have been prepared, the most recent in 1979, during which the exploratory drilling programme was completed. Geophysical methods have not been employed to locate aquifers.

Without raised limestone formations the prospect of producing large supplies of ground water are slim. The fresh metamorphic and volcanic rocks are extremely poor aquifers; only their weathered zones provide a reasonably permeable medium. Yields from the weathered zone are small but apparently reliable. On the island of Yap a weathered zone aquifer of about 100 hectares has been identified. Similar small aquifers probably occur on the other major islands. Also forming permeable aquifers, but of very small size, are recent sediments at the heads of the larger valleys.

The weathered zone is as much as 30 m deep, and the basal 15 to 20 m is of aquifer quality. The water table generally lies less than 5 m below ground surface. Pumping tests using borings 50 mm in diameter at rates of less than 1 l/sec have indicated aquifer and well characteristics, as shown in table 45.

Table 45. Trust Territory of the Pacific Islands, Yap Islands: aquifer characteristics

Aquifer	Depth of well (m)	Specific capacity (1 sec/m)	Hydraulic conductivity (m/day)	Trans-missivity (m^2/day)
Weathered zone of volcanics	< 30	0.3	0.3	10
Metamorphic rock (1 successful test, 2 failures)	30	0.2	0.1	3

The people of Yap have resisted changing their traditional ways of living and most of them continue to rely on streams, seeps, dug wells and catchments for water supply. Coconuts provide the primary drinking fluid of the village people. In 1979 several test borings were drilled into volcanic rocks and pumping tests indicated that small yields could be extracted from the weathered zone.

Ground-water exploration has only just begun in the Yap Islands. The weathered zone appears to be the most promising aquifer but the main volcanic core has not been investigated to determine whether permeable layers occur.

A limited central water system serves Colonia and some villages along the pipeline route from the stream diversion (Gitam Dam) to the town. Elsewhere villages and individual families provide their own supply. Of approximately 91 villages on the four main islands, seven have village-wide systems.

Less than 10 l/sec adequately supply the central system at present. Ground water from small capacity wells (less than 1 l/sec in the weathered zone is seriously being considered to help accommodate future demand. If urbanization takes place, more ground water will be required. The population of the group is expected to double to 10,000 in the next two decades. On the atolls people will continue to obtain fresh water by simple traditional means.

References

The basic geological and hydrological description of the Yap group was completed in 1960 by the United States Geological Survey. Copies of the report have not been widely distributed, nor were many copies printed. In 1979, T. Nance reported results of an exploratory drilling programme but his report is not likely to be available except in Guam, Hawaii and Yap. The following reports constitute the main references in respect of Yap:

Johnson, C. J., R. J. Alvin and R. L. Hetzler. 1960. Military Geology of Yap Islands, Caroline Islands. United States Geological Survey for the United States Army.

Nance, T. 1979. Yap Islands Ground Water Exploration. Lyons Association, Inc., report to Government of Yap State.

Truk Islands

General

The Truk District of the Eastern Caroline Islands includes the large Truk lagoon complex and many atolls to the east and west of it. The six major islands, all of them volcanic, are part of the lagoon and account for 70 per cent of the total district land area of 120 km^2. The largest island, Tol, has an area of 34 km^2 and Moen, the second largest and district centre has an area of 19 km^2. The total population of the district is about 30,000, more than two thirds of which live on the islands of the lagoon.

All of the Truk islands are in the oceanic province and thus limestones occur only near sea level. The volcanic islands are mountainous and steep with coasts consisting of mangrove, embayments or sharp cliffs. The maximum elevation of 439 m is on Tol; on Moen the maximum is 370 m and on Dublon, another large island, it is 349 m.

Climate

On Moen, which is typical of the lagoon islands, the annual average rainfall is 4,065 mm. The average may be slightly less on the atolls. The volcanic islands are dissected by numerous small streams with drainage areas of less than 5 km^2. Some of the streams are perennial but are little more than seeps during the dry season.

Geology

The geology of the main islands has been studied in detail. They are remnants of a large shield volcano that is now partly submerged. Lava flows predominate but pyroclastic deposits are locally interbedded with the flows. The lavas consist of basalt, andesite and trachyte in massive units. Dykes intrude the lavas in some of the islands. Dips of the flow rocks are gentle, normally about three degrees, and faulting is either rare or concealed. Truk is a good example of a subsiding volcanic pile around which coral reefs grow and subside with the central mass.

Ground-water resources

The United States Geological Survey conducted the original geological and hydrological investigations and since then has continued a programme of subsidiary studies and data collection. Although geophysical techniques have not been employed in prospecting for ground water, many exploratory wells on the island of Moen have been drilled in an attempt to secure a stable water supply. Some of the borings were successful and have been converted to producing wells.

The fresh volcanic rocks either do not yield ground water or do so at minute rates. There are no limestones, except on the atolls, so that the only known exploitable aquifers consist of the weathered zone on the volcanics. Weathering may reach as deep as 60 m, although ordinarily it is much less. Breccia and conglomerate beds, and interflow brecciation may act as aquifers, but to date only the weathered zone has proved productive.

Ground-water development

Prior to 1975 several successful wells were drilled, and since then 23 test holes (200 mm in diameter) have been drilled on Moen, eight of which have become producing wells. Yields are small but adequate. Sustained pump rates of up to 4 l/sec have been achieved. One successful well, pumped at 2 l/sec has a specific capacity of 0.2 l/sec/m; another, pumped at 4 l/sec has a specific capacity of 1 l/sec/m. The best specific capacity attained 2 l/sec/m at a rate of 3 l/sec. The average depth of the wells is less than 50 m. More wells are scheduled to be drilled on Moen.

Drilling in Micronesia has been chiefly done with rotary equipment under contract to the Trust Territory administration. All of the wells on Moen, old and new, are in the vicinity of the government centre and discharge into a small unit system, which also obtains water from a 36-hectare catchment. The wells have been providing nearly 40 l/sec. Ground water is being considered as the primary supply to meet future population demands on Moen where the population is expected to increase to 15,000 by 1990.

On the other islands non-centralized village water systems dependent on dug wells and seepages will continue to function for some time in the future. The success of exploiting the weathered zone aquifer on Moen suggests that the same approach could be used on Dublon, Tol, Fefan, Uman and Udot. The atolls will always have to rely on catchment and dug wells.

References

Reports describing the hydrogeology of the Truk Islands, as is the case for much of the rest of Micronesia, are not widely distributed. The following reports are the principal references:

Davis, D. A. 1977. Records of ground-water exploration and development, 1975-76, Moen, Truk, Eastern Caroline Islands. Open File Report 77-739, United States Geological Survey.

Stark, J. T., and others. 1958. Military Geology of Truk Islands, Caroline Islands, United States Geological Survey for the United States Army.

Valenciano, S., and K. J. Takasaki. 1959. Military geology of Truk Islands, Caroline Islands. Water Resources Supplement to United States Geological Survey report to the United States Army.

Ponape Islands

General

The Ponape group in the Eastern Caroline Islands consists of the principal volcanic island of Ponape, including several satellite islands just off its coast; Kosrae (formerly named Kusaie), also a relatively large volcanic island, 450 km to the south-east of Ponape; and several atolls within 720 km of the main island. The total land area of the group is 455 km^2. Ponape accounts for 334 km^2 and Kosrae, 10 km^2. The largest atoll, Pingelap, has a land area of 1.7 km^2. Total population is about 25,000 people, two thirds of whom live on Ponape and one sixth on Kosrae.

Ponape and Kosrae are volcanic islands of the oceanic province. They are ruggedly mountainous with deep, narrow valleys and steep slopes. No sedimentary coastal plain of significance has formed, but mangrove swamps ring much of their inner coasts. Raised limestones do not occur, although modern reef growth is vigorous. The maximum elevation of 791 m is found in central Ponape; on Kosrae the maximum is 628 m.

Climate

The islands enjoy trade-wind weather from January to May and then suffer the doldrums for the following months. Rainfall is plentiful even at the sea coast (at the airport, the average annual rainfall is 4,900 m) and extremely high, probably in excess of 10,000 mm in the mountainous interiors of the main islands. Ponape has the largest rivers in Micronesia and most are perennial. The Nanepil River, draining to the north coast of the island, discharges annually an equivalent of 6,000 mm from its drainage basin above an elevation of 119 m.

Geology

Like the Truk and Marshall groups, the Ponape Islands are subsiding, but the degree of subsidence has not yet been determined. Apparently Ponape and Kosrae are young islands, although their geological history has not been unravelled because comprehensive surveys have yet to be undertaken. They are principally composed of lavas of varieties ranging from melanocratic basalts to trachytes, including olivine basalt, melilite basalt, nepheline basalt, andesite and trachyte. Pyroclastics, mostly as tuff, are less common than lavas and lava agglomerates. Small intrusives in the form of sills, dykes, and stocks occur. The rocks are massive and dense, individual units often exceeding 30 m in thickness and showing columnar jointing. Dips are slight and structural phenomena appear to be unimportant. Weathering has not been severe.

Ground water

Rainfall is so abundant that simple catchment and perennial streams have provided an adequate water supply for traditional living. There has been no compelling need to seek ground-water sources as a water supply, although dug wells are used, nor have hydrogeological studies been conducted. The Ponape Islands were not included in the extensive geological investigations carried out by the United States Geological Survey in Micronesia.

Aquifers have not been identified, exploratory drilling has not been undertaken, geophysical prospecting has not been tried, and no testing programme has ever been seriously recommended. Water supply for the District Center at Colonia on Ponape is obtained from the Nanepil River at a run-of-the-stream diversion where flow has never fallen below 45 l/sec. The reliable flow is about 175 l/sec, considerably in excess of present demand and adequate for projected growth well into the future. An additional reliable supply is obtainable from a second fork of the Nanepil. A need for ground-water development is not pressing.

Elsewhere on Ponape and Kosrae the villages are satisfactorily supplied by streams and catchments. The interiors of the islands remain in their natural condition; most inhabitation is along the coasts, thus minimizing pollution of streams. On the atolls catchments and dug wells are adequate. As elsewhere in Micronesia, drinking fluid is often obtained from fresh coconuts.

References

Few published reports deal with the water supply of the Ponape Islands. The United States Geological Survey maintains a stream-flow data collection programme and has made preliminary hydrological surveys. Several consulting engineering reports have been made but their scope is limited. Weather summaries are published by the United States Department of Commerce. During the Japanese administration two geological reconnaissances were made. The most complete study is as follows:

Tayama, R. 1936. Geomorphology, geology and coral reefs on Ponape Island. Contribution 23, Institute of Geology and Paleontology, Tohoku University (translated by the United States Geological Survey).

Marshall Islands

General

The Marshall Islands comprise about 1,150 islands distributed among 34 atolls and 870 reefs in an area of 466,000 km^2 of the central Pacific between the equator and latitude 10° N and longitudes 160° E and 180° E. Total land area is only 181 km^2. The largest single islands rarely exceed a few square kilometres, and the largest combined land mass within an atoll is the 16.3 km^2 of Kwajalein atoll. Most of the population of about 25,000 lives on four major atolls: Majuro, Kwajalein, Jaluit, and Arno. Majuro, the District Center, has the largest population, about 10,000, followed by Kwajalein. The climate is warm, changing very little throughout the year. Average rainfall is about 3,500 mm and the wettest months are October and November.

Geology

Every island is composed of a fossil reef association lying at an elevation of less than 10 m. The subsident volcanic basement on which the reefs grew normally lies 1,000 or more metres below sea level. The islands exist because the present sea level is moderately low compared with interglacial periods. A rise in sea level, such as occurred 120,000 years ago before the onset of the last major glacial age, would inundate all of the islands.

Ground water

Traditionally, the population depended on rain catchment, shallow dug wells, and coconuts for a water supply. The construction of the missile tracking centre on Kwajalein and the urbanization of Majuro created a need for central water systems in these two areas. At present the major source of water there is catchment from airfields and urban complexes.

The ground-water resources of the larger islands consist of fresh water floating as a thin lens on sea water in accordance with the Ghyben-Herzberg principle. Frequently only brackish water is obtainable. At best, small wells yielding less than 1 l/sec could successfully exploit the fragile lenses for fresh water. Dug wells that avoid draining water from deep in the lens are the most reliable. Fresh water is so precious that on Majuro a separate salt-water system has been installed for uses not essential to life.

Naturally occurring fresh water as a supply source may be adequate for the traditional life style but is deficient in areas where urbanization takes place. Ground water in particular is difficult to develop safely even in moderate quantities because the islands tend to be narrow; therefore the lenses are thin and unstable. Catchment and its storage will continue to be a chief source of fresh water. If carefully exploited and husbanded, ground water may also be an essential component of the total fresh-water supply.

The geology and hydrology of the Marshall Islands have not been investigated, except for the atolls of Bikini, Kwajalein and Enewetak which were studied by the United States Geological Survey. The hydrogeology of the islands is not complex; all of them are composed of limestone, limestone rubble and sand. The volcanic basement is deep and has no role in the fresh-water cycle.

References

The results of studies made of the three atolls have been published as a series of professional papers by the United States Geological Survey and are widely available. The reports include data and analyses concerning geology, paleontology and seismic refraction surveys. They are published as follows:

United States Geological Survey Professional Papers 260 (series A to S).

Northern Mariana Islands

General

The Northern Mariana Islands, which include all the Mariana Islands except Guam, have become part of the United States of America as a Commonwealth. Extending over a length of 450 km from north to south, the Commonwealth comprises 14 islands, the largest of which are Saipan (the capital and urban centre), Rota and Tinian. The total land area of the chain is 475 km^2, 125 km^2 being accounted for by Saipan, 102 km^2 by Tinian and 85 km^2 by Rota. The remaining 163 km^2 are divided among Pagan (49 km^2), Agrihan (47 km^2), Anatahan (33 km^2) and eight smaller islands, none of which is larger than 8 km^2. The total population of the Commonwealth is approximately 15,000, the largest proportion of which lives on Saipan (10,000). The population of Rota is about 1,500 and of Tinian nearly 1,000. Fewer than a hundred people live or have lived in recent years on each of the islands of Pagan, Anatahan, Alamagan and Agrihan.

The islands are the most northerly in Micronesia, reaching nearly to latitude 21° N, and, although generally warm and humid, are a degree or two cooler than the southerly islands. The dry, most pleasant season, when north-east trade winds dominate, extends from January to May. In the summer and autumn the trades dissipate and humid air masses, occasionally converted to typhoons, afflict the islands. Average annual rainfall is 2,000-2,500 mm, the lowest in Micronesia.

Geology

All of the islands are west of the Mariana trench in the andesitic province. Several, including Pagan, are volcanically active. The islands north of Saipan, except Farallon de Medinilla, which is capped with limestone, consist of exposed volcanic rocks, while Saipan, Tinian and Rota display both the volcanic substrate and raised fossil coral reefs. The volcanic islands are ruggedly mountainous and ringed with sea cliffs. On Saipan, Tinian and Rota narrow coastal shelfs occur as well as vertical limestone cliffs. The highest point in the chain is on Agrihan at an elevation of 965 m. On Rota the elevation reaches 491 m, on Saipan 474 m and on Tinian 170 m.

The geology of Saipan, Tinian and Pagan has been studied in detail by the United States Geological Survey, but merely a superficial reconnaissance has been made on Rota. The volcanic-limestone islands resemble Guam in their geological evolution; the northern islands are analogous to Pagan. The entire chain is similar in that it consists of andesitic emergent islands.

Exposed volcanic surfaces have been dissected by streams but limestones are too permeable for extended drainage nets to have formed. The streams are small, with flows averaging less than 0.035 m^3/sec, and often dwindle to trickles. There are no streams on any of the islands large enough to provide a sustainable yield adequate for urbanization.

In the south the earliest rocks resulted from volcanism in Eocene time. Volcanic activity ceased in the Oligocene and was followed by limestone deposition from Miocene to Recent times. On Saipan the volcanics have been divided into three formations: the oldest, the Sankakuyama formation, consists of dacites, both pyroclastics and flows; the intermediate, the Hagman formation, consists of andesitic pyroclastics and flows; and the youngest, the Fina-Sisu formation, of tuffs and lavas. A sedimentary formation, the Densiyama, composed of volcanic debris, was laid down before the Fina-Sisu volcanics. The comparable sequence on Tinian is subsumed in the Tinian pyroclastic formation. The northern islands also may have begun to form in the early Tertiary, but on Pagan more recent volcanics dominate.

The earliest extensive limestone formation formed in Miocene time, just as it did on Guam. The Tagpochau limestone (Miocene) is distributed on Saipan and Tinian and probably on Rota as well. The Mariana limestone of Pliocene-Pleistocene age, similar to the formation of the same name on Guam, caps much of the three islands. Structural deformation of the volcanics took place before limestone deposition. Later faulting, however, moderately affected the limestones.

Aquifers

The water resources of Saipan have been extensively studied by the United States Geological Survey and by consultants. Traditional hydrogeological methods have been employed, and geophysical techniques have yet to be tried. The geology of Saipan, Tinian and Pagan has been thoroughly mapped. As water-supply problems arise, hydrogeological investigations to resolve them are initiated. At present the Government, with the technical assistance of the United States Geological Survey, is carrying out an extensive exploratory drilling programme on Saipan. Neither Tinian nor Rota has yet encountered water-supply problems serious enough to trigger additional studies.

The volcanic rocks of the Mariana Islands have very low permeabilities and are not ordinarily considered aquifers, although small yields can be extracted from some of them. Where only volcanics are exposed, such as on Pagan and the other small islands north of Saipan, the opportunity for producing ground water is restricted to dug wells and drainage trenches in the weathered zone. The raised fossil reefs of Saipan, Tinian and Rota are the only extensive aquifers in the group. These aquifers are either basal, in which a fresh-water lens occurs, or high level, in which the ground water rests on the impermeable volcanic contact at elevations beyond the reach of sea-water intrusion. Basal water is developed on Saipan and Tinian, and high-level water on Saipan and Rota. The head in the basal water is less than 1 m. On Saipan, a prominent high-level aquifer is situated at an elevation of 122 m, and on Rota a large spring discharges at an elevation of 350 m.

The characteristics of the limestone aquifers are the same on each island. The aquifers are not differentiated by formation, but incorporate the entire limestone sequence. Their average characteristics are given in table 46.

Table 46. Trust Territory of the Pacific Islands, Northern Mariana Islands: characteristics of main aquifers

Location of aquifer	Type of aquifer	Depth of well (m)	Yield (l/sec)	Specific capacity (l/sec/m)	Hydraulic conductivity (m/day)	Trans-missivity (m^2/day)
Saipan	Basal	< 80	6	0-1	10-60	600-3,600
Saipan	High-level	< 115	10-15	1-3	5-10	150-200
Rota	High-level spring	...	20-113	...	...	...
Tinian	Basal	5	10-15	High	...	...

Ground water has been the traditional supply source for the islands and dependence on it has increased in the modern era. Rain catchments have always been used, and dug wells, seepages and springs were essential in the native culture. On Saipan a ground-water lake, Susupe, yielded fresh water at one time, but the water has since become brackish. During the Japanese administration wells were dug on Saipan and Tinian and large concrete cylindrical storage tanks on Saipan were installed on Saipan. After the Second World War, the United States constructed infiltration galleries on Saipan and Tinian and drilled wells on Saipan. Rota has always relied on a single, large limestone spring for its water supply. The development of ground water is handled by the Government of the Commonwealth.

Practically all the water on the three main islands is distributed by central systems operated by the Government. Although the ground-water resources of Tinian and Rota have proved adequate to meet the demand, Saipan has suffered supply problems ever since the start of the Trust administration. At present, an average of about 100 l/sec is pumped from two infiltration galleries and about 15 drilled wells and a further 15 l/sec is yielded by two springs. Perhaps as much as a quarter of the total is lost through leakage in the distribution system. Some of the wells are moderately brackish, which diminishes the quality of the water. Ground water will have to supply Saipan's future needs because it is the only significant and reliable resource. Further prospecting is needed, especially exploratory drilling supported by the use of geophysical techniques. The population of the island may double to 20,000 by the turn of the century, which will generate a demand for about 200 l/sec.

Tinian, with fewer than 1,000 people, is well served by an infiltration gallery for domestic supply and two large dug wells for irrigation. The gallery yields an average of 15 l/sec of water of low salinity. Population and future economic activity is difficult to predict; if the island becomes a major United States military installation, as has been suggested, additional ground-water sources will have to be found.

The needs of the people of Rota are served from a single spring that drains the highest limestone terrace on the island. The spring is most productive towards the end of the wet season but even at the end of the dry season it discharges enough water to satisfy demand, and has so far proved adequate, even during unusual droughts. At low flow (approximately 20 l/sec), it could supply about 5,000 people, a population not expected to be attained for more than a decade. Consideration is being given, however, to seeking out additional ground-water sources.

Ground water is essential to the economic and social welfare and prosperity of the Northern Mariana Islands. It has been difficult to exploit ground water successfully in the quantities needed on Saipan, but a concerted government effort is being made to resolve this problem. The present production cost on Saipan is $0.03/m^3; and water is sold at $0.06/m^3. On Tinian the cost is about $0.05/m^3. On Rota, where no source pumping is needed, the cost is considerably lower.

References

Numerous scientific reports are concerned with the ground-water resources of Saipan, several deal with Tinian, at least one with Rota, and another specifically considers Pagan. A number of engineering consulting reports dealing with storage and transmission systems have been written for the Government. The most comprehensive geological and hydrological studies have been made by the United States Geological Survey. The principal water resources publications are as follows:

Cloud, P. E., R. G. Schmidt and H. W. Burke. 1956. Geology of Saipan, Mariana Islands, Part I, General Geology. Professional Paper 280-A, United States Geological Survey.

Corwin, G., and others. 1957. Military Geology of Pagan, Mariana Islands. United States Geological Survey for the United States Army.

Davis, D. A. 1958. Military Geology of Saipan, Mariana Islands, Part 2, Water Resources. United States Geological Survey for the United States Army.

Doan, D. B., H. W. Burke and H. G. May. 1960. Military Geology of Tinian, Mariana Islands. United States Geological Survey for the United States Army.

Mink, J. F. 1970. Ground-water development in the Trust Territory. Report to the Administration of the Trust Territory of the Pacific Islands (includes a discussion of Rota).

TUVALU

Area: about 30 km^2

Population: about 7,000 (United Nations estimate, 1977)

Tuvalu, an independent State in association with the British Commonwealth, comprises a group of coralline atolls and islands (raised atolls), eight of which are inhabited (see map 44). It is located some 600 miles north of Fiji. Funafuti atoll, the seat of Government, is the main population centre and has the only international airport in the country.

Water resources and water needs in Tuvalu have been studied by an adviser of the South Pacific Commission who visited the country in September-October 1976. He reported that there were adequate sources of fresh ground water in most of the islands, with the exception of Funafuti, to provide each of the inhabitants with a reasonable supply of fresh water for domestic use. The resources would have to be properly developed - infiltration galleries might be necessary - and the wells carefully constructed in order to prevent contamination.

Vaitupu island (area, 5 km^2; population, 1,000)

The island has several communal (open) wells, those to the north showing a lower level of salinity. Ground water offers good prospects. It may be extracted by means of hand-dug wells provided with skimming basins. Wells should not penetrate deeper than 1 m below the water-table which, in all the islands, is not more than 4 m below the surface of the soil; the digging of wells in hard coralline limestone by means of conventional hand tools only is not usually possible.

Niutao island (area, 2.3 km^2; population, 900)

There may be substantial ground-water resources in the centre of the island.

Nanumea (atoll) (area, 3.6 km^2; population, 1,000)

Wells holding brackish water are found on Nanumea and Lakina. Fresh-water wells are exploited on Motofoliki islet.

Nanumanga island (area, 3.1 km^2; population, 600)

Sea-water intrusion occurs, owing to coastal erosion. Ground water may be developed east of the village.

Nukufetau (atoll) (area, 3.1 km^2; population, 600)

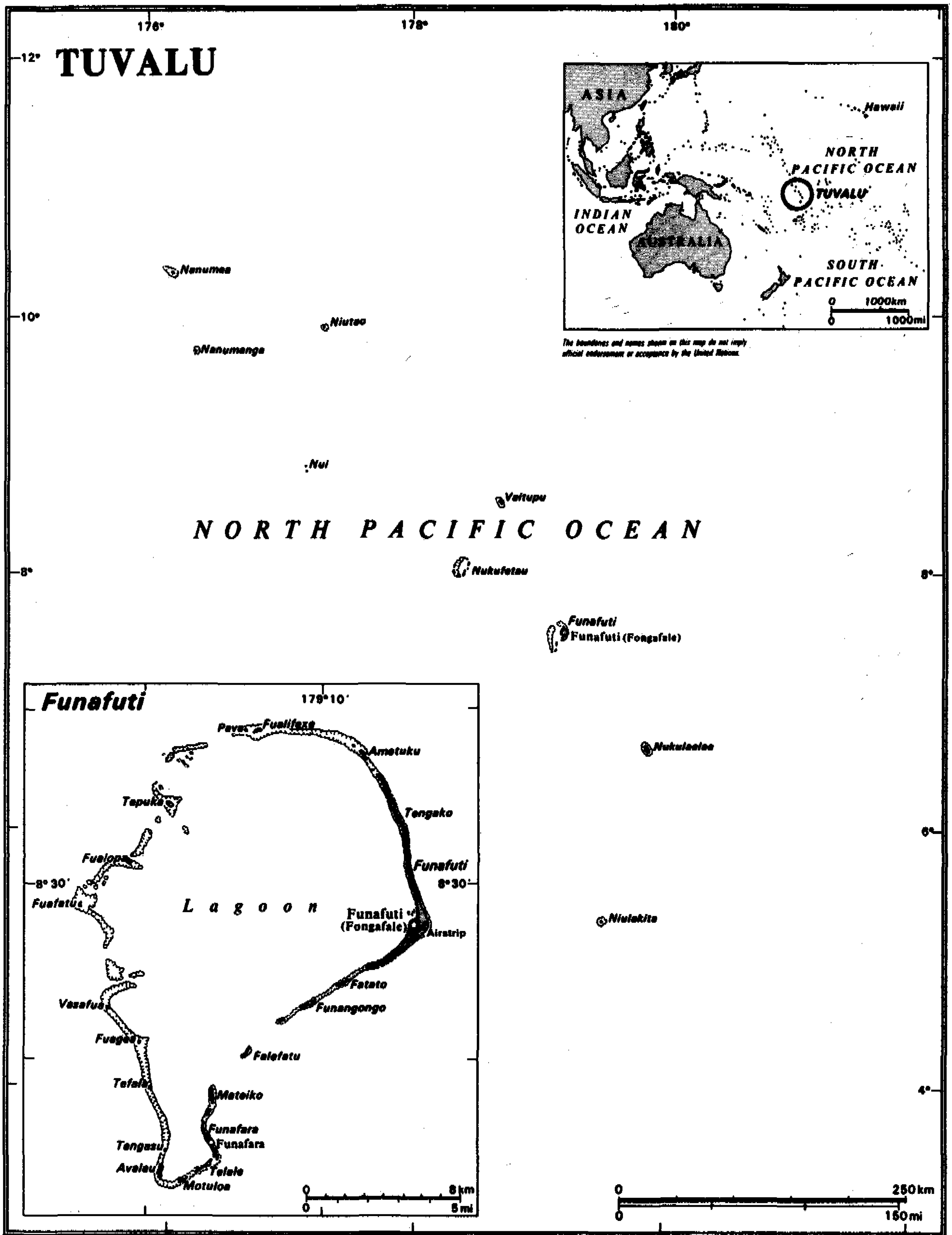
The main village area on Savave islet has several open communal wells with brackish water used only for washing purposes; three shallow wells on the small islet of Fale have fresh water and are used during drought periods. It is recommended that this resource should be developed properly.

Nukulaelae (atoll) (area, 3 km^2; population, 600)

Two open wells have been dug in village areas. Situated close to the sea, they yield brackish water, which is used for washing. Fangaua islet may maintain a fresh-water lens and a well should be dug there, near the centre.

Map 44. Tuvalu

MAP 44



MAP NO. 3226 UNITED NATIONS
FEBRUARY 1983

Niu (atoll) (area, 3.4 km^2; population, 600)

Shallow communal wells provide water for cooking and washing. Most of the larger islets may hold a fresh-water lens. It is therefore recommended that the development of ground water should be properly investigated with a view to achieving proper siting, construction and protection of shallow wells so that both quality and yield of water may be improved.

Niulakita island

No wells exist on this island, but the prospects for ground water are good. The island is not permanently inhabited.

Funafuti (atoll) (area, 2.5 km^2; population, 1,200)

Funafuti offers little prospects for ground water owing to the narrowness of the territory and the high density of the population, with related potential environmental problems. However, it may be interesting to dig three or four wells in the centre of the island, along the north-west boundary of the airstrip.

VANUATU

Area: 14,763 km^2

Population: 99,000 (United Nations estimate, 1977)

Vanuatu is an archipelago comprising 80 islands scattered over a distance of 900 km from north to south, lying west of Fiji and north of New Caledonia (see map 45).

General

Most of the islands are mountainous, the peaks often reaching 1000 m and culminating at 1887 m (Mount Tabwemasana on Espiritu Santo). Their orientation is north-north-west/south-south-east. Coastlines are generally in the form of sheer cliffs. On the larger islands (Espiritu Santo, 3,677 km^2; Mallicolo, 2024 km^2; and Vaté, 915 km^2) coastal platforms have developed as vast plateaux have become lower by degrees from a 400 m elevation down to the coastline.

By and large the climate is of the hot, humid and rainy type. Average monthly temperatures recorded in Port Vila and Santo vary from 20° C in August to 30° C in January. Average yearly rainfall is in the range of 2,500-4,500 mm, with 200-225 rainy days. Rainfall and temperatures decrease from the south to north. South-east trade winds prevail an average of 20 days a month. During the hot period, from December to April, tropical depressions like cyclones sweep across the archipelago from north-east to south-west in the north, and from north-west to south-east in the south.

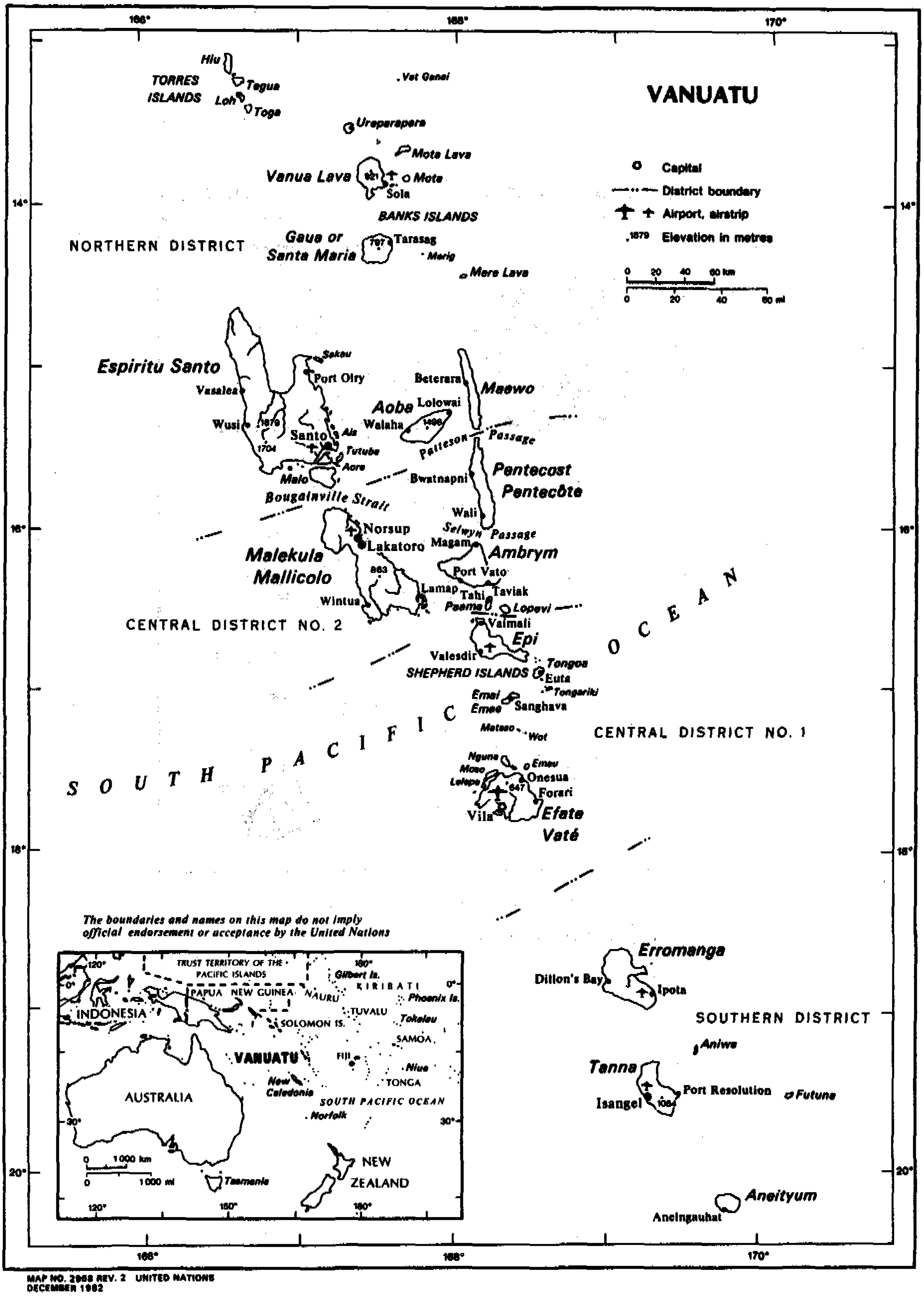
In spite of the abundance of rainfall, most of the islands, because of their small size and their rugged topography, do not have perennial streams. River courses are short and the flows in gullies are short-lived. The only exceptions are the perennial streams on the main islands, namely, the Jourdain, Sarakata and Navaka rivers in Espiritu Santo and the Teouma and Colle rivers in Vaté, the flow of which has not yet been studied. Some lakes occur in the craters of extinct volcanos; their waters, however, are not utilized since they are too far away from human settlements.

Geology

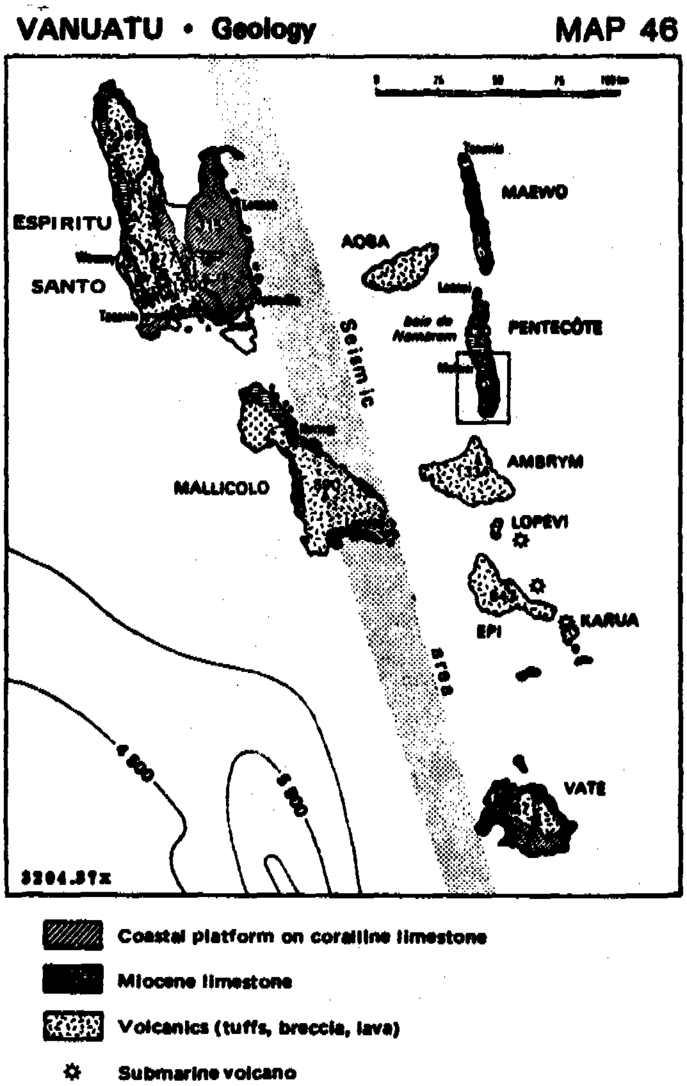
The islands of the archipelago are distributed along two distinct structural features, on both sides of a line of active volcanoes which developed from Pliocene times (Vanua Lava, Gaua, Aoba, Ambrym, Lopevi and Tanna) and which, during historical times, experienced several volcano-tectonic cataclysms (see map 46). At present, three volcanos are active, on Ambrym, Lopevi and Tanna; undersea eruptions and earthquakes are not rare. The external structural arch which includes Maewo and Pentecoste islands is related to a faulted horst which has been raised from time to time since the Pliocene period. Although basic and ultrabasic rocks (e.g. gabbros, peridotites and serpentines) crop out in Espiritu Santo, most of the material is of the basalt and tuff type, underlying Neogene, Pleistocene and Recent limestone.

Map 45. Vanuatu

MAP 45



Map 46. Vanuatu: geology



The geological history of the internal arch (comprising the islands of Torres, Espiritu Santo, Mallicolo, Vaté, Erromanga, Tanna and Anatom) is known from the Oligocene period. Towards the beginning of the Oligocene, thick sediments, including tuffs, argilites, marls and limestone, started accumulating. They were folded during Middle Oligocene. Then andesitic lava flows occurred and developed until Middle Miocene. During the Upper Miocene period, folding occurred preceding the intrusion of granodiorites and diorites. Submarine andesitic eruptions took place during Lower and Upper Pliocene. During the Plio-Pleistocene period vertical movements took place along the faults, which permitted the formation and the uplift of reef limestone. These orogenic cycles have given rise to complex stratigraphic series which include volcanic formations (flows and pyroclastic material) alternating with volcano-sedimentary formations and limestone, sometimes covered with a thin alterite or alluvium layer (see fig. VII).

Ground-water resources

Hydrogeological missions were initiated in 1965, focusing on a preliminary reconnaissance of Vaté island, the south-east parts of Espiritu Santo island and two volcanic islands of the Shepherd group: Tongariki and Tongoa. A full-time hydrogeologist was appointed in 1972. Since then, local water-resouces studies have been developed to back up rural water-supply projects.

Surveys were planned for each island (Vaté, Mallicolo, Ambrym, Espiritu Santo, Maewo, North Aoba, Tanna and Shepherd) as follows:

First phase: reconnaissance (geological data, interviews with the population, visit and identification of springs and wells, rivers);

Second phase: drilling by hand (using an auger) to identify the lithology and to check the water-table, to be followed by the setting of pipes and screens and pumping tests;

Third phase: water-level measurements, pumping tests and water-quality studies.

After 1973, the availability of drilling equipment permitted an upgrading of reconnaissance surveys and also for the drilling of exploitation boreholes.

In some cases, especially at Port Vila (Vaté), ground geophysical (resistivity) surveys were carried out in coastal aquifers, and a tentative water balance of Port Vila basin was made on the basis of the results of a rain data collection programme.

Main aquifers

On the coastal platform, main aquifers include:

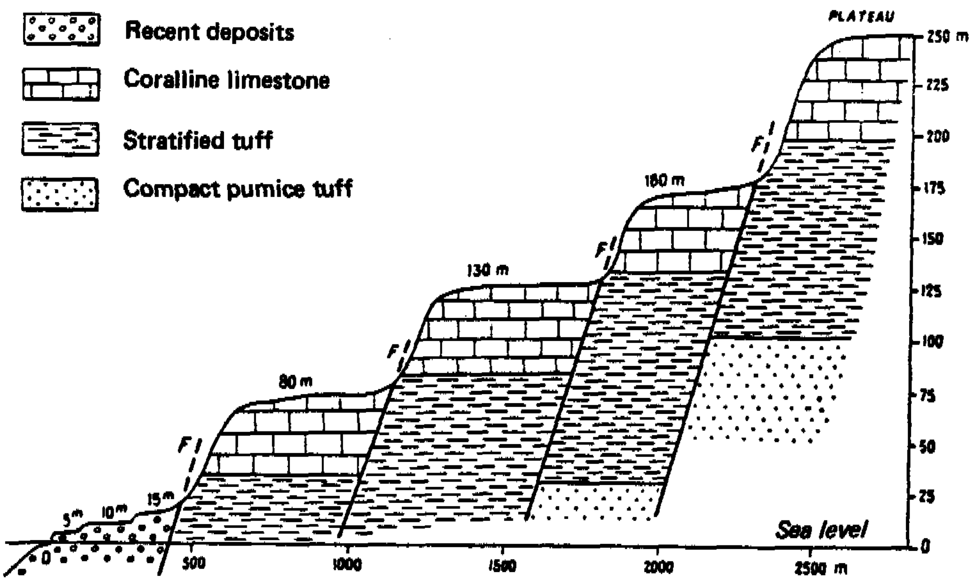
(a) Raised coralline limestone; hydraulic conductivity is good, in the range of 10^3 m/day; there is a high risk of a sea-water intrusion;

(b) Sand deposits; these aquifers are modest in area but may satisfy local needs (hydraulic conductivity varies from 10^2 to 10^2 m/day); the risk of sea-water intrusion is lower than in the case of the coralline limestone;

Figure VII. Vanuatu: geological cross-section

VANUATU • Geological cross-section

Figure VII



Typical structure of coralline limestone holding "plateaux aquifer" and coastal platform - alluvium in some cases.
Example : showing the coastal flanking of the Erskine Plateau (Vaté Island) from J.M. Obellianne, 1961.

8204.38x

(c) Alluvium plains; they are rare in occurrence and very limited in area; they are excellent aquifers (at Port Vila, and on Tanna); the nature and the grain size of the material vary widely; in the Port Vila plain, a 50 m borehole has penetrated sands, silt and pumice-stone, while in mountainous volcanic islands, such as Aoba and Paama, thin layers of big pebbles are found; hydraulic conductivity varies accordingly (from 10 to 10^3m/day).

The plateaux are covered with highly permeable coralline limestone, which may be deeply karstified, overlying tuff and pumice. Good aquifers can be developed through boreholes 15-30 m deep (80 m deep in Espiritu Santo). Drawdowns remain moderate (less than 1 m) for yields which may reach up to 100 m^3/h. The topography contributes to the occurrence of ground-water outflows (which are utilized in some cases) and losses (see fig. VII).

Tuffs crop out in some places at elevations not exceeding 100 m in the form of rounded hillocks. Yields do not exceed 1 m^3/h. Hydraulic conductivity varies from 0.1 to 1 m/day.

In recent volcanic islands (where coralline reefs do not occur) some springs can be observed issuing from the contact between pyroclastic layers with different grain size (cinder/ashes) or from the contact with pyroclastic material/lava flows. Their yield, less than 1 m^3/h, is generally insufficient to cover population needs. In some cases, however, permanent aquifers occur in the fractures of lava flows overlying the tuffs, and yield flows up to 10 m^3/h (e.g. in Aoba).

From the point of view of water quality, ground water can be divided into two groups: hard waters originating from limestone (resistivity coefficient in the range of 1,300 to 1,900 ohm-cm if no sea-water intrusion is involved); and pure waters from ancient volcanic formations with a resistivity coefficient in the range of 2,000 to 4,000 ohm-cm. In active volcanic areas ground water is generally not suitable for use, owing to its high temperature and sulphur content. In spite of inadequate sanitation facilities, no major bacteriological problem has yet developed, since villagers have a deep sense of the importance of water quality.

A reasonable level of knowledge of ground-water resources has been reached considering that the areas and the islands which have not been studied have only sparse populations, if any. The main problem is not that of water-resources prospection, but that of the utilization of the resources. Only 20 per cent of the rural population is supplied from ground-water sources because of the scattering of dwellings. In most cases, the collection of abundant and frequent rain water in barrels, tanks or cisterns, is sufficient to cover the needs.

Apparently no water shortage is envisaged and water is available for irrigation, industry and community water-supply projects.

Institutional framework

By the end of 1980, the Department of Mineral Resources and Rural Hydraulics, which is part of the ministry of lands, was responsible for studies on water resources, the finalization of water-supply projects, and the execution of water development and distribution projects. In villages the management of water-supply systems was the responsibility of community groups and, in cities, of a water service. In recent years, the staff of the Department has normally included one or two hydrogeologists and two assistants, two drilling parties and five teams in charge of the execution of hydraulic works and water-supply systems. A training programme has been carried out every six weeks or so for one week (after a six-week period of field work).

The Department operates two "Southern Cross" percussion rigs, capable of reaching a depth of 40 m (8-inch diameter) in 8-10 days; one combined percussion-rotary Denolo 150; one auger (hand-driven); and three compressors. The Department also has at its disposal a truck, a tractor, four other vehicles, pumps, laboratory facilities etc. Ground water is used mainly for the drinking water supply of humans and cattle. The archipelago has two significant towns which are adequately provided with drinking water, Port Vila and Santo.

At Port Vila, the capital (population, 12,000), daily consumption is 2,000 m^3/day. Water is pumped from two tubewells located in the coastal plain. At Santo (population 5,000) water is supplied by means of a well dug into coral limestone at an elevation of 10 m, some 8 m deep and yielding some 150 m^3/h (no significant drawdown being observed).

However, 80 per cent of the people live in rural areas and only 20 per cent of them are served by a water-supply system. Two distribution systems are available. One provides a standpipe with a tap in the centre of the village, at a per capita rate of 50 l/day; and the other provides a tap for each family (each family having several dwellings) at a per capita rate of 100 l/day.

In coastal areas, drinking water for cattle is provided in addition to drinking water for the population. At the top of the highlands, where ground water would be too deep to develop, cisterns have been built to collect rain water. This has been done in the western part of the coralline plateaux of Espiritu Santo.

There is practically no tourist trade or industry in Vanuatu. In the short term the only potential use for ground water which may be considered, apart from the water supply of the community, would be irrigation. Surface water, however, seems to be preferred; for example, the waters of the Jourdain river are utilized to irrigate Santo plain.

In summary, short-term and medium-term water develoment projects, including the ground-water alternative, will have to be concerned mainly with the water supply of 80 per cent of the rural population on the plateaux and their cattle also.

In Vanuatu, ground water is generally adequate in quantity to meet the need. The main problems are the lack of retention of water in volcanic islands where large quantities of water are lost by run-off to the sea and the excessive depth of the water table under the plateaux.

The solution to these problems would be to tap springs on the flanks of volcanoes and in the alluvium where the valleys meet the plain. Furthermore, on the plateaux, deep wells could be drilled, equipped with submersible pumps.

Regarding water quality, there is a high risk of sea-water intrusion in coastal areas, especially through coralline limestone. The siting of the wells and the level of safe yields should be determined with great care. In addition, on some volcanic islands, hot and sulphur waters may occur. Although such waters constitute potential energy, they are not fit for human consumption. This is the case on Lopevi, which has an active volcano and is uninhabited, and on Ambrym where rain water is the only water resource. It also applies - to a lesser extent - to Tanna, Aoba and Gaua, where a crater lake holds fresh water. To date, earthquakes do not appear to have a marked influence on aquifers and springs, but their importance should not be underestimated when designing waterworks.

Conclusion

In the course of the past 10 years or so, a fair knowledge of the ground-water resources of Vanuatu has been acquired. Ground-water development is in progress to satisfy the needs of communities and their cattle. Wells are equipped with windmills and diesel engine pumps.

Additional hydrogeological surveys will be required, however, if the needs of the population for safe drinking water are to be satisfied within the framework of the International Drinking Water Supply and Sanitation Decade.

Selected references

Benoit, Michel. 1964-1971. Unpublished reports. Department of Mineral Resources, Port Vila.

Coudray, Jean. 1965. Rapport de mission hydrogéologique aux Nouvelles-Hébrides. Service du Génie Rural de la Nouvelle-Caledonie, 22 pp.

Institute of Geological Sciences. Geological Map of the New Hebrides, scale 1:50,000. Crowmarsh Gifford, Wallingford, Oxfordshire, England.

Obellianne, Jean Marie. 1961. Contribution à la connaissance géologique de l'archipel des Nouvelles-Hébrides (Iles Vaté, Pentecôte, Maéwo, Santo). Sciences de la Terre, t. VI (1958), no. 3-4, pp. 139-368, Nancy.

Quantin, Paul. 1971-1972. Atlas pédologique au 1/100 000 des Nouvelles-Hébrides. ORSTOM, Paris.

Saos, J. L. 1972-1980. Unpublished reports. Department of Mineral Resources, Port Vila. 1981. Hydrogeological map of Vaté Island (under preparation).

ANNEX

Ground-water projects in the Pacific region sponsored by the United Nations Development Programme

Country and project	Symbol	Agency	Duration	Ground-water component: Exclusive or major	Substantial (30-50% of project)	Minor
Cook Islands						
Environmental health engineering advisory services	CKI-73-003	World Health Organization	1973-1982			x
Fiji						
Hydrogeological survey	FIJ-69-001	United Nations	1971-1973	x		
Fellowship in hydrogeology	FIJ-74-003	United Nations	1974-1975	x		
Indonesia						
Rural water supply for East Java Province	INS-73-003	World Health Organization	1974-1977			x
Isotope hydrology	INS-72-014	International Atomic Energy Agency	1973-1976			x
Institute of Hydraulic Engineering	INS-70-527	United Nations	1970-1977			x
Rural water supply Nusa Tenggara Timur	INS-78-052	World Health Organization	1980-1984			x
Niue						
Mineral prospecting and water resources	NIU-78-006	International Atomic Energy Agency	1979-1981	x		
Papua New Guinea						
Assistance in the implementation of a water development policy	PNG-77-004	United Nations	1977-1980			x

				Ground-water component		
Country and project	Symbol	Agency	Duration	Exclusive or major	Substantial (30-50% of project)	Minor
Philippines						
Feasibility survey for the hydraulic control of the Laguna de Bay complex	PHI-19	United Nations	1965-1970			x
Improvement of irrigation facilities through ground-water development	PHI-70-531	Food and Agriculture Organization	1970-1977		x	
Samoa						
Hydrodata collection	SAM-74-006	United Nations	1977-1982		x	
Solomon Islands						
Rural water supply and sanitation	SOI-80-002	World Health Organization	1979-1982			x
Tonga						
Tonga Water Board development	TON-75-004	World Health Organization	1976-1982			x

Report of the United Nations Interregional Seminar on Flood Damage Prevention Measures and Management, Tbilisi, Union of Soviet Socialist Republics, 1969.

Publication symbol: ST/TAO/SER.C/144.

Integrated River Basin Development. Revised edition. 80 pp., 2 maps. Report of a panel of experts. English (French, Spanish out of print).

Sales No. E.70.II.A.4.

Solar Distillation as a Means of Meeting Small-scale Water Demands. 86 pp., figures, tables. English (French out of stock).

Sales No. E.70.II.B.1.

Triennial Report on Water Resources Development, 1968-1970. 202 pp. English only.

Sales No. E.71.II.A.15.

Abstraction and Use of Water: A Comparison of Legal Régimes. 254 pp. French, Spanish (English out of print).

Sales No. 72.II.A.10.

Proceedings of the Interregional Seminar on Water Resources Administration, New Delhi, 1973.

Publication symbol: DP/UN/INT-70-371.

National Systems of Water Administration. 183 pp., figures, annexes. English only.

Sales No. E.74.II.A.10.

Ground-water Storage and Artificial Recharge. Natural Resources/Water Series, No. 2. 270 pp., figures, tables. English, French, Spanish.

Sales No. E.74.II.A.11.

Management of International Water Resources: Institutional and Legal Aspects. Natural Resources/Water Series, No. 1. 271 pp., figures, map, tables, annexes. Report of a panel of experts. English, French, Spanish.

Sales No. E. 75.II.A.2.

The Demand for Water: Procedures and Methodologies for Projecting Water Demands in the Context of Regional and National Planning. Natural Resources/Water Series, No. 3. 240 pp., tables, figures, annexes. English, Spanish (French out of print).

Sales No. E.76.II.A.1.

Ground Water in the Western Hemisphere. Natural Resources/Water Series, No. 4. 337 pp., tables, figures, maps. English, French, Spanish.

Sales No. E.76.II.A.5.

Guidelines for Flood Loss Prevention and Management in Developing Countries. Natural Resources/Water Series, No. 5. 183 pp., tables, figures, annexes. English only.

Sales No. E.76.II.A.7.

Report of the United Nations Water Conference, Mar del Plata, 14-25 March 1977. 181 pp., annexes. English, French (Spanish out of print).

Sales No. E.77.II.A.12.

A Review of the United Nations Ground-water Exploration and Development Programme in the Developing Countries, 1962-1977. Natural Resources/Water Series, No. 7. 84 pp. English, French, Spanish.

Sales No. E.79.II.A.4.

Efficiency and Distributional Equity in the Use and Treatment of Water: Guidelines for Pricing and Regulations. Natural Resources/Water Series, No. 8. 175 pp., tables, figures, annexes. English (French, Spanish out of stock).

Sales No. E.80.II.A.11.

Water Resources Planning: Experiences in a National and Regional Context. Report of a United Nations workshop convened in co-operation with the Government of Italy. English.

Document symbol: TCD/SEM.80/1.

Rural Water Supply. Report of a United Nations interregional seminar convened in co-operation with the Government of Sweden, Uppsala, Sweden, 6-17 October 1980. English.

Document symbol: TCD/SEM.81/1.

Ground Water in the Eastern Mediterranean and Western Asia. Natural Resources/Water Series, No. 9. 230 pp., tables, figures, maps.

Sales No. E.82.II.A.8.

Experiences in the Development and Management of International River and Lake Basins. Natural Resources/Water Series, No. 10. 424 pp. Proceedings of the United Nations Interregional Meeting of International River Organizations, Dakar, Senegal, 5-14 May 1981.

Sales No. E.82.II.A.17.

Flood Damage Prevention and Control in China. Natural Resources/Water Series, No. 11. Report of a study and workshop in the People's Republic of China, 16-31 October 1980. To be issued.

83-10272 0855-59c (E)