WATER-RELATED ISSUES AND PROBLEMS
OF THE HUMID TROPICS
AND OTHER WARM HUMID REGIONS

IHP HUMID TROPICS PROGRAMME SERIES NO.2

SMALL TROPICAL ISLANDS

WATER RESOURCES OF PARADISES LOST

UNESCO

INTERNATIONAL HYDROLOGICAL PROGRAMME

MAN AND THE BIOSPHERE PROGRAMME

". . . by the Year 2000 almost one-third
of the world's people will be living in the humid tropics."

Anthony C. Falkland

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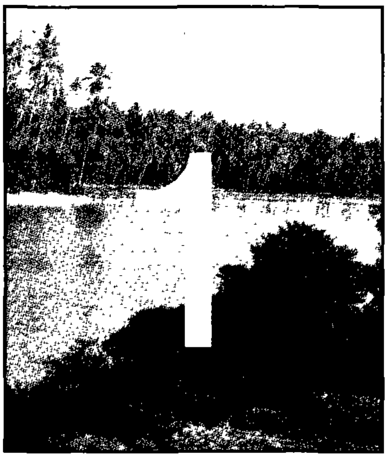


INTRODUCTION

The word "island" often conjures up for many people all sorts of fantasies...idyllic paradises where swaying palms line the edges of long, sandy, pristine beaches which stretch towards glistening seas of turquoise hues, and where the interior is filled with plentiful, luxuriant and mysterious vegetation, clean streams and cool, blue pools set amongst rocky outcrops. . .

Reality is often very different.

When is an island "large," "small" or "very small?"

There is no firm number that automatically classifies an island as being large, small or very small in size. A recent UNESCO study of the hydrology and water resources of islands considered any island larger than 2,000 square kilometres to be in the first category. Most "small" islands, however, are less than 200 square kilometres in area, with those islands of less than 100 square kilometres falling into the "very small" class.

Categorizing islands by their size does make sense. The larger islands tend to have geological features and problems similar to those found on the continents, whereas the small and very small islands have their own characteristics and their own set of unique problems.

This publication examines some of the major hydrological and water resource issues of these small and very small islands. Such questions as where their fresh water is located, how it can be assessed, how it is used and how it can be developed and managed are examined. Approaches to resolving some of the major problems currently being experienced by these smaller water-girded collections of rock, soil, and vegetation also are suggested, including the need for additional training, research and technical cooperation. (Unless it is specified otherwise, the term "small island" will be used in the rest of this text to refer to both "small" and "very small" islands.)

Where are the small islands in the humid tropics?

There are many small islands in the humid tropical regions of the world, being found in the Pacific, Atlantic and Indian Oceans as well as in the smaller seas such as the Caribbean. Many islands are also located in lakes, rivers and some inland seas.

In addition to islands being located nearly everywhere, there are an immense number of them! Over 30,000 small islands are in the Pacific alone—mostly in the humid tropical regions. In the Caribbean, there are several thousand small islands. About 100 are inhabited. Almost on the other side of the globe, the Indian Ocean can boast of several thousand small islands, while in the region of Indonesia, the Philippines, Malaysia, Vietnam and south-eastern China, the island count increases to the many thousands. There are over 13,500 islands in Indonesia alone, nearly all of which are small in size.

A number of nations in the tropics consist entirely of island archipelagos. Examples are: Indonesia and the Philippines in South East Asia; the Cook Islands, Kiribati, the Federated States of Micronesia, Fiji, the Marshall Islands, New Guinea, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu and Western Samoa in the Pacific; the Maldives and Seychelles in the Indian Ocean and the Turks and Caicos and the Bahamas in the Caribbean.

"Run a boat on the sands at high water, and the first step is planted in primitive bush--fragrant, clean and undefiled."
E. J. BANFIELD,
TheConfessions of
a Beachcomber

Small island politics and economics

Many small tropical islands are politically part of the world's developing countries. The fact that some of these nations are made up entirely of small islands adds to the problems, as these nations often have very little in the way of natural resources except what their land and surrounding waters contain.

Some countries in the humid tropics consist of a single island or one main island. The countries of Nauru and Niue in the Pacific, Mauritius in the Indian Ocean and Barbados and Jamaica in the Caribbean are examples.

Other islands are territories of larger continental countries—such as the Galapagos Islands (Ecuador), the Hawaiian Islands (USA) and French Polynesia (France) in the Pacific and the Andaman and Nicobar Islands (India) in the Indian Ocean. Many of the islands in humid tropical South-East Asia belong to Malaysia, Vietnam, China or Japan.

From an economic viewpoint, most of the island countries within the humid tropics are developing rather than developed, with Hong Kong and Singapore being notable exceptions. Most of these small island nations have low per capita incomes, compared with the world average. Many have lower per capita incomes than the average developing country. Some islands, such as Nauru, have high per capita incomes but are still classified as "economically developing."

The economies of some islands and island countries are being currently boosted by income from tourism, mining and military bases. However, the local economic resources of many islands are limited to fish, which may be abundant within their extended economic zones, and such basic commodities as copra. A limited amount of cash crops such as coffee, vanilla, tropical fruits and vegetables, along with some manufactured goods such as handicrafts, are also produced. On some small islands, a substantial proportion of the income is derived from the sale of postage stamps.

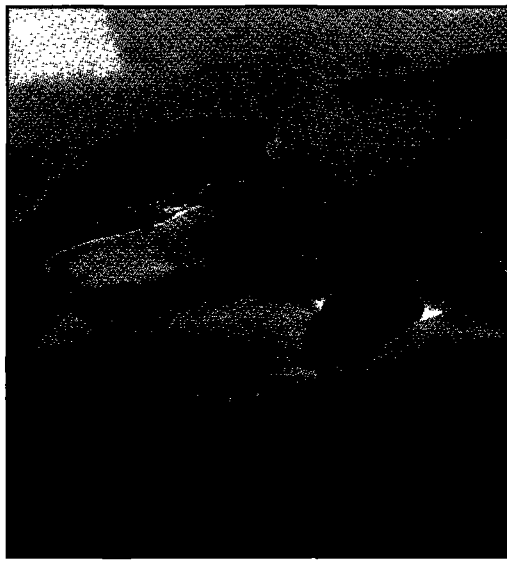
The uniqueness and special problems of small islands

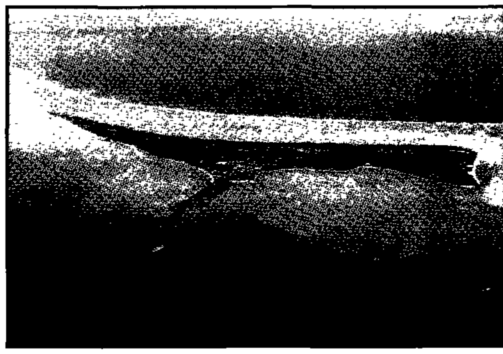
Small islands, especially those situated far from continents or other large islands, are physically, demographically and economically different. Their limited size, their shortage of natural resources (arable land, fresh water, minerals and conventional energy sources), their isolation, the widespread nature of their territories, and their exposure to natural disasters can make the hydrological and water resource problems of these islands very serious.

Their large populations and their fragile economies add to these natural problems. Some small islands have suffered the consequences of over-exploitation of their mineral and hardwood resources. In such cases, not only has their resource base been severely depleted but great damage has been inflicted on their environment.

Most small islands have few or no permanent streams or lakes. Their ground water also is in limited supply. In the small low-lying islands, such as the many coral atolls and limestone islands, what ground water they possess is a thin layer of fresh water "floating" on top of the sea-water. It is particularly susceptible to overpumping which can lead to unwanted increases in salinity.

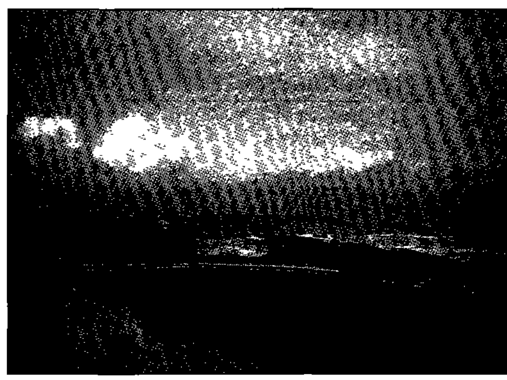
Both the surface water and ground-water resources of small islands can be polluted from urbanization, agricultural activities, mining and the clearing of forests. Faecal pollution of ground water from sanitation facilities located too close to water sources is also a major problem on many crowded islands in the humid tropics. The





Some small islands, like Betio (above), are very limited in size but have a large population. Betio (Tarawa atoll, Kiribati) is about three kilometers long and 600 metres across at the widest spot, yet has a population over 10,000.

A sharp contrast: the developed economy of Hong Kong (at right) and the temporarily resource-rich island of Nauru in the Pacific Ocean (below).



increasing use of pesticides, herbicides and fertilizers is an additional hazard for many islands.

Many islands are part of an archipelago with a number of islands being in close proximity to each other. Others are found many kilometres from each other.

High susceptibility to natural disasters

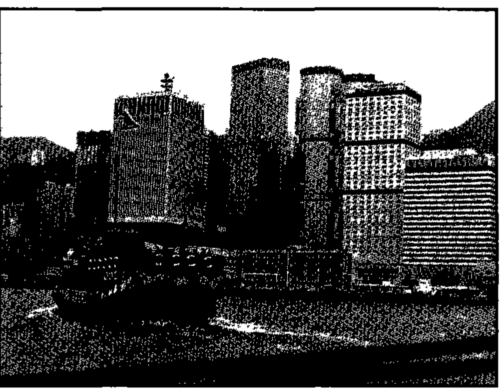
Because of their limited size and resources, the susceptibility of islands to natural disasters and to degradation of their land and water is much higher than on continental land masses. Their isolation from sources of supply, the high costs of freight and a frequent lack of trained staff, add to the problems being experienced by island communities.

Despite their small area, many small islands have very high population densities which place great stress on the naturally-occurring water resources. Population densities of over 10,000 persons per square kilometre occur on some islands. On Malé in the Republic of Maldives, the population density exceeds 30,000 persons per square kilometre—admittedly an extreme example.

Such dense populations create not only high demands for water but also increase the risk of pollution since the people are often living not too far above their ground water. In a few cases, the available water has been fully utilized or polluted to the extent that off-island sources of water are required. Such measures include desalination of sea-water and importation of water from other islands or continents.

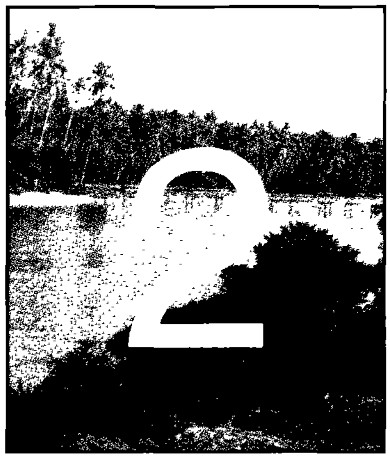
In those island countries which are characterized by dense population and high birth rates, their accession to independence or internal self-government generated great hopes among their people for improvement in their living conditions. Accordingly, the demand for water has increased significantly in all sectors of their economies following the drive of these countries towards their economic self-sufficiency. Competition has developed between the urban and rural communities, and between tourism facilities (one of the major sources of income in tropical islands), small agro-industries (sugar, oils, copra) and irrigated agriculture for the limited amount of water available.

The following chapters will look at some of the factors which may determine whether these problems can be lessened, beginning with an examination of the physical structure of the tropical small islands.



"There were so many islands I scarce knew to which one I should go"
CHRISTOPHER COLUMBUS

PHYSICAL CHARACTERISTICS OF SMALL ISLANDS



To better understand the water resources of small islands in the humid tropics, it is worth spending some time examining the various types of islands and some of their physical characteristics.

Small islands in the humid tropics can be conveniently classified according to their geology and topography. These two factors have a profound influence on the type and quantity of fresh water resources on these islands. Other major determining factors are the local climate, the vegetation and the soil conditions.

Their geology

Geologically speaking, all small islands can be described as being either volcanic, limestone, coral atoll, bedrock, unconsolidated or mixed in nature.

Examples of the first category, the volcanic islands, are common in tropical regions of the Pacific Ocean (the Hawaiian Islands and the many islands of Micronesia and French Polynesia) and in the Caribbean Sea. They also occur in the Atlantic and Indian Oceans.

Limestone islands are also common in the humid tropics. Examples include the "old carbonates" such as Bermuda in the Atlantic and the Bahamas in the Caribbean, and the "raised atolls" such as Nauru, Niue and many of the islands of Tonga in the Pacific. These raised atolls are uplifted coral atolls that have undergone subsequent erosion.

The coral atoll-type of island is common in the Pacific (Kiribati, Tuvalu and the Marshall Islands) and in the Indian Ocean (the Maldives and some of the Seychelles).

Bedrock islands are those which have been formed by igneous or metamorphic rocks such as granite, diorite, gneiss and schists. They are mainly found on continental shelves or adjacent to large islands of similar geology. This type of island occurs in all parts of the world, including the humid tropics.

The unconsolidated type of island typically consists of sand, silt and/or mud and is generally found in the deltas of major rivers (off the coast of Bangladesh, for example).

Islands of mixed geology are common, with mixtures of volcanic and limestone rocks frequently occurring amongst the oceanic islands.

Their topography

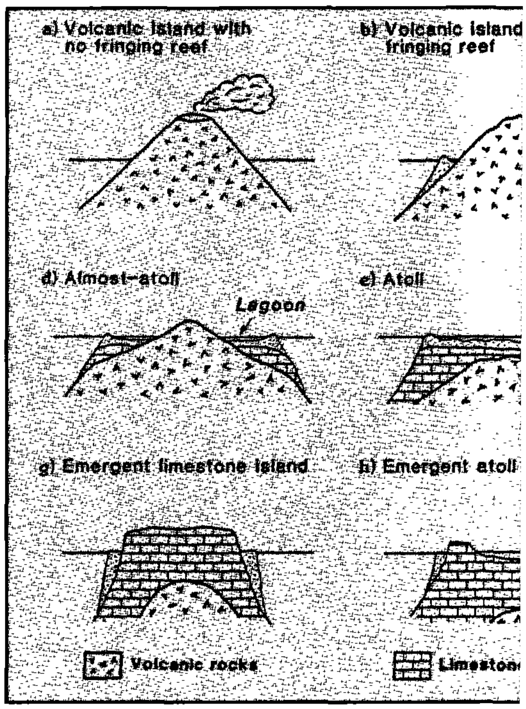
Small islands can also be classified according to their topography as being either "high" or "low." Volcanic islands are typically high in structure while the coral atolls are low in elevation. The former is more likely to have some surface water resources in the form of streams and rivers while the latter seldom experience surface runoff.

Their climate

One of the marked features of tropical climates is the small variation in temperature. Other climatic features, however, such as rainfall, are far from constant and are affected by a range of weather conditions which have short-, medium- and long-term cycles. As described by the climatologist, M.J. Manton, the range of significant weather features—on an increasing time scale—are diurnal convection, easterly waves, tropical cyclones, the 30-60 day oscillation, monsoons, quasi-biennial oscillations, the El Niño-Southern Oscillation (ENSO) events and the Greenhouse Effect.

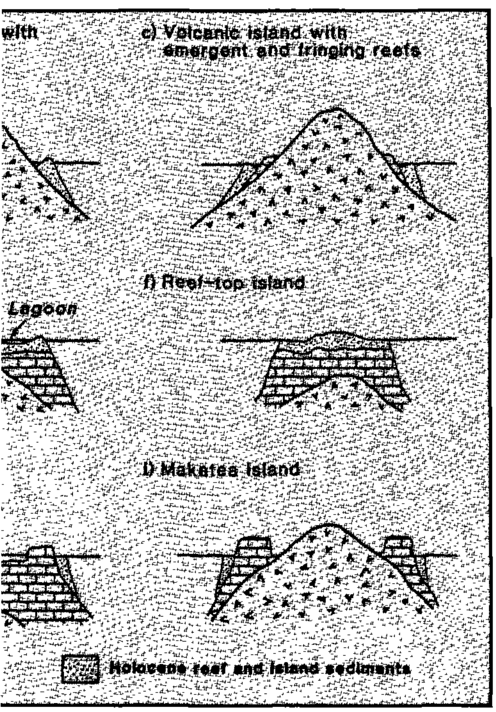
The tropics also are regions of dynamic weather patterns as is characterized by the enormous energy and destructive forces asso-

Main types of mid-oceanic islands. Variations of volcanic, limestone and coral atoll type islands are shown in the drawing. The other two types of islands, namely, the bedrock and unconsolidated types, are generally found close to continents or large islands (After Woodroffe, 1989).



"Clusters of islands, strings of islands, single lonely specks in the oceans of the world . . . Islands, their heads in the clouds, islands set low against the sea . . ."

LESLIE THOMAS,
A World of Islands, 1983



ciated with tropical cyclones. In non-cyclonic periods, the northeast and southeast Trade Winds are the dominant winds of the tropical regions of the world. These winds meet in the Inter Tropical Convergence Zone which lies near the equator.

Some islands within the tropics are greatly influenced by summer monsoons and have distinct wet and dry periods while others are less influenced by the seasons. Extensive dry spells can and do become critical for islands, particularly those with streams and springs that reduce to little or zero flows.

Extended dry spells not unknown on some islands

Island water resources are also influenced to different degrees by the longer time-scale mechanisms such as the ENSO events. The ENSO phenomenon, which has been reported upon by the popular press in recent years, has a profound effect on rainfall patterns in the Pacific Ocean and the eastern parts of the Indian Ocean. In fact, strong ENSO events are blamed for major weather disturbances on a global scale. ENSO event causes are still largely unknown.

What is known is that there are complex interactions between the ocean and the atmosphere and that the onset of a strong ENSO, as occurred in 1982-1983, can cause widespread disaster to islands and continents alike. The influence of ENSO on rainfall patterns on islands in the central and eastern Pacific is very marked, as shown for one island in the diagram on the following page.

Very wet and very dry cycles

ENSO and anti-ENSO (also referred to as La Niña) events can produce very wet and very dry cycles. On some islands, periods of up to six months may elapse without significant rainfall. This phenomenon was particularly evident during the major 1982-1983 ENSO event. During the first half of 1983, the rainfall in many parts of the western Pacific was only 10 to 30% of the long-term average.

In addition to their effect on precipitation, ENSO events can cause temporary sea-level rises due to elevated sea surface temperatures and a consequent thermal expansion of the ocean. This can add to the problems of small, low-lying islands. A sea-level rise caused by the 1987 ENSO event resulted in damage to crops on many atolls in the Federated States of Micronesia, adding to the effects of drought conditions also induced by that ENSO event.

Their Vegetation

Vegetation also affects an island's water supply in a number of ways. The trees, shrubs and grasses intercept a part of the rainfall; they participate in transpiration; they slow the surface runoff; and they reduce erosion. The first two effects often decrease the available ground water as water is lost to evaporation and transpiration.

Slowing the surface runoff helps increase the infiltration of water into the ground. Reduced erosion losses are desirable as the banks of rivers will not be washed away as soon. The useful life of lakes and reservoirs also will be extended.

Vegetation cover is desirable for both low and high islands from many viewpoints—the provision of food, forest exploitation, agriculture, soil conservation and other environmental, aesthetic and social factors. However, its desirability is not so clear from the viewpoint of water resources. Even in the cases where net losses of water occur, such as when the vegetation transpires water directly from the ground water, the negative effect of vegetation on water resources may be outweighed by its positive aspects. The effects of vegetation on water resources are discussed later in more detail.

Their soils

The soils of the different kinds of islands can affect water resources by influencing surface runoff, evaporation and transpiration.

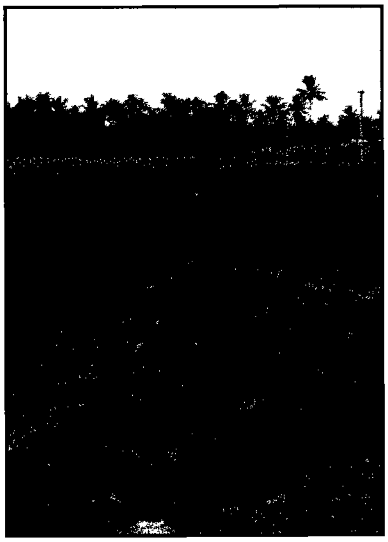
Limestone and coral islands, for example, have sandy soils of high permeability which result in high infiltration rates and very little or no surface runoff. Volcanic islands, for their part, tend to have clay soils produced by weathering of the igneous rocks. These soils thus have a lower permeability than the sandy soils and surface runoff is common.

The water-holding capacity of soil is an important factor for ground-water recharge. High water retention favours the evaporation and transpiration of any infiltrated rain, thus reducing the effective precipitation. Coarse soils with a low water retention capacity allow rainfall to quickly penetrate below the root depths in vegetated areas, thus decreasing evaporative losses.

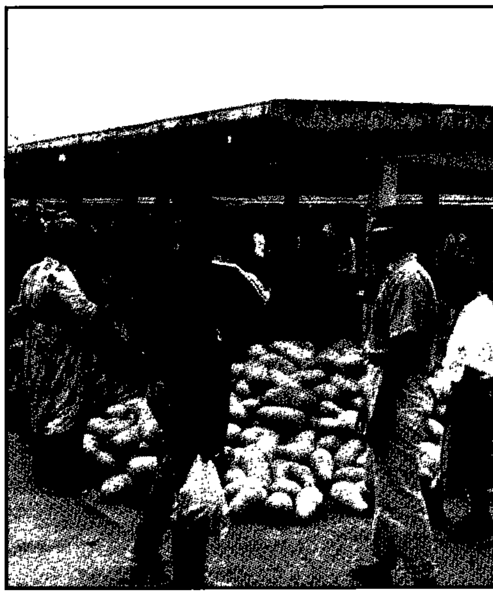
Clayey soils, after prolonged dry seasons, may develop cracks. If these cracks are deep enough, they allow some precipitation to infiltrate below the root depth before they close by swelling, thus enhancing recharge of the aquifer. The same is true for rock outcrops where the fractures are sufficient for rain to penetrate.

Soil also is an effective agent in preventing or minimizing groundwater pollution. This is an important factor in water resource management and protection. Unfortunately, some tropical islands have very thin soil layers—unless there has been some special event such as a fall-out of volcanic ash.

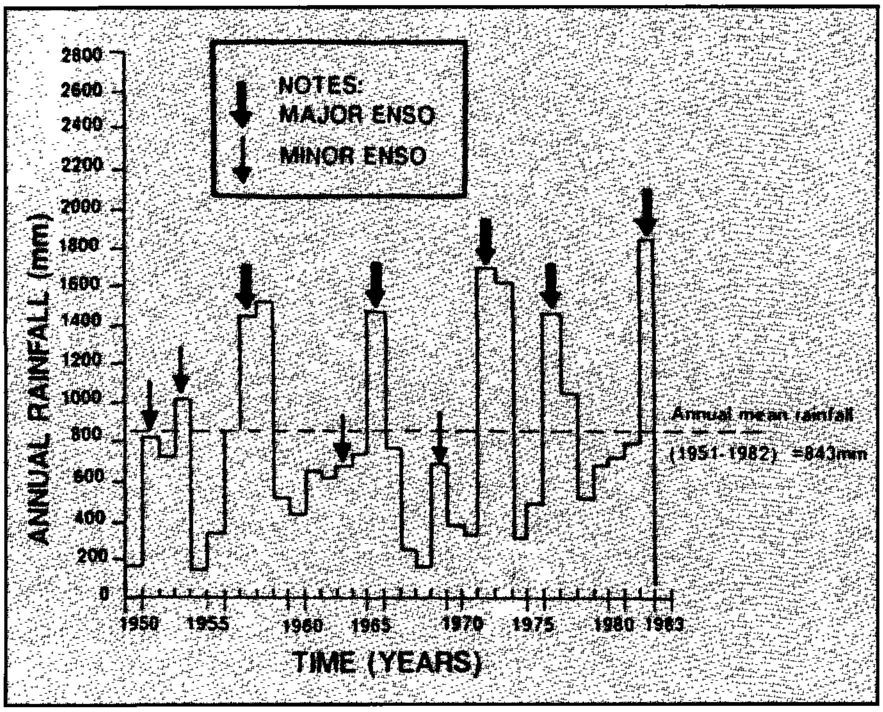
Although papaw does reasonably well, many fruits and vegetables do not do well as the thin, sandy soil lacks nutrients.

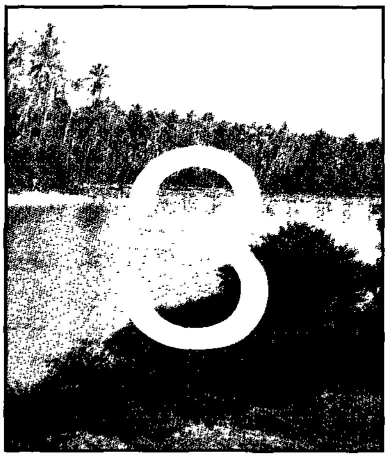


Those fortunate islands (such as Tongatapu, Tonga) which have a layer of volcanic ash over their coral limestone rock (above) can grow a wide variety of fruits and vegetables, as illustrated by the market below.



ENSO (El Niño-Southern Oscillation) effects on Christmas Island, Kiribati rainfall. An ENSO increases the rainfall in the central and eastern Pacific but decreases it in the western Pacific.





WHERE IS THE FRESH WATER ON SMALL ISLANDS?

Fresh water can occur naturally on small islands as surface water or as ground water. The type and quantity of fresh water on small islands is dictated by many factors, including those discussed in the last section, the size of the island and the amount and variability of rainfall.

Even on Christmas Island, described at the left by Captain Cook, now called Kiritimati (Republic of Kiribati), fresh water is available, albeit in limited quantities. A population of about 2,500 now live on this island which, strictly speaking, is in a drier part of the tropics—the central Pacific. The average annual rainfall occurring there is about 840 mm, compared to the higher rainfall experienced on most small tropical islands.

High volcanic islands are more likely to have surface water

Where suitable hydrological and geological conditions prevail on the high islands, surface water is found in the form of rivers, streams, springs, lakes and wetlands. Conditions for the occurrence of surface water are considerably more favourable on the volcanic islands than on those of limestone or coral. Low-lying or raised flat islands rarely have surface water, except as lakes or ponds where the permeability of the surface is sufficiently low.

Volcanic islands with raised topography and low permeability surfaces often have small streams but these are normally non-permanent in nature. Surface runoff often occurs rapidly after rainfall and may diminish to little or no flow within several minutes. Volcanic islands may also have perched lakes—generally found in the caldera

Some small limestone islands have surface water lakes such as Buada Lagoon on the island of Nauru. About five hectares in area, Buada is "perched" above the regional water table, thanks to an impermeable lining of phosphatic alluvium.

"There was not the smallest trace of any human being having ever been here before us; and . . . should anyone be so unfortunate as to be accidentally driven upon the island . . . it is hard to say that he could be able to prolong existence. There is, indeed, abundance of birds and fish; but no visible means of allaying thirst, nor any vegetable that could supply the place of bread, or correct the bad effects of an animal diet; which, in all probability, would soon prove fatal alone."

CAPTAIN JAMES COOK,
A Voyage to the Pacific Ocean, 1784

(crater). On many raised islands, particularly where volcanic rocks underlie limestone, perennial springs are found. These often occur around the base of an island, either slightly above or sometimes below sea-level. If the geological formations are very permeable, the ground-water discharge along the coast is diffuse rather than concentrated and may occur as submarine coastal springs. Such outflows are not regular along the coast but vary according to changes in the permeability and aquifer thickness. Concentrated discharges are common from older limestone islands.

Some high islands possess springs

Springs and seepages often appear on high islands, even at high altitudes, if the recharge is sufficient and if there are favourable hydrogeological conditions. In wet climates, permanent springs may appear on high islands, some with significant flows.

Ground water on high islands can occur in the form of elevated (high-level) or basal (low-level) aquifers. However, ground water on low islands occurs only in basal aquifers.

On many small islands, such a basal aquifer takes the form of a fresh water lens which underlies part or the whole of the island. Such fresh water lenses are very important water supply sources on many small islands. Generally, they are the most economical source of water to develop.

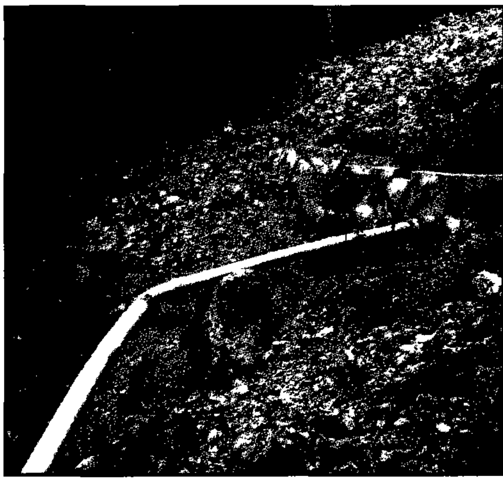
There are a number of factors which influence the formation of these fresh water lenses on low-lying islands, particularly the coral atolls and the small limestone islands. The amount and distribution of the recharge to the ground water, the size and shape of the island, the permeability of the sediments and the reef rock, and the magnitude of the tides are the most important.

Fresh water lenses are ground-water sources at and below sea level

The term "fresh water lens" can conjure up a misconception of the true nature of ground-water bodies underlying islands. In reality, there is no distinct fresh water body floating on sea-water but rather a gradual transition from the freshest water at the water table to sea-water at some depth below. Drawings of fresh water lenses, such as the diagram on the opposite page, are normally shown with an exaggerated vertical scale. This can lead to a false impression of the depth of the fresh water zone. In practice, the fresh water zones are often less than 10 metres thick although the island may be 500 or more metres wide. The deepest part of the fresh water zone is often displaced towards the lagoon side rather than the ocean side of coral atolls, due to the presence of sediments with a lower permeability on the lagoon side.

According to one commonly-expressed theory, which is based on the differences in density between fresh water and sea-water, the depth of fresh water below mean sea-level is calculated to be approximately 40 times the height of the water table above the mean sea-level. This theoretical relationship, which has been found to be a reasonable approximation for continental coastal aquifers, is not correct for many small islands as there is a substantial mixing or transitional zone between the fresh water and the sea-water. Serious errors in the estimation of the fresh water thickness have been caused by blindly applying the theory to small islands.

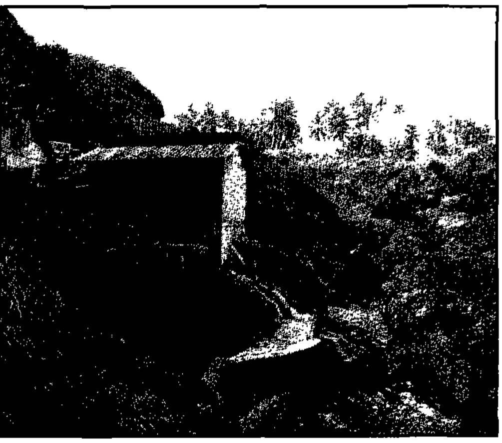
In addition to natural influences, the design and operation of



The spring shown at right is approximately at sea level. At high tide, the sea covers the beach below the discharge point.

At right is a spring located within a cave. The spring, which discharges about 20 litres a second, is located at sea-level and is inundated at high tide. Although fresh at the point of discharge, the water becomes more saline as the mouth of the cave is approached.

Springs shown on these pages are on a raised limestone island that is situated on an Indian Ocean volcanic basement. The spring at left is located about 100 metres above sea level and was "capped" with the concrete wall.



The spring at the left is discharging onto the beach in a concentrated outflow. Often such outflows are diffuse, taking place below the surface of the sand.

pumping facilities can have a major impact on the sustainability of fresh ground-water resources on small islands. Pumping at higher rates than the ground water can withstand (that is, above the "sustainable yield") has caused the temporary destruction of fresh water lenses by sea-water intrusion. Luckily, it has been found that this process is reversible, provided that there is sufficient recharge from rainfall to the ground water and that pumping is restricted to a level at or below the sustainable yield.

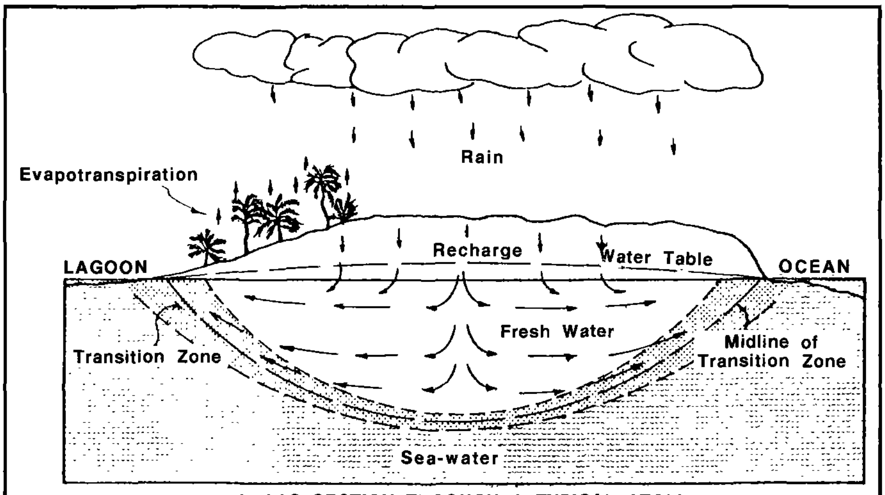
The relative importance of surface water and ground water on islands depends on the particular nature of the island. Ground water tends to be the more important resource of the two. Furthermore, basal aquifers tend to be more important than perched aquifers because not all islands have the latter. Where both types occur, the former normally have greater storage volume. However, basal aquifers are vulnerable to saline intrusion, owing to the fresh water/sea-water interaction, and thus must be very carefully managed to avoid over-exploitation.

Other sources of fresh water on small islands

When climatic, geological and other conditions are not favourable for the occurrence of sufficient fresh water, it may be necessary to use artificial or non-conventional methods to provide fresh water. Some of these alternatives are proven while others are doubtful.

Fresh water can be made available by treating highly saline water (desalination) or used water (waste-water reuse). Nowadays, there are a number of successful desalination systems based on distillation or membrane techniques. Small islands are surrounded by an abundance of sea-water which has the potential to supply very high demands for fresh water, provided the desalination process is affordable and is within the economic capacity of the community to operate

An idealized cross-section through a typical small limestone or coral island, showing the main features of a freshwater lens. In most cases the thickest part of the freshwater lens is not in the centre as shown but is displaced towards the lagoon side. This is due to the lower permeability sediments on the lagoon side slowing down the mixing of the fresh water and sea-water, thus enabling a thicker fresh water zone to develop.



CROSS SECTION THROUGH A TYPICAL ATOLL
Vertical scale exaggerated

and maintain.

Similarly, treating waste-water—sewage effluent, industrial discharges and stormwater runoff—is a technically feasible option for some purposes. Although improved purification techniques have been developed, the adoption of waste-water treatment and subsequent recycling as a means of supplying fresh (but non-potable) water is determined largely by economic factors. For potable purposes, its adoption is not only governed by economic but also by public health and aesthetic considerations. As a result, the process is rarely used.

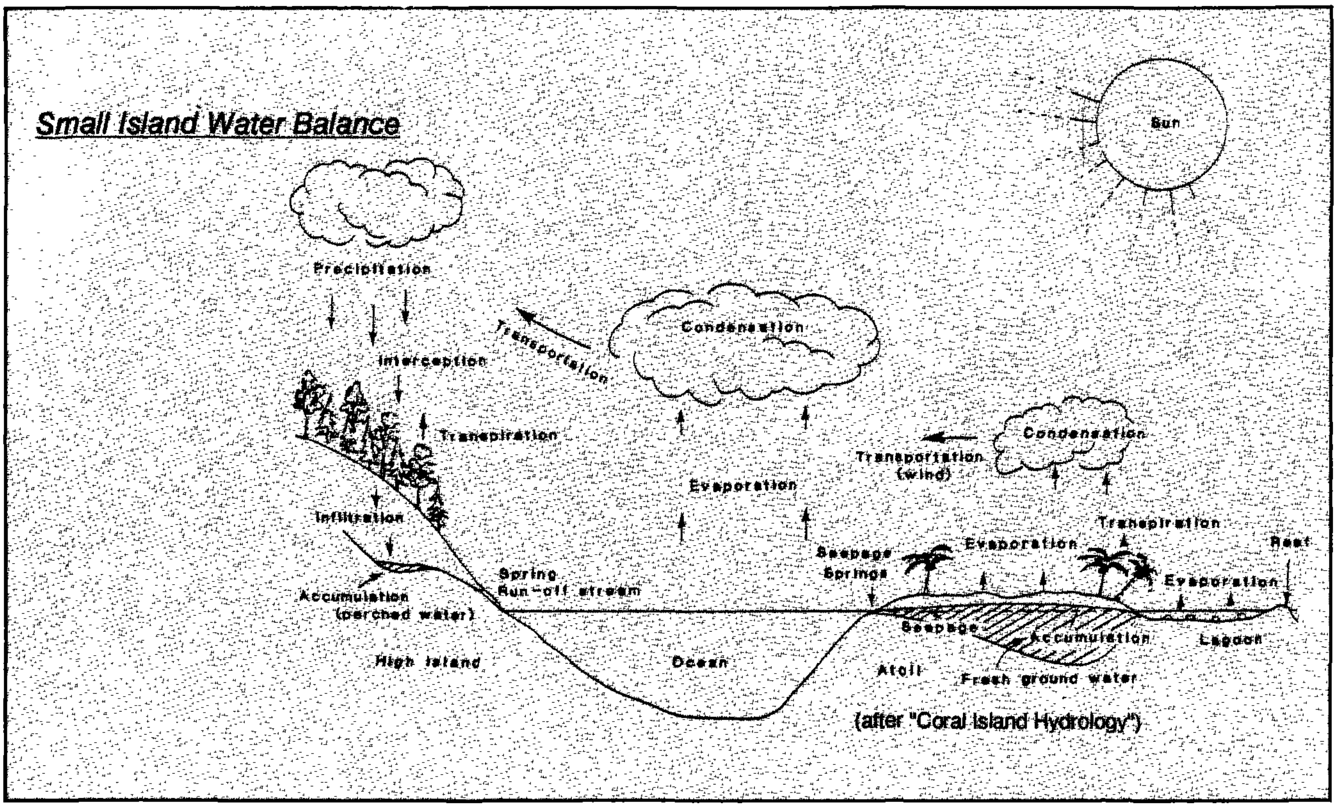
Importation through pipelines and barges

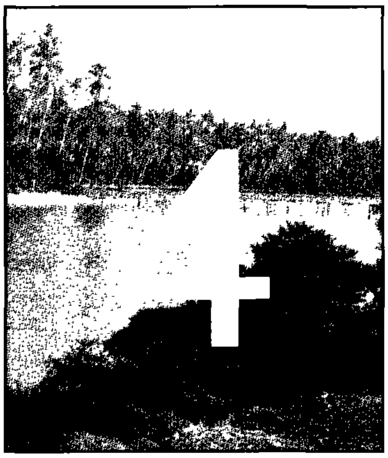
Another alternative to naturally-occurring fresh water is importation. Where small islands are situated close to a continent, submarine pipelines may be a practical solution. For more distant islands, transporting water in ships or barges is a possibility.

Obtaining water from different sources and using it for more than one purpose is another possibility. Many small islands do operate such "conjunctive use" schemes. Typically, these methods include the utilization of the naturally-occurring ground water and rainwater, but may also include desalination, waste-water reuse and/or importation. The direct use of brackish water and/or waste-water for irrigation and sea-water for sanitary flushing and cooling is often a good option on many small islands with limited fresh water. Such non-fresh water sources are discussed in more detail later.

A fresh water lens can underlie even some narrow islands such as the one above. The width of the island between the ocean on the left and the lagoon on the right is approximately 300 metres. Water is supplied to villages along this thin atoll via pipelines from selected pumping points in less inhabited and wider parts of the atoll.

Some of the main elements of the hydrological cycle as applied to the water balances of the main types of small, mid-oceanic islands. (After Dale et al.)





"Islands are natural hydrologic units inasmuch as their physical, economic, and biologic boundaries are effectively coincident. But islandic hydrology cannot be described via simple scaling of continental hydrology. The contrast between the two hydrologies suggests the adaptation of the concept of a hydrologic island in furthering hydrologic knowledge . . . which for the most part is presently limited to that gained through continental experience."

N. C. MATALAS,
Hydrology in an Island-Continent Context, Resources and World Development, 1987

ASSESSING SMALL ISLAND WATER RESOURCES

Water resource assessment involves the measurement or estimation of key hydrological variables and the analysis of the results so as to make informed estimates of the sustainability of water resources. Such estimates are essential for the rational planning and management of water resources.

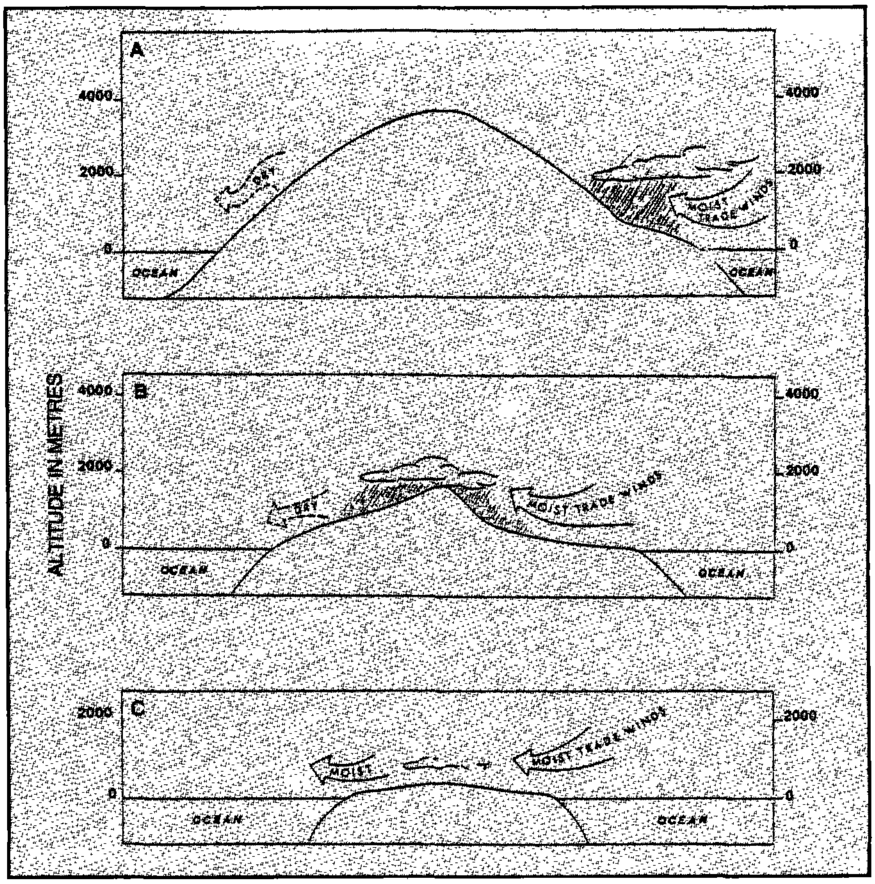
Carrying out such assessments on small islands presents some special problems. Often there is very limited data available with which to assess the long-term "yield" of streams or ground-water aquifers. Without such knowledge, it is very easy for development to proceed in an uncontrolled fashion with the almost inevitable consequence of over-exploitation. It is essential, therefore, that at least some relevant data be obtained about key hydrological variables.

Precipitation records

On many islands, particularly the more populous ones, there is generally a reasonable record of rainfall, often being recorded daily at one or more locations. One raingauge on a small low-lying island may be sufficient to represent the rainfall patterns over the whole island.

However, problems occur with small "high" islands, as there can

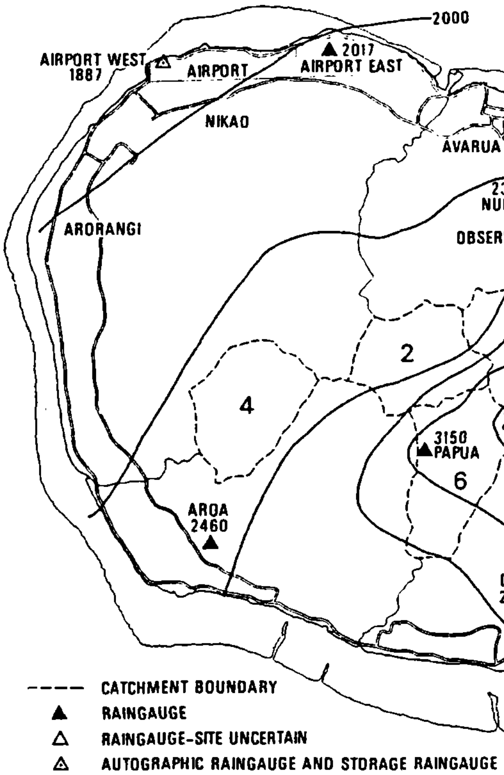
The effects of topography on rainfall over small islands are shown in the diagrams below. These examples of "orographic effects" are based on examples from the Hawaiian Islands, as described by Takasaki (1978).



be considerable rainfall variability over relatively short distances, owing to the presence of elevated terrain and its effect on precipitation. On those high islands exposed to the influence of the moist Trade Winds, rainfall on the windward side is considerably higher than on the leeward side as the moist air currents are forced to rise upwards and condense as rainfall (the orographic effect). On the leeward side of high islands, arid conditions can prevail due to the "rain-shadow" effect. This mechanism is shown in the diagram on the previous page.

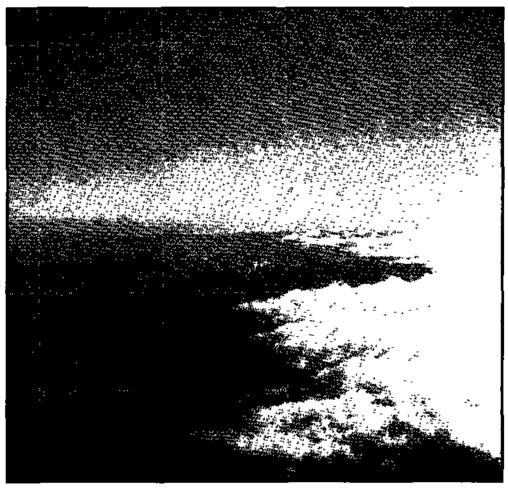
Abrupt rainfall change over short distances

Annual rainfall gradients (the change in rainfall over a horizontal distance) are often very steep on the small high islands. For example, the annual rainfall gradient isclose to 850 mm per kilometre on Kauai in the Hawaiian Islands. The diagram at the right shows the annual rainfall contours on Raratonga in the Cook Islands where the rainfall gradient reaches 1,000 mm per kilometre on the eastern side of the island.



On the small, low-lying islands, orographic effects are negligible and the rainfall tends to be more sporadic. Apart from a greater variability in time, significant differences in rainfall have been observed on some low-lying islands over distances of just a few kilometres. These rainfall variations are important in the overall water balance of a small island. Therefore, a single raingauge may not be sufficient to yield the needed information.

The number and location of raingauges thus should be matched to the size and topography of the island. Problems do exist on small high islands where the steep and often inaccessible terrain makes it extremely difficult to operate raingauges located in the island's interior. As a result, in such situations, most raingauges tend to be situated around the rim of the islands. The very high rainfalls that occur in the peaks or highlands thus may not be recorded. In some instances, where measurements have been taken in the higher altitudes, annual rainfall depths exceeding 10 metres have been recorded, yet the official rainfall records may show typical values of only two to three metres for the island.



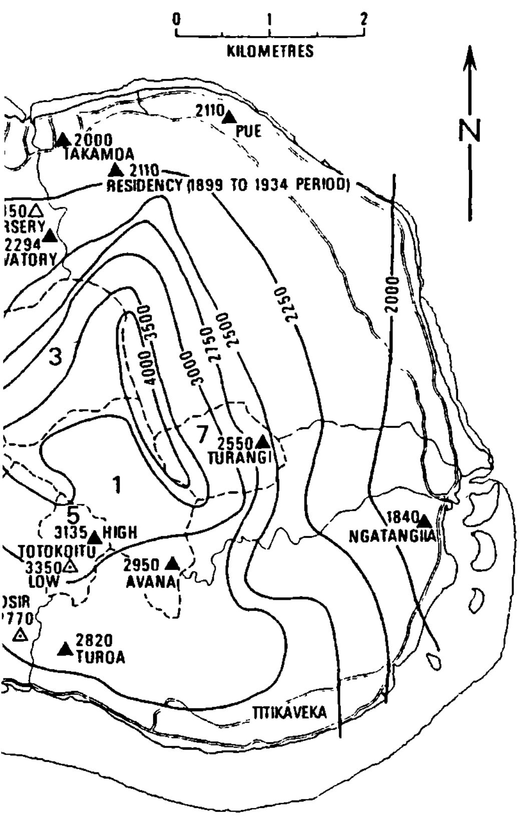
Rainfall on low islands in the humid tropics can be "hit or miss." In some parts of the humid tropics, islands experience distinct wet and dry seasons, but in others there is a more even distribution throughout the year—on the average. In some years, long droughts are experienced due to major climatic influences such as the onset of an El Niño event.

The combined process of evaporation and vegetational transpiration, often referred to as evapotranspiration, is one of the most important components of a small island's water balance. Evapotranspiration can be more than half of a small island's rainfall on an annual basis and often exceeds the rainfall for individual months or consecutive months during dry seasons or drought periods. Despite its importance, evapotranspiration is probably the least known water component on small islands. This is due to the lack on many islands of climatic or pan evaporation data which are used to derive evapotranspiration estimates.

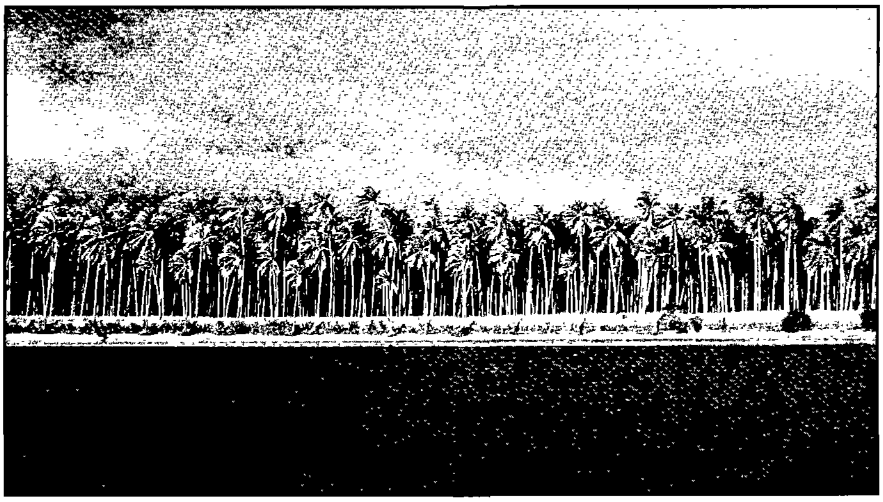
The amount of evapotranspiration on an island is affected by solar radiation, temperature, humidity and wind speed and by factors specific to each island such as the degree of exposure, the type and density of vegetation and the soil types.

Two factors which can cause a reasonably large variation in evapotranspiration on small, low-lying tropical islands are the type and density of vegetation. The evapotranspiration from areas where there are dense growths of deep-rooted vegetation, such as the ubiquitous coconut tree, is much greater than in areas predominantly covered by shallow-rooted grasses and shrubs. Coconut tree roots can penetrate to the water table, generally found at a depth of two to three metres on many small coral islands. Thus these roots can obtain water even during droughts, enabling the trees to survive.

Direct measurements of transpiration from coconut trees have added to the knowledge of the evapotranspiration process on small islands in the humid tropics. Transpiration from individual coconut trees, as measured on one of the atoll islands in the Cocos (Keeling) Islands in the Indian Ocean—using a special instrument called a heat pulse velocity meter—was found to be between 70 and l30 litres per day. Using other techniques, transpiration rates of up to 200 litres per day from individual coconut trees have been measured in the Philippines. By comparison, people in rural areas of the developing



How topography affects rainfall on the small, high island of Rarotonga (Cook Islands) is shown by the rainfall contours drawn above. The photograph at left (Viti Levu, a large island in Fiji) demonstrates how it may change suddenly from cloudy to clear and thus from wetter to drier conditions.

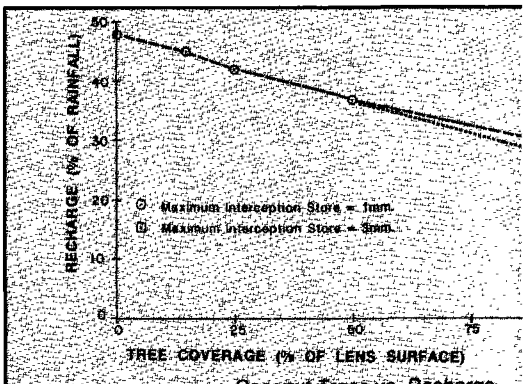


Many small islands have dense plantations of coconut trees. The photograph above illustrates how close such trees can grow towards a beach. In some cases, the roots are in sea-water at high tide. The photograph below shows the thick mat of roots which form at the base of coconut trees. The hard tip of such roots can easily penetrate through soils and coral sediments.

countries use about 50 litres each day.

Measurements indicate that in those areas where coconut trees are spaced about eight metres apart, the total transpiration rate from those trees will be equivalent to a depth of water of about 400 to 750 mm per year. The recharge to ground water is thus reduced in areas where there are large numbers of coconut trees. The effects on recharge to ground water in the Cocos (Keeling) Islands are shown graphically in the diagram opposite for different percentages of tree cover.

This water withdrawal has implications for island water supply management. It may well be prudent to selectively clear coconut trees from some fresh water lens areas to maximize the supply of water. Where coconut trees have been totally cleared, as occurs with airfield development, a significant increase in fresh water lens thickness can be noticed. Other forms of vegetation, particularly other large trees, need also to be examined for their retention in areas otherwise suitable for ground-water development.



Coconut Trees vs. Recharge

Surface runoff measurements

Surface runoff, as already described, only occurs on high islands with favourable topographical and geological conditions. Runoff is generally non-existent or is a very small fraction of rainfall on young volcanic islands and coral islands but can be a major component of the water supply on bedrock islands. The magnitude of surface runoff increases with the island's size and decreasing permeability. Steep slopes in high islands favour surface runoff. Sometimes deep gullies may be incised into canyons. Volcanic and carbonate islands are prone to being deeply dissected.

The coconut tree below is being "wired up" to a heat pulse velocity meter. Direct measurements of tree transpiration have added to the understanding of the evapotranspiration process.

Islands where surface runoff occurs are generally characterized by many small-sized catchments with steep slopes on which runoff occurs very rapidly. As a result, flash-floods can take place. Due to the erosive power of the streams, erosion and sedimentation problems also are prevalent. A number of islands have experienced soil and vegetation losses with consequent high turbidity problems in streams as well as damage to water intakes and other on-stream structures.

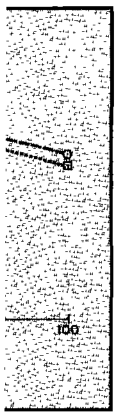
Structures used to measure flows in streams are called stream gauging stations. Such stations need to be robust and the equipment needs to be well-tested in tropical environments. Modern electronic data-logging devices offer some distinct advantages over more conventional mechanical recorders which use pens to record variations in stream height on paper charts.

Calibrated weirs, such as the V-notch shown below, are reasonable flow measuring devices for low to medium discharges. During high flows, alternative methods are required.

"High tech" solutions offer advantages to small islands

The acquisition of runoff data from remote sites via satellite telemetry may appear to be a "high tech" solution for small islands. However, it has considerable advantages as the data can be regularly recovered and processed at a base station, thus saving time and costs. Site visits for maintenance can be restructured to some extent to respond to known problems at stations, rather than being done solely on a periodic basis.

Telemetry also has an additional and even more important part to play when "real time" information is required for flood warning and forecasting. The use of satellites for data collection thus should not be viewed as unusual. Unfortunately, this problem is fundamental in the thinking of some organizations and governments because of the



How the number (leaf coverage) of coconut trees can affect the amount of rainreaching an aquifer is shown in the diagram at left. Where there are no coconut trees, the recharge to ground water is about 50% of the rainfall. However, as the coconut trees increase to a full cover, the recharge can reduce to about 30% of the rainfall. Data for this diagram were derived from studies in the Cocos (Keeling) Islands

low priority given to water resource assessment programmes.

Ground-water information

One of the main problems on many small islands is the lack of accurate knowledge of the extent and sustainable yield of their fresh water lenses. The usefulness of drilling observation holes and obtaining vertical salinity profiles from the water table down to seawater has been identified by some detailed studies on small coral islands in the Pacific and Indian Oceans. The installation of simple monitoring systems inside these holes enable valuable post-drilling salinity profiles to be obtained. The need for good quality, long-term records of groundwater salinity data cannot be overemphasized. Too often, groundwater development schemes have been designed for small islands without any knowledge of the extent or yield of their ground-water resource.

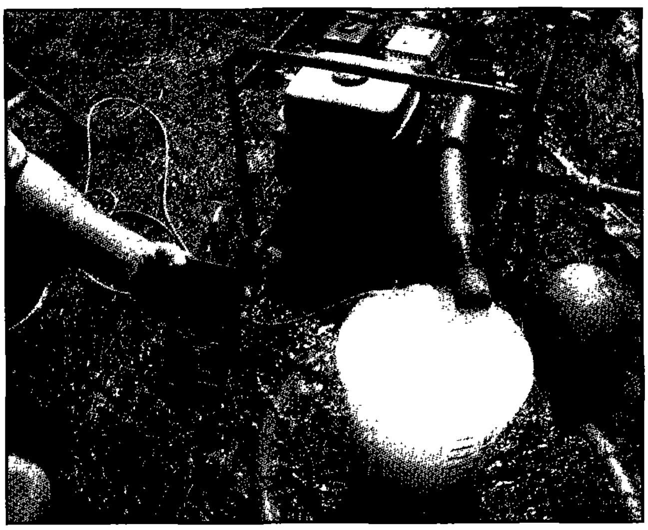
Geophysical methods are well-suited to low islands with their relatively small depths from the surface to the water table. In particular, tπwo techniques which use induced electrical signals in the ground to determine the thickness of fresh water layers are especially useful on small islands where the depth to the water table is only a few metres. These methods, electromagnetic and electrical resistivity, have been successfully used in a number of studies to determine fresh water lens thickness. Careful site selection is required, however, to avoid buried objects such as pipes and cables as these can give misleading readings.

Geophysical techniques applicable to small low islands

The use of geophysics is recommended for preliminary reconnaissance of fresh water resources on small islands, particularly the low coral islands. The application of geophysics is less useful on high islands, particularly where complex geological structures are present.

Measurement of the water level fluctuations at the top of the fresh water lenses (the water table) cannot be used to determine fresh water zone thickness because there is no direct relationship between

Ground-water investigations on small islands are an essential component of the water resource assessment process. Small drilling rigs , such as at left, can be used to drill an investigative/monitoring borehole through a fresh water lens. Salinity (electrical conductivity) of a borehole water sample is being measured in the bottom left photo. At the bottom right is the equipment used to obtain a borehole's vertical salinity profile.



the height of the water table above mean sea-level and the fresh water zone thickness. This fact has not always been realized. Some past assessments of fresh water storage volumes, based on water level measurements alone, were incorrect. Such measurements, however, are useful for monitoring the drawdown effects of pumping and for setting design levels for infiltration galleries and other ground-water abstraction facilities.

More inter-island transfer of knowledge needed

Although some islands have been studied in detail, there appears to be a gap in the transfer of this knowledge to other island situations. The advantages and limitations of the various ground-water investigation and monitoring techniques should be well understood by field workers assigned to assess the ground-water resources on small islands. As a good initial guide to field practices, the publication, "Coral Island Hydrology," by Dale *et al.* and produced by the New Zealand Department of Scientific and Industrial Research for the Commonwealth Science Council, is to be commended. Where major ground water abstraction works have been built or are being designed, funding should be provided to establish proper monitoring systems, particularly, properly constructed monitoring boreholes for obtaining vertical salinity profiles.

Better methods needed to determine water yields

There is a need, moreover, for the development of simple yet accurate methods of determining the sustainable yield from fresh water lenses. In the absence of detailed computer modelling for a particular island, approximate assessments of sustainable yield can be made from other studies. Based on a number of different approaches, sustainable yields of between 6 to 12% of the annual

Some small islands are well-equipped with weather stations, often with a good range of measuring sensors, as shown above. Unfortunately, others have limited meteorological data collection facilities which makes water resource assessment more difficult.

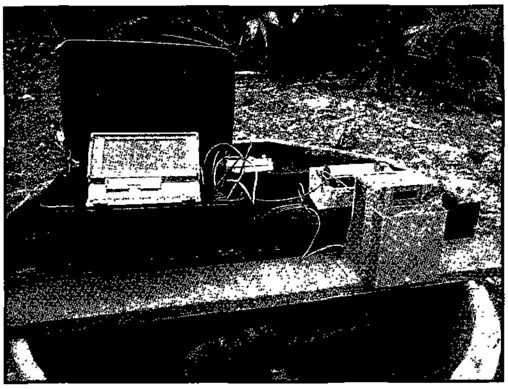
Fresh water lens thickness can be estimated rapidly on small coral islands by electrical resistivity (below) and electromagnetic (right) methods.

rainfall are derived. Actual vegetation conditions, however, should be considered in the derivation of estimates for a given atoll.

The estimation of sustainable yield of an individual gallery system located in a fresh water lens on a small coral island is a real problem. A number of approaches have been used for the design of gallery systems but it is apparent that further theoretical and practical research in this area is warranted. In the meantime, it is essential that monitoring of the behaviour of fresh water lenses, using salinity profiles from properly constructed monitoring systems, be continued or commenced. The response of lenses under ground water-abstraction conditions can thus be analyzed and calibration and testing of computer models be undertaken.

Large island methods often inappropriate

Hydrological studies based on concepts and criteria appropriate for large islands and continents are frequently carried out on small islands. Often there is a lack of skilled local personnel and it is necessary to obtain external assistance, including specialists and equipment, to carry out these water resource assessment surveys. Such an arrangement is both difficult and expensive, especially in those countries composed of many isolated small islands.



Small portable computers and electronic data logging devices can assist with small island water resource studies. A portable computer is being used above to retrieve information from a data logger attached to a ground-water level measuring device.

It is also difficult for small island states to adapt the results of hydrological investigations from large islands or continents. Small islands require either island-specific or, in favourable cases, regional studies to properly identify their water resources and to implement their own effective development and management programmes.

Remote measuring equipment may be necessary

In some mountainous small islands, in spite of their limited area, the lack of access roads or tracks often means using a combination of a boat, aircraft, helicopter, motorcycle, bicycle, horse or other animal and walking on foot to carry out hydrological studies. This access problem often increases the cost of obtaining basic water data and may require the installation of sophisticated remote measuring equipment. There also is good justification for the increased use of personal computers for the processing, storage and reporting of water data and for the use of computer programs for hydrological analysis. Some small island nations have already started to utilize these modern-day tools. Others have insufficient personnel skilled in their use.

HOW IS WATER USED ON SMALL ISLANDS?

The essential nature of water

Water is used on small islands for the same purposes as elsewhere in the world: water supply (for domestic purposes, tourism and industry), irrigation and even hydroelectric power generation. Many small islands, however, do not have sufficient water resources or adequate land resources to allow for irrigation or suitable topographic features for the development of hydroelectric schemes. Hence, most fresh water on small islands is used for water supplies.

Fresh water that is potable (drinkable) is used for drinking, cooking, bathing, washing and cleaning. Other potable water uses include toilet flushing, cooling, heating, freezing and drinking water for domestic animals. There are many cases, however, where non-potable water supplies, such as sea-water or brackish ground water, are substituted. In particular, non-potable water is used on some islands for toilet flushing, fire-fighting, power station cooling and ice making for the fishing industries. Brackish ground water is sometimes used on very small islands, such as coral atolls, for all purposes except drinking and cooking. Sea-water is sometimes used for bathing while treated sewage effluent, another source of non-potable water, is sometimes used for garden and lawn watering.

Many factors affect amount of water used

The domestic consumption of fresh water varies considerably among islands and within islands, depending on the fresh water's availability and quality, the type and age of the distribution system, the cultural and socio-economic factors and the administrative procedures. Water consumption on islands with limited ground water and where limited uses are allowed, is about 50 to 100 litres per person per day. Larger consumption of water occurs where water resources are more plentiful, where water distribution systems leak

Fresh water is very scarce on some small islands. Limited quantities can be used for some activities, such as the washing of clothes."

"Recruitment for the Phoenix [Islands] took place between 1938 and 1940. Families who were short of land were recruited together with others who volunteered. All seemed fine . . . but there were difficulties, especially with water. As one of the delegates who settled in the Phoenix Islands said, had there been good well-water, they would all have been prepared to settle there permanently. Another worry was that the settlers felt

they were losing their ancestral lands. But. . . this feeling would have been drowned by good well-water. Water was the main problem: it was too saline. Water was also limited because the food trees were immature and the soil was too salty for babai (swamp taro)."
SISTER ALAIMA TALU *et al.*, Kiribati: Aspects of History, 1979

Cultivation of taro in pits dug to the water table is common on some low-lying islands in the Pacific Ocean

or are abused, where water flush toilets are used and where modern water-using facilities such as washing machines have been introduced. There are some reported cases of small islands where the water consumption, including leakage and wastage, exceeds 1,000 litres per capita per day.

Tourist water use—often about 500 litres per capita per day—tends to be higher than per capita domestic use. Tourist consumption of fresh water thus can represent the largest use of water on many small islands.

The use of water for industrial purposes, including mining, tends to be minor on most small islands. On particular islands, however, the use of water in some industries may be a major component of the overall use.

Irrigation

Much of the natural vegetation—a variety of trees, particularly the coconuts, and a range of bushes and grasses—on small, tropical islands receives adequate rainfall for growth. Irrigation is not required as they have adapted to local climatic conditions. In extreme droughts, some of the more sensitive plants will die. However, some of the natural vegetation, such as the coconut tree, is remarkably tolerant to droughts and to salt-water.

Irrigation schemes on small islands, where they exist, tend to be relatively minor in scale, although there are exceptions. Many small islands, particularly coral atolls, do not have suitable soil, being both highly permeable and lacking in organic material. Relatively small-scale irrigation is possible, however, on some of the high islands.

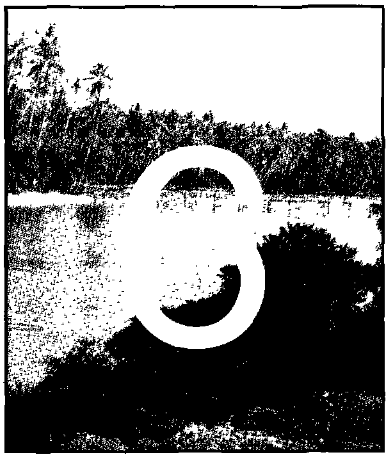
Cultivation of root and tuber crops is practised on some islands, mainly those located in the Pacific Ocean. One important example is the cultivation of swamp taro (called by many names, including *babai* in Kiribati) on some coral atolls by digging a pit to the water table in areas where the ground water is low in salinity.

At the higher water-use end, cash crops such as sugar cane are commercially grown on some islands through the use of irrigation. On the Hawaiian Islands and Fiji, the greatest use of water is for agriculture, primarily sugar cane cultivation. On islands in South-East Asia, rice is cultivated by methods similar to those used on continents.

Hydro-power generation

There are a number of small, high islands where hydroelectric power generation schemes have been implemented. These installations tend to be on a relatively small scale but where conditions are favourable, they can supply the major proportion of total power requirements. Islands where electricity is generated by hydro-power are Vitu Levu in Fiji, Western Samoa, Tahiti, the Marquesas Islands, Pohnpei and Hawaii in the Pacific Ocean, Mauritius in the Indian Ocean and Dominica, Grenada and St. Vincent in the Caribbean Sea. Many other high islands have the potential for hydroelectric power generation.

HOW IS WATER DEVELOPED ON SMALL ISLANDS?



The comment at right applies to the lack of a fresh water supply in a sea of salt-water. It can equally apply to a very small island where the water resources are scarce, are hard to develop in a way which maintains their integrity and are easily polluted by insufficient attention to sanitation and land management practices.

Many water resource development methods are used on islands. Methods which directly exploit or produce fresh water are rainwater and surface water collection, ground-water abstraction, desalination and importation.

In addition, other methods assist in either the conservation of fresh water by reuse, substitution, or enhancement. These include waste-water reuse, direct substitution, non-potable water systems and potable water enhancement techniques.

Rainwater collection

This is one of the most commonly used methods for domestic water supply, particularly on those islands with relatively high rainfall. Surfaces for rainfall collection include both roof and ground catchments, with roof catchments being the most common. Ground catchments can be either natural or artificial. Examples of artificially prepared ground catchments include airport runways (Majuro in the Marshall Islands), sealed surfaces made specifically for rainwater collection (sealed rock outcrops in Bermuda and a paved hillslope in St. Thomas, the U.S. Virgin Islands) and synthetic liners (Coconut Island, Torres Strait, Australia).

Storage facilities for rainwater on islands have been made of timber, steel and other metals, clay, concrete and fibreglass. Discarded 200 litre fuel drums are often used for such purposes.

Surface water collection

Island surface water development methods are generally of three types: stream intake structures, dams or other storages and spring cappings.

Stream intake structures generally consist of either in-stream weirs or buried collector pipe systems laid in, or adjacent to, the stream bed.

Water-retaining structures are constructed as dams within the stream or as "off-channel" storages. Neither are very common on small islands due to unsuitable topography or geological conditions and to economic considerations. However, some water supply dams are to be found. Guam in the Western Pacific is one example.

Spring cappings typically consist of an open or covered containment structure that is usually constructed from concrete or masonry. Spring flows contained by the structure flow to an intake pipe.

Ground-water abstraction

Ground-water abstraction methods on islands are generally of five types: dug wells, boreholes (drilled wells), use of natural sinkholes or cave systems, infiltration galleries and tunnels.

Dug wells, generally with diameters of between one and two metres are common on many small islands. On low islands, particularly coral atolls, such wells need only to be about two to three metres deep before the water table is reached. Where conditions are favourable, fresh water is available in moderate quantities. Dug wells also provide a source of fresh water in some areas on high islands, generally in sedimentary formations located on the coastal margins. In some instances, shallow-dug holes on beaches are

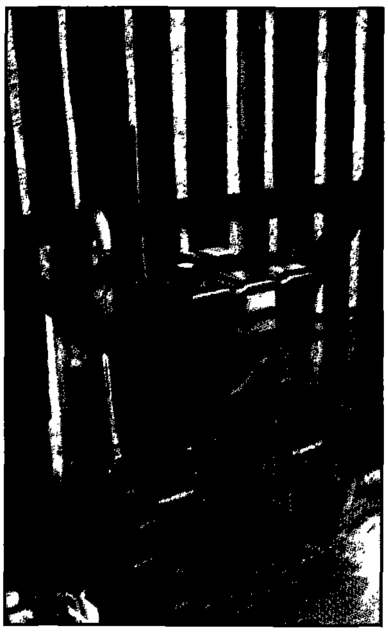
"Water, water everywhere but not a drop to drink."

SAMUEL COLERIDGE, The Rime of The Ancient Mariner

A typical small island dug well. The raised concrete is important for preventing polluted surface water from entering the well.

Rainwater collection systems require a collecting surface and a storage facility. House roofs are often used as the collecting surface, with a variety of innovative containers (at left) ranging from steel drums to ferrocement and fibreglass tanks being utilized.

A diesel motor is often used to power a borehole pump where the depth to the water table is too great for a dug well.



used as a source of fresh water during low tide periods. However, these holes often are covered by sea-water at high tide.

Water is obtained from dug wells by hand bailers or pumps. Hand bailers are often buckets or discarded food or drink containers. Pumps range from simple hand pumps, of which there are numerous designs, to more sophisticated mechanical pumps. The latter utilize conventional energy sources such as diesel or electrically-powered motors. However, where conditions are favourable, renewable energy sources such as wind- or solar-powered pumps are sometimes utilized.

Boreholes are a common means of developing ground-water resources on islands, particularly on high islands where the depth to the water table is excessive or the rocks are too hard for surface excavation. Where fresh water lenses are relatively thick, borehole abstraction systems have been used successfully. The main requirements are that a network of boreholes be drilled and individual pump rates be kept sufficiently low so as to prevent the occurrence of excessive localized drawdowns and consequent upconing of the underlying sea-water.

On high islands, boreholes have been used to develop high-level or perched aquifers. In Tahiti and the Hawaiian Islands, vertical and horizontal boreholes have been used to obtain water from aquifers contained behind impermeable volcanic rock formations.

Sinkholes and caves in limestone may contain water

In some limestone islands, fresh water found in sinkholes or cave systems has been used by pumping it to the surface. Christmas Island in the Indian Ocean, the islands of Grand Bahamas and Eleuthera in the Caribbean and northern Guam in the Pacific utilize such sources.

Infiltration galleries, also referred to as "lens wells" or "skimming wells," have been used on low islands and in the coastal areas of high islands. This method of development is particularly effective in such locations. Relatively large volumes of water can be abstracted compared to other methods, without causing sea-water intrusion.

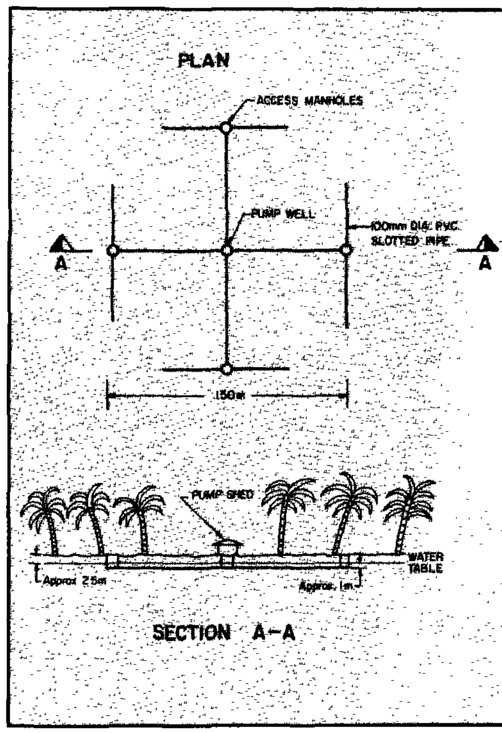
On coral atolls and other low limestone islands, such infiltration galleries generally consist of a horizontal conduit of slotted plastic pipe laid in a trench just below the water table. The conduits are joined to a central pumping pit so that the action of the pump causes water to be drawn through the pipe slots from a wide area. This process is akin to skimming water off the surface of a fresh water lens (hence the name, "skimming well").

Buried conduits of this type are successfully operating on a number of atolls, including Tarawa in Kiribati, Kwajalein in the Marshall Islands and Diego Garcia in the Indian Ocean. On Tarawa, over a million litres of water are pumped each day from two fresh water lenses, supplying a population of 25,000 people.

Tunnels are probably the most technically difficult and least common method of island ground-water development. They have been used, however, to develop both high-level and basal ground-water bodies on high islands. In the Hawaiian Islands, tunnels or "Maui-type wells" have been used for many years to produce large quantities of fresh water from the basal ground water located in coastal areas. These tunnels were constructed by sinking a vertical or inclined shaft from ground level to a pump room just below the water table. A series of horizontal collection tunnels radiate out from the pump room, allowing the abstraction of water from a relatively large area.

To increase well yields, tunnels have been constructed at the base of large diameter wells or shafts at sea-level. On Barbados in the Caribbean, such tunnels have been excavated up to 60 metres in length.

A typical layout of a gallery system for extracting water from a fresh water lens .



Desalination

Desalination plants are used on some islands to meet specific requirements, such as tourist resorts and military installations. However, there are few small islands where desalination is used as the main source of water. An exception is the U.S. Virgin Islands.

Desalination systems are based on a distillation or a membrane process. The former includes multi-stage flash (MSF), multiple effect (ME) and vapour compression (VC) while the membrane processes include reverse osmosis (RO) and electrodialysis (ED). All types have been used on islands.

MSF plants with a combined capacity of 30 million litres per day operate on the island of Aruba, in the Netherland Antilles (Caribbean). There are a number of ME plants in the U.S. Virgin Islands with a combined capacity of about 25 million litres per day. VC plants with a combined output of 2.6 million litres per day operate in the Cayman Islands. A number of sea-water RO plants also operate in the U.S. Virgin Islands, in Bermuda and on Malé in the Maldives.

In addition to the "high technology" desalination processes, solar stills can offer a "low technology" solution in certain cases. They have been used for the production of small quantities of fresh water from sea-water, generally on a temporary or research basis. With the typically high daily solar radiation values in the humid tropics, fresh water yields of about three litres per day per square metre of solar still surface can be produced. While solar stills have some major advantages, such as the use of readily available energy and the high-quality of the water obtained, there are some significant problems for the large-scale production of fresh water by this method. The stills can be used, however, for emergency purposes.

In general, desalination is a suitable technology for use in

At left, construction of a fresh water lens gallery (skimming well) on a coral atoll. Slotted plastic pipe has been laid at the base of a trench (dug to below the water table) and connected to a central pumping pit. The photograph above is of the inside of a covered "open trench" gallery. Although simpler to build than the buried conduit system, it can be easily polluted.

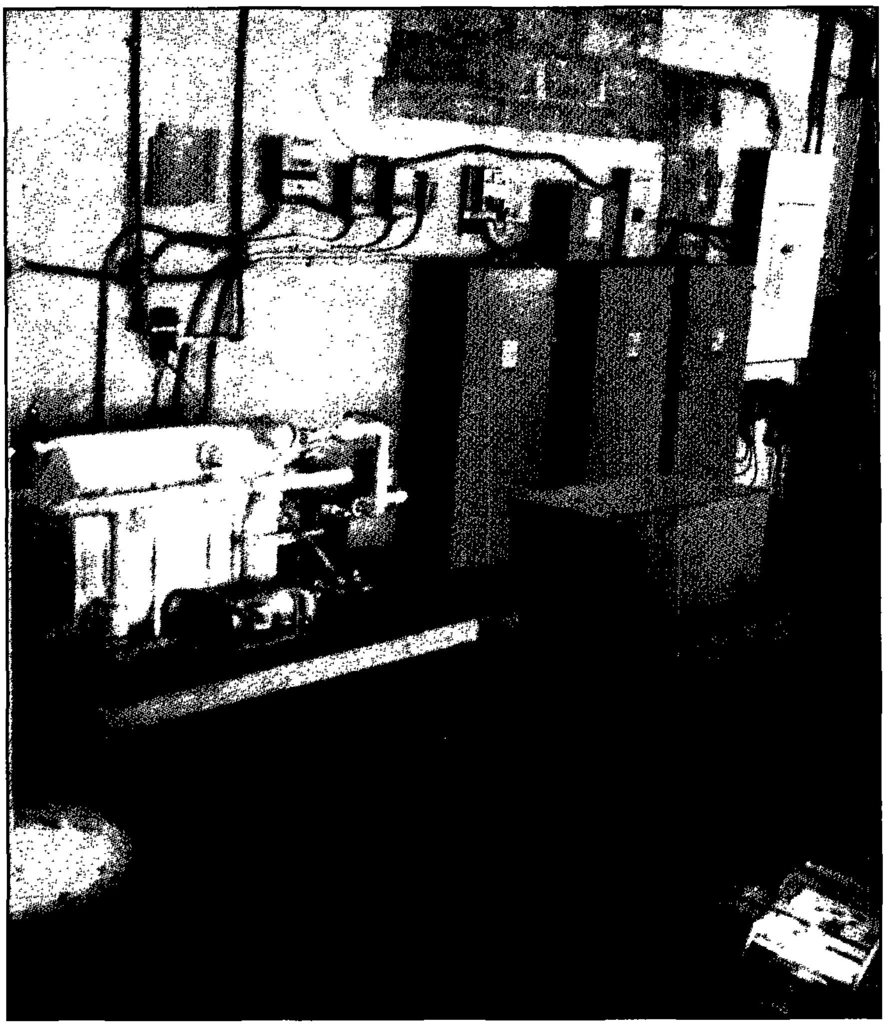
developed nations but is too sophisticated for those which are still developing, including many of the island countries located in the humid tropics. Unless there are well trained and skilled operators, as well as a ready and reliable source of spare parts and chemicals, desalination is not appropriate. It has found some success, however, at island tourist and military installations and as a temporary measure in the aftermath of natural disasters.

Importation

Water importation, used as an emergency measure during severe drought situations, is used as a sole or supplementary source on a regular basis on some islands. Methods of importation include piping via submarine pipelines or sea transport using tankers or barges.

Hong Kong receives about 50% of its potable water requirements via twin pipelines from the adjacent mainland. Penang in Malaysia also receives some of its water from the Malaysian Peninsula via submarine pipelines. Aruba in the Caribbean has received water imports by tanker from Dominica, while approximately 30% of the total water supply for the island of New Providence in the Bahamas is imported by barge from a nearby, larger island (Andros). The island of Nauru in the Pacific Ocean has received most of its water as return cargo in ships used for exporting phosphate. During the droughts that have been experienced since the early l970s, some of

A small desalination plant such as at right can supply high quality water. This one obtains water from a nearby gallery with brackish water, changing it into desalinated water for a hotel. Much larger units are in operation on a number of small tropical islands, particularly where tourist resorts are situated. However, well-trained staff and an adequate supply of spare parts and chemicals are necessary if such installations are to be a viable water supply option.



the smaller Fijian islands have received barged water from the larger islands of the group. The service has become increasingly more routine in recent years. In Tonga, some of the smaller islands of the archipelago obtain water from nearby islands during dry periods.

Waste-water reuse

Waste water is generally used for such non-potable applications as sanitary flushing, irrigation and industrial cooling. If the waste-water, including that discharged in either sewerage or stormwater systems, is adequately treated, it can also be used as potable water.

In Singapore, treated stormwater is used to supplement drinking water supplies. Surface runoff from a number of urban catchments is collected into ponds and subsequently transferred into holding dams. Such collection facilities are designed to collect about 70% of the surface runoff. Extensive treatment of the water then follows to ensure that it satisfies drinking water standards. This technology, however, is not generally feasible for many developing island nations.

Substitution

In extreme situations such as droughts, substitutes for fresh drinking water have been used, the most notable being coconut juice. People on some of the smaller and drier islands in Fiji, Kiribati and the Marshall Islands have been known to survive on this substitute during drought periods. The coconut tree is remarkably salt-tolerant and can produce "fresh" juice from ground-water bodies having high salinity levels.

Non-potable water systems

Among the non-potable water sources are sea-water, brackish ground water and waste-water. There are many examples of the use of these waters to conserve valuable fresh water reserves on islands. Sea-water is used for both toilet flushing and fire-fighting on a number of islands, including St. Thomas and St. Croix in the U.S. Virgin Islands, Tarawa in the Republic of Kiribati and Hong Kong. Many islanders, particularly in the less-developed islands, make use of sea-water or brackish well water for bathing and some washing purposes. Sea-water is also used for cooling of electric power generation plants and for ice making (for fishing purposes), as well as in air conditioning plants and swimming pools.

Potable water enhancement techniques

There are a number of methods which are aimed at, or happen to cause, an increase in the available fresh water storage in the ground. These methods include artificial recharge, sea-water intrusion barriers, ground-water dams and weather modification.

Artificial recharging aims to increase the sustainable yield from aquifers by directing surface water into pits, trenches, boreholes and infiltration basins or storages. Surface water possibilities can be naturally-occurring sources (streams, springs or lakes), storm runoff from impervious surfaces, waste-water and leaking pipelines. Examples where artificial recharge occurs are Hong Kong and Bermuda. Leaking water lines in Hong Kong are known to contribute from 260 to 3,000 mm per year in some parts of the island, compared with an average annual rainfall of about 2,000 mm. The recharge from sanitation systems in unsewered urbanized areas of Bermuda appears to be about twice that occurring under naturally vegetated areas.

The ubiquitous, graceful coconut tree can be a source of life-sustaining fluids during severe droughts.

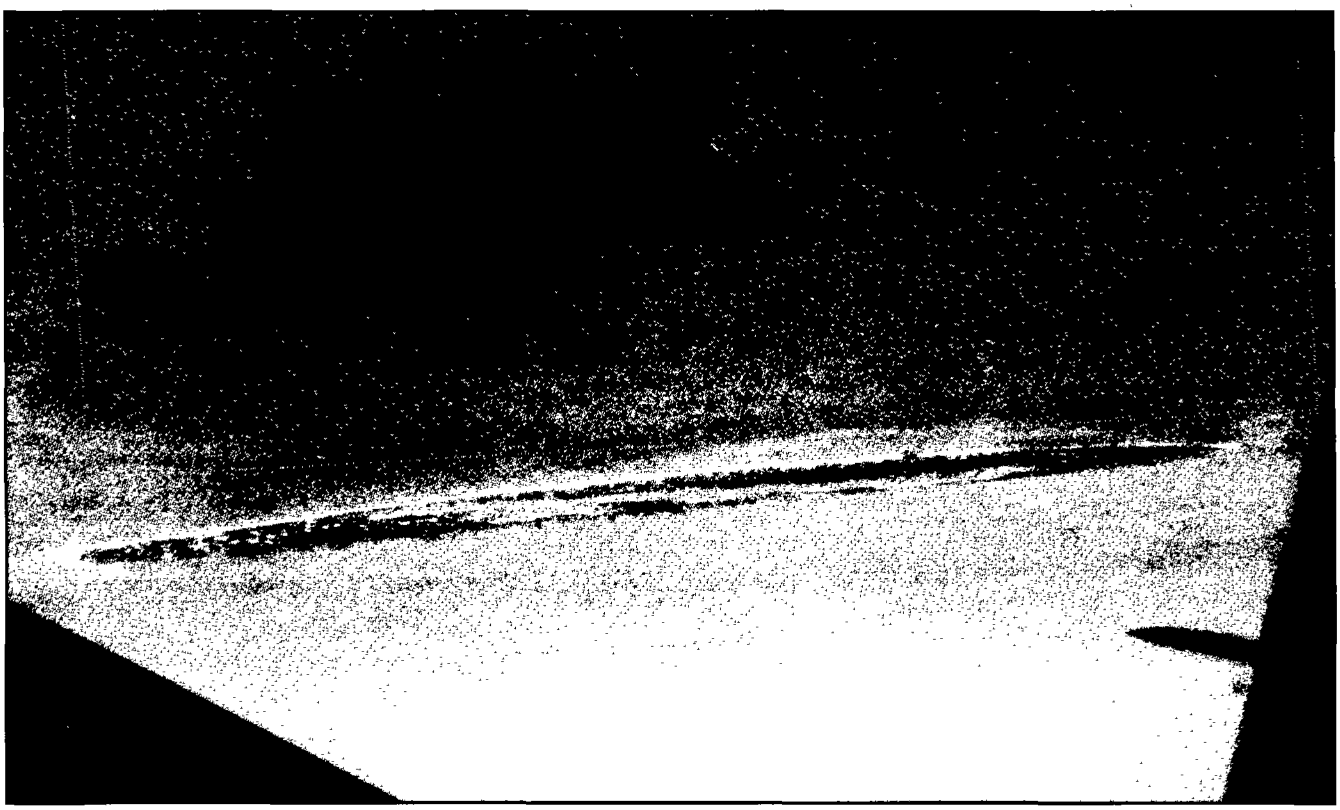
Some remote islands truly seem to exemplify the reality of Coleridge's lament: "Water, water, everywhere, but not a drop to drink."

Artificial sea-water intrusion barriers can be constructed below the surface to impede the outflow of fresh water or the inflow of sea-water into basal ground-water bodies. The effect is to increase ground-water storage, at least in the short-term, thus increasing the availability of fresh water. On Miyako-jima, an island in the Ryukyu Archipelago of Japan, an experimental subsurface barrier was constructed in 1978 in a small buried valley. The barrier was designed to be semi-pervious so that seepage could occur and, hence, minimize the concentration of agricultural chemicals in the stored ground water. The overall goal was to increase the yield for irrigation purposes. The barrier was found to be successful at delaying sea-water intrusion into adjacent fresh water aquifers (under pumping conditions) by at least two months. This type of technology requires a large capital expenditure and the results may not be easily attainable on other islands.

Below-the-surface dams

Ground-water dams have been used to store water in both Africa and India. These dams are constructed under the surface in stream channels to impede and store ground water as it flows under the surface during the periods when the above-ground stream has dried up. The only known example of such an installation on a small island is in the Cape Verde archipelago in the Atlantic Ocean, which is not actually in the humid tropics. Such installations, however, do have potential application in humid tropical islands.

Weather modification, often known as "cloud-seeding," has been the subject of research in a number of continental countries, including Australia, Israel and the USA. It has not been applied to small islands. Until further knowledge is developed in this area, the technology is not very relevant to small tropical islands.



MAJOR ISSUES AND PROBLEMS IN WATER RESOURCE DEVELOPMENT AND MANAGEMENT

General

Although the issues and problems related to water resource development and management on islands are in many cases similar to those found elsewhere, some are unique to islands because of these mini-continents' small sizes, limited water resources and isolation.

Broad water policy issues which affect small islands are the need for a reliable and safe source of water supply for the inhabitants, the protection of water resources from pollution and contamination (both natural and human-induced) and the rational allocation of water resources—particularly in the more developed islands.

Quantity problems

In some islands all "conventional" water sources (rainwater catchments, surface water and ground water) have been fully exploited and other methods such as desalination or importation are required to meet the demand.

Temporary problems can arise as a result of several factors, including drought, which can last for many months, or seasonally large demands associated with an influx of tourists.

More permanent problems have arisen—and are emerging—on some of the smaller islands, particularly those atolls with high population densities, such as Malé in the Maldives. There the problem is so severe that consumption of water exceeds the recharge from rainfall and the fresh water lens is gradually being depleted. A number of options to increase the availability of fresh water have been implemented, including the installation of a desalination unit. However, there are many examples of failures with desalination techniques in islands. Careful selection of the water source and design of appropriate pre-treatment facilities are particularly important if desalination is viewed as a realistic option on small islands.

In some cases, existing sources, particularly fresh ground water on coral atolls, are overpumped to the extent that wells in infiltration galleries are drained after a small number of hours. This problem can be overcome by lengthening the galleries, reducing the pump rates or both. Another problem is the depletion of perched aquifers during periods of drought. Supplies from these sources are thus often unreliable in the long-term. Springs emanating from perched aquifers also tend to suffer from the same seasonal problem.

Major intrusions of salt-water, caused by the construction of waterways and boat marinas, have caused the loss of fresh water lens areas on some islands.

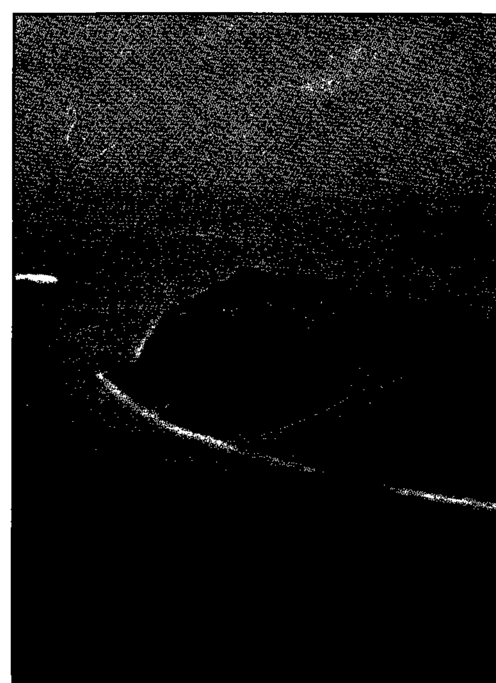
Rainwater systems often suffer from insufficient tank volumes or roof areas. Leaking tanks due to poor design and/or construction also cause problems in some systems.

Quality problems

Sea-water intrusion due to overpumping from fresh water lenses is a serious problem for the water quality of small islands. Increased demands of the residents, tourists, industries, and sometimes farms, impose great pressure on the available ground-water resources. It is easy for over-abstraction to result if administrative control mechanisms are not in place. Sea-water intrusion is generally caused by localized overpumping from wells, boreholes and infiltration galler-

The potential mobility of pollutants from a rubbish dump clearly shows in the photograph at the right.

Very small islands, such as the one below—being about one kilometre wide and two kilometres long—obviously have a finite water resource. Development proposals must bear this in mind. Otherwise, severe water shortages will be experienced or more expensive options such as desalination and importation will be required.



"Most developing island countries have a modest or small territorial extent and a major water problem."
ROBERT DIJON,
Some Aspects of Water Resources Planning and Management in Smaller Islands, Natural Resources Forum, 1983.

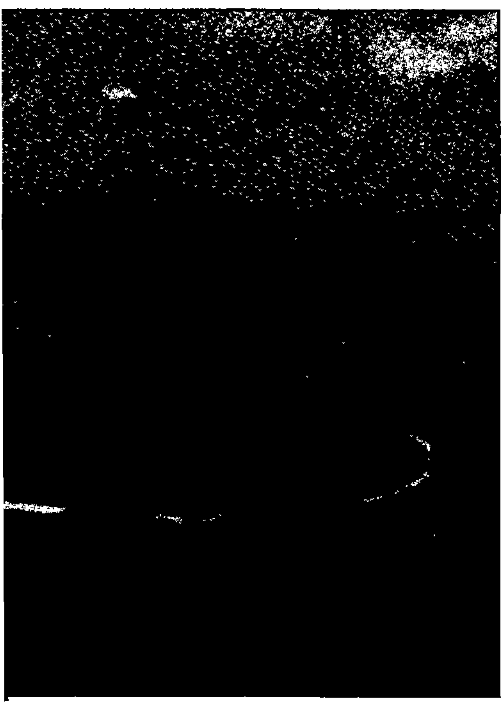
ies. In other cases, the problem is far more widespread and severe and is caused by over-abstraction from many different systems.

Island water quality at risk from many sources

Chemical, biological and microbiological pollution is associated with urban development and with some rural communities, especially on heavily populated islands. Pollution from sewage disposal systems, including pit latrines, septic tanks, pumping stations and treatment plants, located too close to ground-water sources is of particular concern. Pollution from animals such as pigs and dogs is also a problem on many islands.

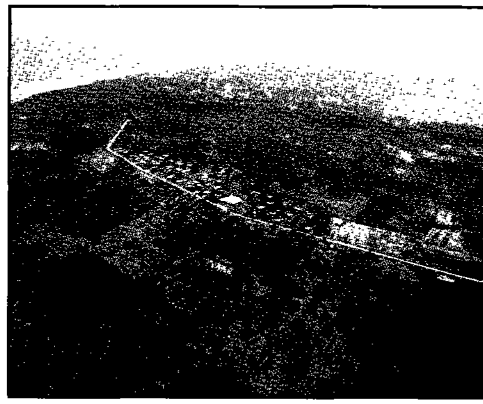
The ground-water resources of coral atolls and low-lying limestone islands are particularly susceptible to pollution, owing to their relatively thin and highly permeable soil. As a result, the normally accepted minimum distances from sewage disposal facilities (such as pit latrines) to ground-water abstraction points are often inadequate to prevent contamination. To overcome this problem, each situation

Land-based rubbish dumps (above) pose a threat to the ground-water's quality on small islands where the depth to the water table is small and the sediments are highly permeable.



should be assessed on its own merits, giving due regard to the way the ground water is flowing. On very small islands, this will generally mean that sewage disposal facilities should be sited close to the beach and water should be abstracted from the middle of the island.

Pollution from solid waste disposal areas and leakage of fuels from pipelines and storage tanks pose a major problem to fresh water lenses and other ground-water resources on many islands. Seepage from disposal areas located directly over, or in some cases cut into, fresh water lens areas—such as old quarries excavated down to the



water table—can pose a specialized threat. On low-lying islands, large quantities of fuel are often stored near airport runways which may be favourable locations for the development of ground water. Oil and fuel leaks have occurred over fresh water lens areas of some small islands, including the Bahamas.

Chemical pollution can result from the use of fertilizers, pesticides and herbicides. Traces of potentially hazardous organic pesticides have been found in water supply wells on Oahu and Maui in the Hawaiian Islands. There is a potential problem with the direct spraying of insecticides onto taro, commonly grown in pits dug down to the upper surface of fresh water lenses on many coral atolls in the Pacific Ocean. This situation is particularly dangerous as no natural filter in the form of an unsaturated soil zone is present in such cases to at least partially absorb or immobilize these chemicals.

Reservoir siltation cuts capacity

Tropical islands are often exposed to frequent torrential rains. When such rain is combined with steep topography, short river channels and easily erodible soils, deforestation and siltation of reservoirs can result. Consequently, there can be a reduction in reservoir capacity. The high turbidity also may cause the water to become non-potable or, where treatment plants are used, the performance of the plant may be severely impaired. In some islands, silt may have to be removed from reservoirs at the end of every wet season.

The quality of surface waters is often adversely affected by petroleum products, general urban litter and toxic chemical spills. Concern has been expressed about the presence on some islands of timber treatment industries which use copper-chromium arsenates for preservation purposes.

Rainwater system problems

Rainwater systems often suffer from water quality problems due

Large quarries (above), when excavated for construction materials, including seawalls (left), present a pollution threat to the ground water. The quarries are dug down to the water table, leaving no "buffer zone" between potential pollutants and the ground water. Suggestions of using quarries for rubbish dumps are very dangerous and should be resisted unless special containment measures are implemented.

Intensive agricultural activities are now being undertaken on many small islands—with a steadily increasing rate of application of agricultural chemicals: fertilizers, herbicides, insecticides and others. Extreme caution in the levels of use of these chemicals is necessary to ensure the long-term viability of the fragile water resources.

Direct damage to property and landslides (above) causing loss of valuable land and soil erosion problems are experienced on small high islands from the torrential rains associated with cyclones. Extensive clearing of vegetation for raising of crops on steep slopes can accentuate the problem.

to inferior roofing materials (coconut leaf thatch, for example, can lead to taste and odour problems) or inadequate filtration (leading to bacteriological contamination). It is necessary that adequate roofing materials be used and, where seasonal patterns prevail, that simple systems be used to divert the "first foul flush" away from the storage tank(s). Rainwater bailed from rainwater tanks (or cisterns) with buckets and other containers also can easily become contaminated.

Water supply distribution system problems

In some cases, the ground-water or surface water sources may be unpolluted, yet the water supplied to consumers may be unsafe. Contamination can occur in distribution systems by water passing through faulty joints or defective pipes at times when the pipeline is not pressurized. Other sources of water contamination can be cross connections between potable and non-potable water distribution systems, contaminated tools and fittings used during operational and maintenance activities and the deterioration of pipes and fittings.

Many problems are evident with the distribution of water. Where water is collected by hand in buckets and other containers due to the lack of piped or delivered water, the water sources are sometimes a long way from village areas. The time-consuming effort of obtaining water adds to the potential problem of contamination from the open containers used to transport the water.

Piped water supply systems often suffer from major leaks due to cracks, holes, poor joints and other defects. Shortages of proper materials and improvisation may increase leakage rates. Examples include the heating of PVC pipes over open fires to form bends and the laying of PVC pipes without the use of recommended jointing materials (solvent cement or rubber rings). Many water supply systems in small islands are old and in need of major rehabilitation. Losses as high as 80% of the supply have been measured in some island water systems.

Where water deliveries are utilized, the road tankers are often poorly maintained. Consequently, they suffer from breakdowns, resulting in disruptions to supply.

Mining on small, high islands, if uncontrolled, can cause extensive erosion. However, if the depth to the water table is considerable, the effect on the ground water may not be detrimental, provided care is taken with the potential sources of pollution. At the right is a phosphate mine located on a small limestone island.

These problems can be resolved by efforts to install appropriate distribution systems where required and to repair and rehabilitate existing systems where leaks are excessive.

By necessity, many water supply authorities on small islands operate at the "crisis management" level. Often only urgent repair jobs are done. There is generally a lack of preventative maintenance, resulting in equipment breakdowns. Relatively large distances to water supply facilities such as pumping stations, coupled with often poorly maintained tracks and vehicles, increase the problem.

Allocation problems

A major problem, particularly on the more developed islands, is the conflict between alternative uses for the available water. Decisions are often required to allocate water to various users in the domestic, industrial, tourist, agricultural and energy sectors. This problem needs to be resolved, based on the local economic, social and political factors. The only generalization that can be made is the need to satisfy as a first priority the most basic requirement, the domestic water supply.

Inadequate water legislation

Legislation dealing with water resources and supply systems on small islands varies from almost non-existent to very complex. Where legislation does exist, it is often outdated, redundant, ambiguous and hard to enforce. Many problems have arisen due to non-recognition of the problem of having inadequate or no legislation and difficulties in enacting new legislation or enforcing the existing regulations. Specific problem areas are: inadequate control of the quantities abstracted from wells or boreholes, poor protection of ground-water quality, lack of procedures for the rational allocation of water and inadequate control of the misuse or wastage of water supplied to consumers.

Even when legislation has been introduced, it is often difficult to enforce, mainly due to reluctance on the part of enforcement agents to enforce legislation in the small community to which they belong.

Problems of water administration

On many small islands, the water resources are administered either by a governmental department concerned with much broader responsibilities or by a number of departments. Inevitably, there is intense competition for the very scarce funds and manpower. (This phenomenon, however, is not unique to small island communities.) Such a fragmentation of responsibility among a number of organizations also can lead to long delays in reaching decisions which may not necessarily be based on sound technical or economic grounds.

There also is often insufficient expertise to properly administer the many-faceted functions of a water supply utility, regardless of how small it may be. This problem is due to insufficient training, inadequate resources—particularly funds for operation and maintenance tasks—and inappropriate technology.

Often there is little or no co-ordination between a multiplicity of agencies including water and health authorities, non-government organizations, bilateral and international aid agencies and United Nations organizations.

Difficulties of transport and communications due to large distances from supply and information sources are common. This often

Major leaks in pipelines due to inadequate maintenance can mean that much of the water available at the source never reaches its destination.

Small tropical islands are susceptible to a wide variety of natural disasters, including wind damage, floods, droughts, volcanic activity and tidal waves.

results in long delays in obtaining necessary supplies. Large distances between islands of an archipelago add to this problem.

Reliance, in many cases, on short-term expatriate advisory and management staff often leads to lack of continuity in projects, with a consequent wastage of resources and inefficiency.

There is often incompatibility of materials and equipment supplied from different sources. This is especially true for the many islands in developing countries where project assistance is obtained from different aid donors. The problem is made worse if aid donors have conditions requiring the purchase of materials and equipment from the donor country.

The largely unskilled work-forces on many small islands can result in water development and water supply projects not being operated and maintained correctly.

High incidence of and major effects from natural disasters

Many small islands located in the humid tropics are susceptible to damage from the destructive forces of storms and cyclones. Water resources can be contaminated and water supply system components damaged or destroyed during such events. In extreme cases, storm-generated waves have washed over some low islands and caused saline water to contaminate fresh water lenses. In other cases, landslides and floods have been known to damage or destroy the surface water collection systems. Other destructive natural phenomena that can affect small islands are tsunamis (tidal waves) and severe volcanic activity, including earthquakes and eruptions.

HOW MIGHT SMALL ISLANDS BE AFFECTED BY THE SUGGESTED GLOBAL CLIMATE CHANGES?

Climatic change caused either by natural phenomena, or by human activities such as the "Greenhouse Effect," can dramatically influence the water supply situation on small islands. Some predicted consequences of this widely discussed phenomenon are changing rainfall patterns in some areas and a general increase in sea-level. The average rainfall on some islands also is predicted to decrease while on others it may increase. A rise in the level of the sea, however, may have a greater impact than a change in rainfall.

Earlier predictions that the sea-level by the year 2030 could rise about 0.2 to 1.4 metres have now been revised to rises of 0.2 to 0.5 metres. Potential sea-level rises of these magnitudes are still of concern to many small island nations, particularly the very low-lying coral atolls and cays (small islets of coral or sand). As a measure of this concern, there have been a number of workshops and conferences held on this topic in recent years, particularly by groups of small island nations.

Amount of sea-level rise uncertain

It is apparent that there is some doubt as to the magnitude of the sea-level changes. There also is some question as to what the exact effect of such changes would be on small island nations. In a recent review of available data, Klaus Wyrtki, from the University of Hawaii, showed that if present trends continue, the mean sea-level of the oceans should not rise by more than 50 to 100 mm in the next 50 years. This is a much lower estimate than what has been previously presented in much of the scientific literature. Wyrtki concluded that the problems caused by an exponentially-rising population will be much more severe than those produced by a sea-level rise, the "Greenhouse Effect" or any foreseeable climatic change.

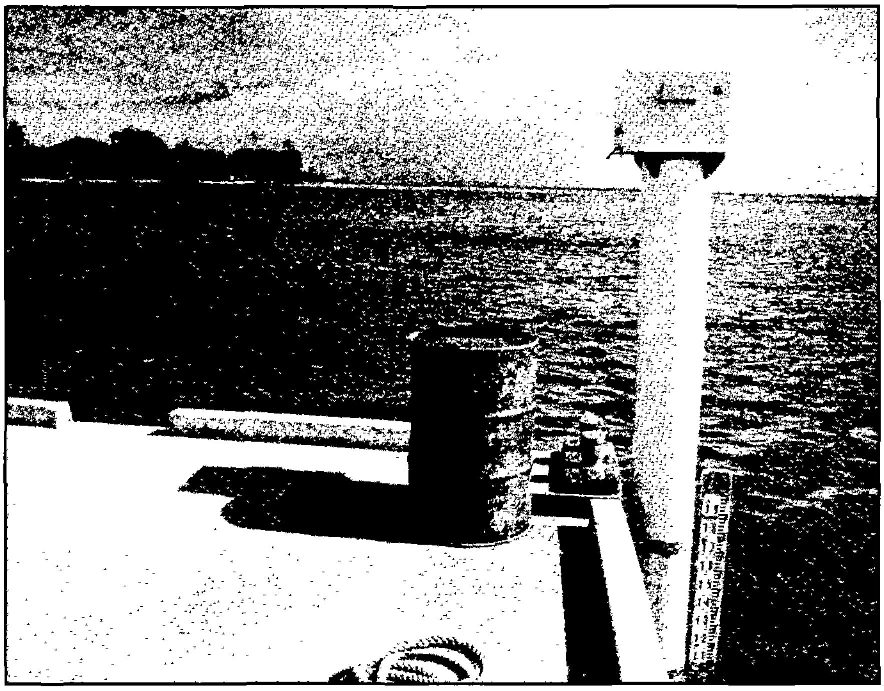
Studies of large colonies of corals found in intertidal environments on coral atolls provide a natural means of tracking sea-level changes. Called "micro-atolls," the upward growth of these corals—normally found on reef flats—are constrained by the sea-level and through prolonged exposure at the lowest spring tides. Two researchers, Woodroffe and McLean, have dated the growth of these micro-atolls on a number of islands by using radiometric methods. They have found that there has not been any substantial net rise in sea-level over the last few decades.

Some potential "Greenhouse" scenarios for fresh water lenses on small islands have been analyzed using complex computer models. Investigators from the Lawrence Livermore Laboratory in the USA have postulated the effects of some "Greenhouse" scenarios on an Enewetak atoll island in the Marshalls. They found that if the rise of sea-level does not result in sea-water encroachment onto the land, the fresh water lens volume can actually increase. The whole lens would not only rise at the surface to the same degree but the base would tend to move into a less permeable zone of sediments, thus slowing the fresh water outflow rate. The major issue, therefore, is whether the water level rise will lead to a significant loss of available land. This would be dependent on the magnitude of the sea-level rise, which is an unanswered question at this stage.

Because of the uncertainty of sea-level predictions, it is imperative that present sea-level monitoring programs for small islands be encouraged and expanded. Some funding of this activity has

"Although the entire world would be adversely affected by these processes, low-lying, small, coastal and island states will face a decidedly greater predicament. Sea-level rise would cause extensive damage to the land and infrastructure of those countries and even threaten the very survival of some island states. The possibility also exists of an increase in the frequency and/or intensity of natural disasters related to climate change, global warming and sea-level rise."

Malé Declaration on Global Warming and Sea Level Rise, Small States Conference on Sea Level Rise, Malé, Republic of Maldives, November 1989.

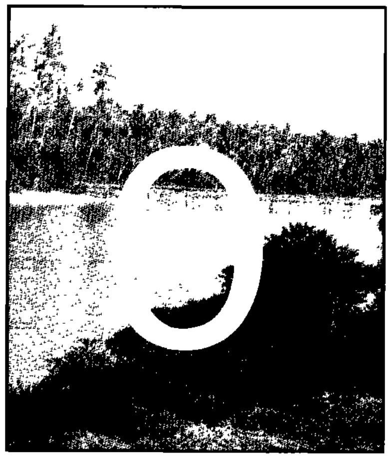


Installation of tidal recorders on selected islands is essential for the study of long-term trends in sea-levels.

occurred in recent times, which will assist in monitoring the long-term trends. A combination of standard recorders and the biological micro-atoll "recorders" referred to earlier may be a sensible compromise.

With ocean waves beating close by on one side and a lagoon just on the other side, a modest rise in sea-level could severely damage many low-lying islands such as this one.

DEVELOPING AND MANAGING ISLAND WATER RESOURCES



Planning

Assessment of water resources and their sustainable yields is a most important step in the planning of water resource development. This is generally the most technically complex step in the planning phase and must precede any substantial development. Initially, the available "conventional" resources, which include rainwater, surface water and ground water, need to be assessed. Analysis of other options, including desalination and importation, may be required where the former are limited and where the economy can afford these generally more expensive choices.

Water demand, including the current use patterns and the projected increases in demand from population growth or increasing requirements, should be evaluated. If there are urban areas on a small island that are increasing rapidly, they may demand special attention. It must be recognized that economically supplying water to meet all demands may not be possible. The demands must then be satisfied on a priority basis. Minimum requirements must first be met in the case of domestic water supplies. A minimum amount of 50 litres per capita per day is considered appropriate in most cases, although more water is required if water-borne sewerage systems are used.

Choice of water source depends on many factors

Selection of a water source is important. Where a choice between alternative sources of fresh water resources is available, it should be made after assessing the engineering, economic, social, environmental, legal and administrative factors. As part of the selection process, the conjunctive use of different classes of water should be considered since there is often more than one source of fresh water on small islands. Rainwater catchments and shallow ground-water sources, either fresh or brackish, often are available options even on the smallest of islands. Rainwater may be used in minimum quantities for the most basic of needs, such as drinking and cooking, leaving the higher salinity water for bathing and washing. Where existing or potential water supplies are scarce, the use of dual or multi-quality supplies should be strongly considered (for example, the use of sea-water for toilet flushing).

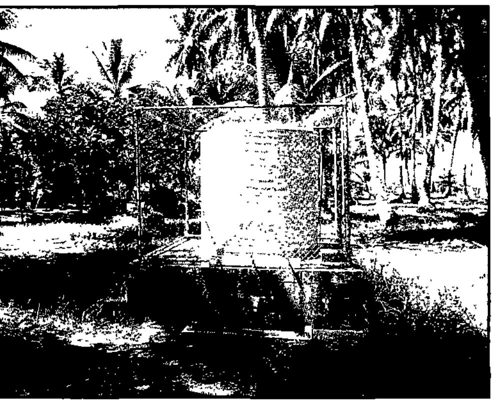
Quality criteria should fit local conditions

Appropriate water quality criteria should be set. Existing guidelines need to be adapted to suit local conditions. In particular, given the heavy dependence on water supplied from fresh water lenses by small island communities, the criteria related to salinity need to be carefully assessed in the knowledge that island populations are often used to higher salinities in water than are specified in many guidelines.

Co-ordination with other sectors is important. Where there is a potential for alternative water uses, the development of water resources must be viewed in the wider context of island development. Where there is a potential for hydro-power generation, relevant development proposals can influence both the water and energy sectors. Irrigation proposals can have a strong impact on an island's economic development and land management practices, in addition to influencing the water supply.

Solar-powered pumps are ideal for remote islands where water demands are low and electricity is unavailable, unreliable and/or expensive. Where only one or a small number of solar pumps are installed, backup diesel-driven pumps are advisable to cover solar pump down-time.

Steel-sided water tanks (such as at left) must be protected from rusting in the highly corrosive marine atmosphere of small islands. A better solution for small tanks in many circumstances is fibreglass (immediately below). For large tanks, reinforced concrete (bottom left) generally is the most appropriate material.



Water resource development also may produce potential conflicts with other land uses. In particular, it is necessary that water supply and sanitation be seen as complementary developments. The public health of a community is strongly influenced by the level of both the water supply and the sanitation facilities. This aspect is particularly important on small islands where limited land area means that there is a real threat of pollution of water from sewerage systems and solid waste disposal sites. Human habitations are often located close to water sources. The creation and retention of water reserves separate from village areas should be considered to minimize such a pollution threat.

Appropriateness to community important

Evaluation of potential water resource development options should include an assessment of the technological level required. This level must be appropriate to the community it is intended to serve, particularly "rural" communities on small islands. The ability of the community to participate in implementing the water development projects and to accept responsibility for their ongoing operation and maintenance are vital factors. Such community participation at all stages of the planning process is an important but often forgotten component. General principles for the selection of appropriate technology—based on a World Health Organization list—are: minimal cost, participation by the village communities, where possible, in the selection process, capability for operation and maintenance by the local community, utilization of locally available materials wherever possible, use of local labour and compatibility with local customs.

When designing water resource development projects for islands, particularly small ones, certain basic criteria should be adopted. Simple, proven designs which have been used in similar conditions should be adopted. Technical criteria from other regions can only be used as guides and should be adapted to local conditions.

Locally available materials should be used whenever possible to minimize the cost of imported components and spare parts. Standardization of materials and equipment also is desirable to minimize the level of knowledge or experience and the variety of spare parts required for operation and maintenance. To avoid the problem of different supplies from different aid donors, it is necessary to specify requirements, which may include preferred and well-tested equipment, as a prior condition to receiving aid funding.

Corrosion-resistant materials also should be used due to the proximity to the sea and airborne salt spray.

Village-Level Operation and Maintenance (VLOM) needed

For rural water supply projects, operation and maintenance requirements must be minimized to enable Village-Level Operation and Maintenance. Renewable energy sources should be examined for their suitability. Such sources include solar and wind energy which can reduce the operational costs of pumping systems. Designs should minimize the use of expensive imported energy sources where possible.

Management

Water resource management is a difficult term to neatly define. It can be viewed in broad terms as the rational allocation, use, control and protection of water resources. Water resource management is a particularly important issue on islands, especially small islands, as the water resources are very scarce, easily polluted and the demands on them are often high.

In the case of those independent island nations which consist of one or more islands, the overall management of their water resources should be conducted at the highest government level. Utilization of that water affects the livelihood of the whole community and involves interaction among a number of governmental agencies. The institutional framework which is in place must ensure that the assessment, development and management of the resource takes place in the context of national planning. It must also ensure co-ordination between the agencies responsible for water resources.

There needs to be a co-ordinating agency within the government for providing advice to the executive arm of government on matters of policy and planning. For small island nations, this should normally be a "water resources committee" of representatives from the departments with interests and responsibilities in water. For small islands which are part of large nations, such policy and planning is often done by off-island government agencies in co-operation with island administrations or councils.

Broad membership needed on water resource committee

Representatives from planning, natural resources, energy, agriculture, health, public works departments and from a water supply authority typically would be on a water resource committee. At this level, matters of mutual importance such as national water policy, allocation of water resources between various sectors (for example, between water supply and agriculture) and legislative aspects, need to be discussed and recommendations made. A planning department would normally take the lead role in such a committee.

There also needs to be an agency for water resource assessment, monitoring, licensing and control. It is preferable that this function be undertaken by a department or ministry which is not a user agency. This ensures that there will be no conflict of interest in allocating the available water resources. If a single user agency such as a water supply authority is charged with this responsibility, it may favour the use of water resources in its own sector. It may also lack incentive to make the most efficient use of water.

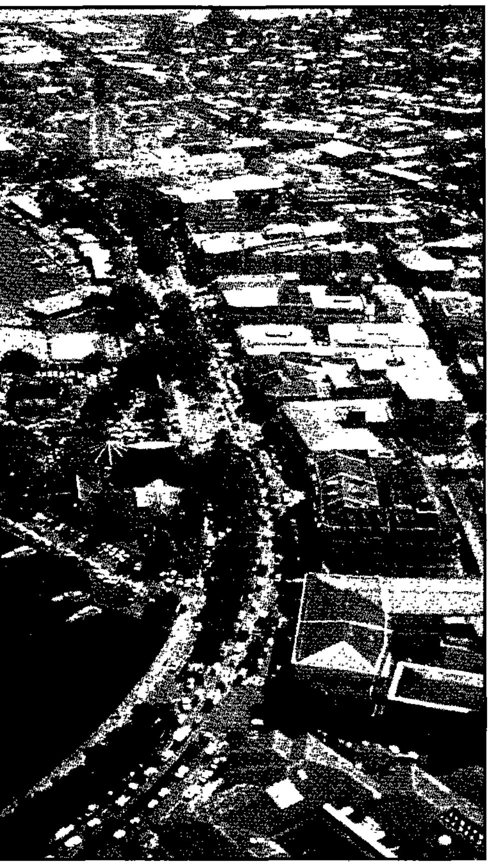
Control of island water resources at the village level is best exercised by elected or appointed persons. At the village level, the management of water issues can generally be done most effectively by a group of elected or appointed people, such as a village council. Support for this group should be available from governmental agencies when needed. Larger villages and towns normally have a water utility consisting of technical and professional staff to manage their water supplies and water-related issues.

At the household level, water management often means maintenance by individuals of their private wells, rainwater tanks and associated catchment areas and the allocation of water from different sources to various required uses.

Many island countries do not have a policy on development, conservation and protection of their water resources. This leads to an often disjointed approach to water resources. Hence, there is a need for island countries to develop national water policy plans which should outline the resources available and the policy for their development.

Water resource management issues on small islands, especially on very small islands, tend to be dominated by the requirements for

Development of facilities for tourists can improve a small island's economic situation but attention must be given to the sustainability of the water resource.



water supply for use by the island's inhabitants. Demands from the industrial, tourist, agricultural and energy sectors are generally low or non-existent on very small islands. But as the island size increases and other determining factors for natural water occurrence improve, so does the demand from these other sectors—thus raising the potential for competition for the limited amount of water.

Legislation developed for other islands may be a guide

National water legislation is an essential step in ensuring the effective management of water resources. A reasonable approach for the drafting of water legislation for islands is to review legislation from other islands, with due consideration to local customs and conditions. It is essential that customary law be taken into account, especially in islands with long-standing traditions; otherwise, the legislation may not be accepted. Public participation may be necessary in the legislative process. For independent small island nations, external assistance may be required, generally through international or bilateral aid agreements. The United Nations Department of Technical Cooperation for Development (UNDTCD) and the Food and Agriculture Organization (FAO) have assisted a number of island countries in the Caribbean and the Pacific with a review of current legislation and the preparation of new regulations.

Although legislation should be comprehensive, it should be framed in the simplest way possible. A good approach is for the main body of legislation not to be too detailed but to provide a general framework of powers, responsibilities and restraints. Detailed rules and regulations subsequently can be drafted as subsidiary legislation. This approach enables modifications and amendments to be made without tedious and time-consuming parliamentary processes.

Catchment protection and management vital

Appropriate protection and management policies for water catchments are essential for a safe water supply. It may be appropriate, especially on islands with diverse hydrological characteristics or relatively large areas, to subdivide the island into water management "protection" zones. This mechanism can assist in controlling extraction and minimizing pollution. Such a zone concept has been adopted on Barbados in the Caribbean and on Guam in the Pacific. Where possible, legislation should be introduced, if not already present, to allow for such zoning and, in particular, for the establishment of "water reserve areas." Such set-asides should disallow the land uses which have the potential for polluting water—including residential, commercial and industrial developments. This measure may be only partially achievable on those islands where the population is already dispersed.

On coral atolls and other low-lying islands where the soils and geological formations are highly permeable, all development other than the necessary water supply extraction and distribution components should be sited away from the known or potential fresh water lenses. In some situations, it may be possible to reserve individual islands within an atoll for water supply purposes. Another, and often more appropriate solution, is to site all residential and other development on the edge of the island—as far as practicable from the centre of the fresh water lens.

Thin soils may be no barrier to pollution

Some small islands are so populated that there is insufficient area remaining for such "reserves" to be established. In these cases, the population may be living on top of its water supply with the thin permeable zone between the surface and the water table providing no barrier against pollution. This is the case in highly populated, very small islands such as Malé, in the Republic of Maldives. In these locations, the other measures listed below may be necessary.

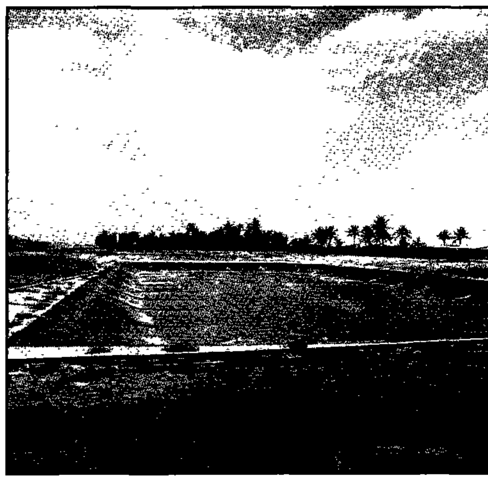
Introducing sanitation and solid waste disposal schemes which "export" waste material from water resource areas can improve the quality of the ground water. Piped sewage systems, although expensive, are effective in removing sewage. Solid waste disposal areas should generally be sited close to the edge of islands or areas where there is limited potential to develop fresh water.

Sewage discharge points are best located at the edge of islands. While expensive, water-borne sewerage systems have the advantage of removing much of the potential contaminants from the island's freshwater lens areas. However, studies should be made of the effects of the sewage on the marine ecology.

Another positive action is the introduction of measures to properly control the ownership and location of animals. Restrictions on the number and types of domestic animals may be necessary. Reserved areas for the rearing of some animals, such as pigs and poultry, can minimize the pollution of the underlying ground water.

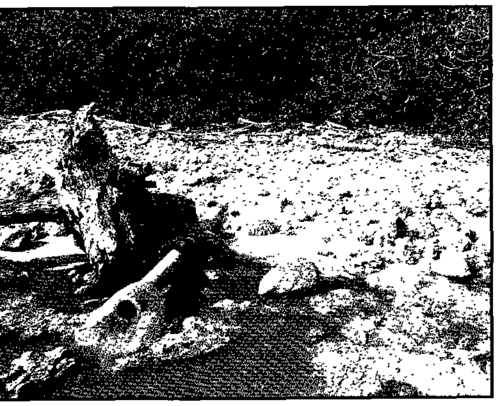
Introducing measures to ensure proper storage and use of potentially harmful materials and substances may also be necessary. This is important for fuel depots, mechanical workshops, hospitals, laboratories and chemical stores. Suitable measures would be to site these as far from water resource areas as possible, to minimize their storage requirements and to exercise extreme care in the disposal of toxic substances.

Acceptance of the fact that the ground water is polluted and using it only for non-potable purposes is another option. This implies that other sources such as rainwater catchments or desalination are required for potable purposes.



Innovative solutions for water supply have been used on some very small islands. The photographs at left and above show where a large rainwater collection surface was prepared with an impermeable membrane. The long, thin, low-lying island has limited fresh ground-water resources.

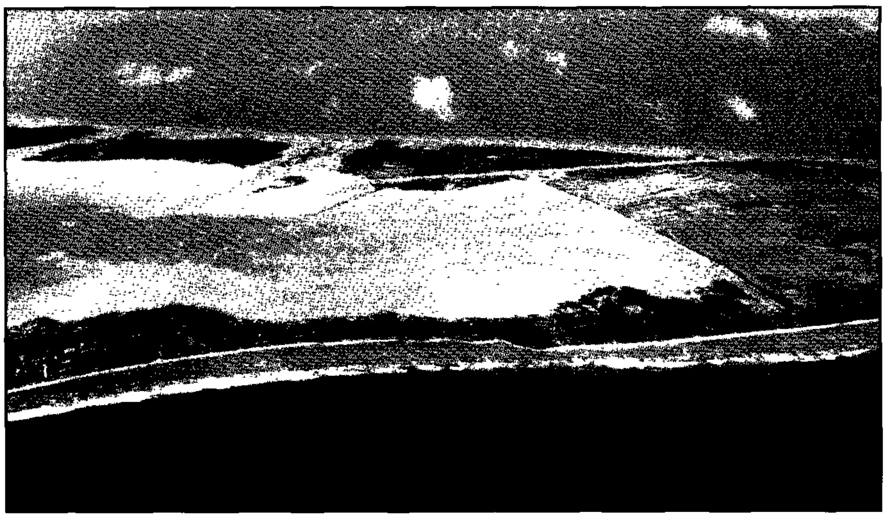
The use of non-potable water for as many uses as possible may need to be encouraged, leaving the basic needs to be satisfied by available potable sources. In this respect, dual-piped systems—one with potable and the other with non-potable water (for example, salt-water)—can limit the demand for potable water. Other conjunctive use schemes are available when piped systems are not present.



Transmigration or resettlement of people from overcrowded islands to other locations may be necessary in extremely water-short situations. Such measures have been undertaken in the past and may be necessary in the future in the event of major earthquakes, volcanic eruptions, overtoppings by waves or extreme drought. Such disasters not only affect water supplies but all the other aspects of a small island community's infrastructure.

Demand management also is important for maximizing the amount of quality water on small islands. Particularly in urban areas, demand management measures should include appropriate pricing policies and consumer education to reduce waste. Other measures may include reduction in water supply pressures to minimum levels and the use of water-conserving devices.

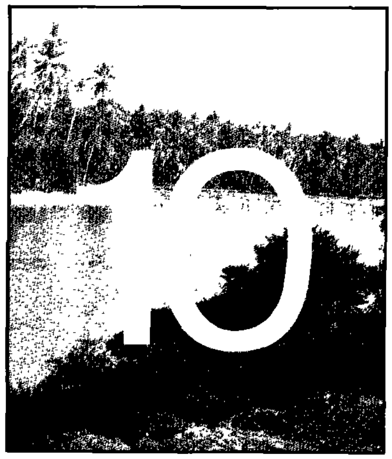
As many water supply systems have substantial leaks, an active leak detection and repair programme is essential. The savings in water can often have positive benefits in delaying the need for development of new sources.



The water reserve concept is ideal for small islands with large water demands. Water for approximately 25,000 people (about 1,200,000 litres per day) is obtained from the two islands in the centre (the dark green areas) of the photograph at the right.

Animal enclosures are essential in small islands and should be sited away from known or potential freshwater areas.

WHAT KIND OF HELP IS NEEDED AND HOW CAN IT BE PROVIDED?



The needs of small islands have probably increased in the years since the statements at the right were made. Many problems still exist and in some cases have worsened since the mid-l970s, due to increased pressures on island resources, including water supplies. Technical and financial assistance are required now more than ever before by many of the small islands.

However, it would be inaccurate to report that there has been no progress. Some positive steps have been taken and it is worth reporting on the achievements to date before moving on to see what should be done next and how it should be achieved.

What has been done?

The efforts of a number of international and bilateral aid donors are to be applauded. These efforts have ranged from a number of major regional, interregional and international seminars and workshops on the topic of small island water resources to direct assistance with water resource assessment, planning, development and management. A selected list of meetings specifically devoted to water resources of small islands held in the last decade is presented below. These meetings have involved representatives from many small islands and a range of technical consultants with expertise in one or more areas of small island hydrology and water resources.

. Seminar on Small Island Water Problems, organized by United Nations Department of Technical Cooperation for Development (UNDTCD) and the Commonwealth Science Council (CSC), Bridgetown, Barbados, October 1980.

. Meeting on Water Resources Development in the South Pacific, organized by ESCAP, Suva, Fiji, March 1983.

. Workshop on Water Resources of Small Islands, organized by the CSC, Suva, Fiji, July 1984.

. Interregional Seminar on Development and Management of Water Resources in Small Islands, organized by UNDTCD and Government of Bermuda, Hamilton, Bermuda, December 1985.

. Southeast Asia and the Pacific Regional Workshop on Hydrology and Water Balance of Small Islands, organized by Chinese National Committee for the IHP and UNESCO/ROSTSEA, Nanjing, China, March 1988.

. Interregional Seminar on Water Resources Management Techniques for Small Island Countries, organized by UNDTCD and CSC, Suva, Fiji, June 1989.

The proceedings of each of the above meetings provide a good overview of the range of problems confronting islands and some of the solutions which have been implemented. It has generally been agreed that these seminars are useful forums to discuss and hopefully resolve some of the many water sector issues confronting small island nations. Probably more importantly, they have given water technicians and professionals from small island nations the opportunity to exchange views and foster relations with agencies that have something positive to offer. For these reasons, it is essential that such meetings continue. The magnitude of their effect is not great but at least they are recognized as being beneficial.

One of UNESCO'S initiatives in this regard has been a specific project related to small island hydrology and water resources. This project has produced a major report for use by practitioners in this

"... take effective measures towards meeting the needs of the developing island countries ..."
Resolution 3338, United Nations General Assembly, 1974

"Aid donors, and in particular, international organizations, should be urged to pursue and intensify studies and technical assistance efforts to assist small islands to plan rationally in order to deal with the peculiar problems which their precarious environment and rugged topography impose upon human settlement ..."
Resolution 98 (IV) para. 61, United Nations, Conference on Trade and Development, 1976

field—at both professional and technical levels. While the report does not deal exclusively with the humid tropics, much of the information and case studies relate to that region.

The United Nations Department of Technical Cooperation for Development has been actively involved during the last two decades with assessing and developing water resources on small islands. Projects were conducted on individual islands in the early 1970s. By the end of the 1970s, a regional project was started in the Caribbean to co-ordinate activities in 11 small island countries. In 1986 a similar regional project was launched for small island countries in the Pacific region. As part of the project, considerable information (studies and reports) on small island hydrology and water resources has been assembled at the UNDTCD office in Fiji.

The Commonwealth Science Council has also been active in the area of small island hydrology. The Council sponsored a major workshop on the topic in 1984 and has funded additional studies, including the production of a training guide to field practices, entitled "Coral Island Hydrology" by Dale *et al.*

In addition to the above regional and international efforts, a number of studies and projects to assess and develop water resources on small islands have been conducted by or through national agencies such as ORSTOM (France), USAID and the US Geological Survey (USA), AIDAB (Australia) and DSIR/Ministry of Works (New Zealand) and private consultants. A number of studies have also been carried out on small islands which are part of mainland countries, using their own national organizations, particularly their universities.

What are some of the major assistance requirements?

There is a general conclusion arising from the various meetings and discussions about small island water resources that there is much to be done. There is also a general consensus that it needs to be done soon. One of the major requirements is training and education for personnel at all levels in the island's water sector. The level of training at present is marginal to non-existent in many cases. Some small island nations have very few qualified water scientists and engineers (including hydrologists and hydrogeologists) to undertake even basic studies in their own islands. In most cases, expatriate staff are seconded for periods of time to undertake these activities and to assist in training the locals. However, finding sufficiently qualified counterpart local staff to be trained in some of the more complex techniques and procedures is often difficult. Where promising qualified counterpart staff are available to be trained, they are often whisked off to other areas of government where there are managerial shortages. Worse still, some become frustrated at the local conditions and are lured away from their own countries to seek more lucrative opportunities in developed countries.

A second major requirement is for further basic research into the hydrological cycle as it affects small islands. Considerable research and many detailed studies have been undertaken in continental countries to solve their problems. In some cases, these studies can be applied to conditions found on small islands but many times they cannot. What is needed is a number of projects specific to small islands.

A third major requirement is technical co-operation. As has been mentioned, many of the small islands in the tropics (and, indeed, elsewhere) are part of the developing nations. Consequently, they are in need of assistance from the more developed countries. What practical steps can be taken?

Training

There needs to be a greater emphasis placed on courses or elements of courses which deal specifically with water resource issues on small islands — particularly those in developing countries. Existing water resource courses commonly focus on continental hydrological or hydrogeological issues, with only brief, if any, mention of small island hydrology.

Attendance at international courses for professionals is preferable to organizing local courses and seminars where difficulties are often experienced in arranging for lecturers, workshop facilities and practical examples. However, purely academic courses in developed countries often miss many of the needs of participants, since attention is focused on details, research and new developments. Such courses also use systems, equipment and methods that are rarely available on islands, not only in developing countries but also in the developed ones.

Training of technical staff is done mainly at the organizational level ("on-the-job" training) for both office and field personnel. In

The environmental impacts of tourist visits to small islands need to be carefully assessed, both for their effect on fragile ecosystems and on the usually limited supplies of water.

some cases, large organizations have permanent training departments for their own needs, but they are rare, if they exist at all, for small islands.

Practical training in workshops and field work has to be done using equipment and methods not very different from those actually available at the home islands. For developing countries, it is essential that attendees learn not only about the use of equipment, but also about its maintenance and repair. The same is true for laboratory personnel. In some instances, manufacturers of equipment (laboratory instruments, drilling machinery and complex hydrological equipment) offer special training courses but they are rarely convened in small islands. It is advisable to carry out these courses in conditions similar to where the equipment will be used and, if possible, on the island itself. Instruction in appropriate techniques in a familiar setting to participants is likely to maximize the benefit of the training. A good example of the latter form of training for water technicians from small island countries was the 'REFRESHR' workshops held in the Pacific region. Further specific information on the training needs of personnel involved in the water and sanitation sectors in Pacific islands is contained in a publication by Dale (1988).

Research

Studies of the hydrological cycle, including the surface water components on small islands, have largely been done on a case-by-case basis in order to solve immediate local problems such as the supply of water for domestic, tourist, industrial or agricultural needs. Very few studies have been undertaken to study the hydrological cycle on islands with a view to generalizing the procedures for other islands. There is a need for a co-ordinated research effort to address the major components of the hydrological cycle on some typical islands. It is recognized that generalizations are not always possible, especially in relation to small high islands, but there is at least some scope for this to be done in relation to small, low-lying islands.

Some of the more important components of the hydrological cycle are addressed in more detail below.

Interception is an important hydrological parameter which is often disregarded in hydrological studies. There is a need for experimental data to be obtained on interception losses from typical vegetation found on small islands and for these to be used in water balance studies.

Detailed research into evapotranspiration of selected vegetation/soil/sub-climate associations on small islands should be conducted. Existing approaches to the estimation of evapotranspiration should be re-evaluated in the light of such investigations. As a first stage of the investigation, a database of typical soil/vegetation/sub-climate associations, including relevant hydrological parameters, should be assembled.

The use of remote sensing applications to small island hydrology is encouraged. Developments in this rapidly expanding field should be monitored to ensure that appropriate technology and methods are introduced to the study of small island hydrology.

Further research into rainwater catchment systems is warranted. In particular, experimental data on initial and continuing losses from typical island roof materials are required.

Probably the most needed research for small islands is that leading to accurate and reliable but simple methods of calculation of the exploitable ground-water resources, and then how to develop those resources—especially under the threat of salt-water intrusion—and how to manage them. Emphasis has to be put on simple methods since hydrological and water management teams on small islands are necessarily few in number and many issues have to be solved at the island or archipelago level, with only occasional resort to external assistance. Simple calculation methods need to be accompanied by straightforward and affordable data-gathering procedures, preferably using existing networks and capabilities.

Recharge calculation is still one of the issues that needs further research, not only to understand the mechanisms, but also to find methods that yield sufficiently accurate results when using commonly available meteorological, soil and vegetation data.

It is important to develop simpler yet theoretically correct ground-water flow models for use on microcomputers rather than on larger computers. The former type of computer is becoming more common on small islands but the latter type is rarely found. Ground-water models which allow for a transition zone, rather than sharp interface models, should be used where transition zones are thick.

Abstraction of ground water in coastal areas and fresh water lens situations is a practical problem that still needs research to determine the sustainable yield without encountering sea-water contamination. There is a need for simple and appropriate computational procedures for the design of borehole and infiltration gallery systems in fresh water lenses. Existing ground-water theory should be reviewed, taking into account the special features of fresh water lenses. Existing systems on small islands also should be reviewed to determine their effectiveness and/or problems. Additional research may involve scale-model studies using sand boxes and variable density fluids and/or construction and monitoring of a prototype on a selected island.

Further research into ground-water pollution is required. Special attention has to be given to pesticide behaviour and transport, especially in terrain devoid of soil cover or with small adsorptive capacity. The behaviour and transport of biological contaminants in densely populated areas, especially in thin, highly permeable soil conditions as are found on coral islands and in the coastal areas of other islands, also need study. Guidelines for minimum distances between sanitation and water supply facilities need to be re-evaluated for island conditions with due consideration given to the ground-water flow direction, the permeability of soils and the underlying geological conditions, the rate of extraction and the type(s) of sanitation disposal.

Geophysical technology has a great potential for helping in understanding, assessing and measuring many hydrogeological situations, but existing methods can yield uncertain or erroneous results. More sophisticated methods are being introduced, but these are not a solution for small island teams which require simple methods.

Data collection networks for water resource assessment should be expanded. In particular, there is a need to increase the coverage of rainfall recording stations (particularly in the high parts of islands) and net solar radiation recording stations (due to the importance of such radiation in evaporation studies). More ground-water investigation boreholes for monitoring salinity profiles in fresh water lenses and sea-level monitoring stations also are needed. National agencies should be encouraged, not only to install such monitoring stations, but to provide sufficient resources to ensure their ongoing viability. Assistance from external aid donors should be sought where local funding is inadequate to cover this important aspect of water resource assessment on small islands.

The use of electronic data-logging equipment should be encouraged for data collection programmes. This will, in many cases, require re-equipping and training of the local staff. In addition, the acquisition of data from remote sites via satellite telemetry should be encouraged.

Further research into appropriate technology for the development of water supplies and the utilization of water resources for other needs should be encouraged. Areas which are very important are the use of alternative energy sources, particularly solar and wind energy for pumping, the reuse of water and the use of alternative water sources, such as sea-water, for some purposes.

Developments in the area of desalination should be actively followed. At present the cost of this approach is too expensive for most small island communities, other than those with a significant tourist demand for water, or where more economical water resources have been exhausted.

Technical cooperation

There is scope for greater technology transfer to islands in the fields of hydrology and water resources. Options available for technology transfer are via international agencies such as FAO, UNDTCD, UNESCO, WHO and WMO, via bilateral aid agreements and through cooperative arrangements between island countries on a regional basis. The UNDTCD water projects which have operated within a number of island groups in the Pacific and in the Caribbean are good examples of an international agency's approach to the problem.

Seminars and workshops on the topics of hydrology and water resources of islands have assisted participants from many islands in the past. These should continue on a regular basis. Specific meetings of technical experts would help to resolve ongoing practical issues such as optimal ground-water abstraction systems and pumping rates from fresh water lenses. Sponsoring of meetings and seminars by those United Nations organizations involved in water resource issues on islands in the humid tropics is particularly appropriate. Studies and reports which address the water resource issues and problems faced by islands in the humid tropics should also be encouraged. UNESCO's initiative to produce a guide on hydrology and water resources of small islands will hopefully assist in this regard. As more information and knowledge is acquired, revised and updated, publications on this topic will be required.

Greater co-ordination is required between those agencies involved with small island hydrology and water resource assessment, development and management. It is recommended that a library service be established for the collection, storage and dissemination of technical information, data and reports dealing with, or relevant to, small island hydrology. The service could be via a network of institutions on islands in the humid tropics.

Enhanced communication between personnel engaged in research and the technical administration of island water resources should be encouraged. Technical and financial assistance for the production of a newsletter or newsletters dealing with small island water resource issues should be encouraged. The example set by the CHOC (Contacts for Hydrogeology of Coral Islands) newsletter, established in 1983 at the Pacific Science Congress in Dunedin, New Zealand, could be used as a guide.

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The International Hydrological Programme

The developing nations of the humid tropics of the world will represent about one-third of the earth's population by the end of the present decade. In the Twenty First Century, these nations will pass the developed countries in numbers of people. Such a population shift will alter existing international economic and geopolitical relationships.

With this major change looming on the horizon, coupled with the need to treat the tropical resources wisely, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the United Nations Environment Programme (UNEP) joined with twenty-two other organizations in July 1989 to hold the International Colloquium on the Development of Hydrologic and Water Management Strategies in the Humid Tropics. The International Hydrological Programme of UNESCO was the lead organization.

The Colloquium developed strong evidence that the present situation, including the question of tropical forest depletion, was not only in need of serious consideration, but that the potential for vastly increased negative human impacts will be quite significant if they are not adequately considered now. It was noted that although the general characteristic of the humid regions is an overall abundance of water, this very abundance—and the variability of its distribution—is one of the leading contributors to the difficulties.

This volume on small tropical islands is one of several publications having their origin in the Colloquium. An executive summary of the Colloquium, *Water-Related Issues and Problems of the Humid Tropics and Other Warm Humid Regions,* was released shortly after the Colloquium was held at Australia's James Cook University. *The Disappearing Tropical Forests* was made available for distribution in May l991. Additional popularized volumes on selected aspects of the water-related problems in the humid tropics and other warm humid regions are being prepared. A formal scientific text embodying the Colloquium papers and supplementary material also is being prepared.

Further information on any of these publications can be obtained from the International Hydrological Programme, Water Sciences Division, UNESCO, 7, place de Fontenoy, 75700 Paris, France.

MAB programme activities in the humid tropics

Improving the scientific understanding of natural and social processes relating to man's interactions with his environment, providing information useful to decision-making on resource use, promoting the conservation of genetic diversity as an integral part of land management, enlisting and co-ordinating the efforts of scientists, policy-makers and local people in problem-solving ventures, mobilizing resources for field activities, strengthening of regional co-operative frameworks. These are some of the generic characteristics of the Man and the Biosphere Programme -- one of the sister environmental programmes of IHP within UNESCO.

MAB, launched in the early 1970s, is a nationally- based, international programme of research, training, demonstration and information diffusion. The overall aim is to contribute to providing the scientific basis and trained personnel needed to deal with problems of rational utilization and conservation of resources and resource systems, along with the problems of human settlements.

One of the international research themes of MAB is specifically concerned with the ecology and use of island ecosystems. Field projects in all regions of the world are complemented by workshops, training courses, conferences and symposia on such topics as the Sustainable Development and Environmental Management of Small Islands (UNESCO, 1990). UNESCO has also contributed to the setting-up in late 1990 of the International Scientific Council for Islands Development (INSULA), a new non-governmental organization whose aim is to promote the sustainable development of small islands. The first major conference of INSULA took place in Giardini-Naxos (Sicily, Italy) in May 1992, under the title of "Islands 2000--The World of Islands: What Development on the Eve of the Year 2000?"

"All that's beautiful
drifts away
Like the Waters."
W.B. YEATS,
The Old Men Admiring
Themselves in the Water

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