Hydrology and water management on small tropical islands

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Abstract Small islands are prevalent in the humid tropical regions of the world. Most are part of developing countries and have scarce natural land-based resources. In particular, the water resources of small islands are often very limited. Many have no surface water resources and rely on limited groundwater resources in the form of thin freshwater lenses. The exposure of islands makes them particularly vulnerable to natural disasters such as cyclones, floods and droughts. Pollution from population centres and from agricultural and other activities are an increasing problem. This paper explores some of the basic concepts of small island hydrology including the types and occurrence of water resources and the water balance. It outlines some of the water resources assessment and development techniques used in small islands. It also addresses water resource planning and management issues and suggests approaches for resolving some of the major water resources problems.

INTRODUCTION

Small tropical islands abound in the major oceans (Pacific, Indian and Atlantic) and smaller adjacent seas such as the Caribbean Sea. In the Pacific Ocean alone there are over 30 000 small islands most of which are in tropical regions. The number of populated islands is in the order of 1000. Several thousand small islands are found in the Indian Ocean. The number of islands in the Maldives alone amounts to 1300 of which about 200 are inhabited. There are several thousand small islands in the Caribbean Sea of which about 100 are inhabited. The region of Indonesia, the Philippines, Malaysia, Vietnam and southeastern China, comprises many thousands of islands. In Indonesia alone, there are over 13 500 islands nearly all of which are small islands.

Small tropical islands are found in countries comprised entirely of islands and in others consisting of continental land as well as islands. The countries of Indonesia and the Philippines are examples of island archipelagos comprising both small and large islands. Examples of countries consisting only of small islands are the Cook Islands, Kiribati, the Federated States of Micronesia, Fiji, the Marshall Islands, Tokelau, Tonga, Tuvalu and Western Samoa in the Pacific Ocean, the Maldives, Mauritius and Seychelles in the Indian Ocean and the Turks and Caicos and the Bahamas in the Caribbean Sea. Nauru and Niue in the Pacific Ocean and Barbados in the Caribbean Sea are examples of countries comprising a single small island. The Hawaiian Islands

(USA), the Galapagos Islands (Ecuador) and French Polynesia (France) in the Pacific Ocean, and the Andaman and Nicobar Islands (India) in the Indian Ocean are examples of small islands which are part of much larger countries.

Most of the small tropical islands of the world are politically part of developing countries. Singapore and Hong Kong are notable exceptions. Some island countries such as Nauru have high per capita incomes but are still regarded as developing countries.

This paper addresses a range of hydrological and water resource planning and management issues including the occurrence of water resources and the factors which influence them, the water balance, water resources assessment and development, and water resources management problems and suggested solutions.

SMALL ISLAND DEFINITION

Islands can be classified as either small or large. To distinguish between the two sizes, areas of 5000 km^2 (Commonwealth Science Council, 1984) and 2000 km^2 (UNESCO, 1991) have been selected. The UNESCO definition, adopted in this paper, also classifies any island with a maximum width of 10 km as small.

The reason for making a size distinction is that large islands tend to have features and problems similar to those of continents. Small islands have additional special problems.

Most small islands are less than 200 km^2 in area and many fit into a category of "very small islands" with are less than 100 km^2 or have a maximum width of 3 km (Dijon, 1984). Examples of very small islands are the sand cays of the Caribbean Sea and the coral atolls of the Pacific and Indian Oceans, where surface water does not exist in an exploitable form and fresh groundwater resources are very limited. On these islands, conventional options for fresh-water supplies are limited to groundwater development and rainwater collection. Other examples are very small volcanic and raised coral islands where fresh groundwater is very limited or non-existent, and geological conditions are not favourable to surface water storages. On these islands, the only conventional fresh-water option is rainwater collection which can only satisfy relatively small water requirements.

SPECIAL PROBLEMS OF SMALL ISLANDS

Small islands, especially those situated far from continents or other large islands, are unique in many ways.

Small islands have special physical, demographic and economic features. Their shortage of natural resources (land, fresh water, minerals and conventional energy sources), their isolation and the often widespread nature of their territories, their exposure to natural disasters make the hydrological and water resources problems of these islands usually very serious.

Many small islands have very high population densities which places great stress on their water resources. Population densities of over 10 000 people per km^2 occur on some small islands. An extreme example is Malé in the Republic of Maldives where the population on the 1.3 km^2 island is over 50 000. Pollution from population centres, agricultural activities and in some case mining operations are a real threat to either or both surface water and groundwater resources. Sea-water intrusion due to over-pumping from fragile groundwater resources has led to the depletion of groundwater resources on a number of small islands.

In extreme cases, available water on the island has been fully utilized or polluted to an extent where off-island sources of water are required. Such measures include desalination of sea water and importation of water from other islands or continents.

Small islands are highly vulnerable to natural disasters such as cyclones, earthquakes, volcanic eruptions and storm surges. They are also susceptible to floods and droughts. The potential for rising sea levels on small islands as a result of the much publicized "greenhouse effect" is an added problem.

A number of small island nations are dependent for development projects on aid funds from other countries or multilateral sources. The economies of some islands and island countries are boosted by tourism and in limited cases by other activities such as mining projects and military bases. The local economic resources of many islands are limited to fish, which may be abundant within their extended economic zones, basic commodities such as copra, limited cash crops such as coffee, vanilla, tropical fruits and vegetables, and perhaps some manufactured goods (e.g. handicrafts). The isolation from sources of supply, high costs of freight and often a lack of trained professional and technical staff adds to the problems experienced by small island communities.

OUTLINE OF WATER RESOURCES

The water resources on small islands can be classified as surface water, groundwater and other water resources. These are considered below together with the main influencing factors on the occurrence of surface water and groundwater resources.

Surface water

Where conditions are favourable, surface water can occur on small high islands in the form of ephemeral and perennial streams and springs, and as fresh-water lagoons, lakes and swamps.

Perennial streams and springs occur mainly in high volcanic islands where the permeability of the rock is low. Low-lying islands rarely have surface water. Many high islands, particularly where volcanic rocks underlie limestone, have perennial springs. These often occur around the base of the island either slightly above or sometimes below sea level.

Fresh-water lagoons and small lakes are not common but are found on some small islands. These can occur in the craters of extinct volcanoes or depressions in the topography, or even on small coral islands where rainfall is abundant (e.g. Washington Island (Teraina), Kiribati). Most small island lakes, lagoons and swamps, particularly those at or close to sea level, are brackish.

Groundwater

Groundwater occurs on small islands as either perched (high level) or basal (low level) aquifers.

Perched aquifers commonly occur over horizontal confining layers (aquicludes). Dyke-confined aquifers are a less common form of perched aquifer and are formed when vertical volcanic dykes trap water in the intervening compartments (e.g. some of the islands of Hawaii and French Polynesia).

Basal aquifers consist of unconfined, partially confined or confined fresh-water bodies which form at or below sea level. Except where permeabilities are very low, as on some volcanic and bedrock islands, most islands would have some form of basal aquifer in which the fresh-water body comes into contact with sea water. On many small coral and limestone islands, the basal aquifer takes the form of a fresh-water lens which underlies the whole island.

Basal aquifers tend to be more important than perched aquifers because not all islands have the latter, and where both types occur, basal aquifers normally have greater storage volume. Basal aquifers are, however, vulnerable to saline intrusion owing to the fresh-water/sea-water interaction and must be carefully managed to avoid over-exploitation with resultant sea-water intrusion.

The relative importance of surface water and groundwater on islands depends on the particular nature of the island. In general, however, groundwater tends to be the more important resource of the two.

Fresh-water lenses

Because of their importance as a source of water supply on many small islands, a more detailed description of fresh-water lenses is warranted.

The term "fresh-water lens" can be misleading as it implies a distinct fresh-water aquifer. In reality, there is no distinct boundary between fresh water and sea water but rather a transition zone (Fig. 1). The base of the fresh-water zone can be defined on the basis of an objective salinity criterion such as chloride ion concentration or electrical conductivity (e.g. 2600 μmhos cm^{-1} in the Cocos (Keeling) Islands: Falkland, 1988).

The lens may have an asymmetric shape with the deepest portion displaced towards the lagoon side of the island (Fig. 1). Typically, the fresh-water zone of a thick fresh-water lens on a small coral island is about 10-20 m thick. Depths of up to 30 m have been measured (e.g. the island of Buariki, Tarawa atoll, Kiribati: Jacobson & Taylor, 1981; Murphy, 1982). Where the fresh-water zone is less than about 5 m thick, the transition zone is often thicker than the fresh-water zone. For thicker fresh-water lenses, the transition zone is generally thinner than the fresh-water zone. For a given fresh-water lens, the fresh-water and transition zone thicknesses are not static but vary according to fluctuations in recharge and possibly abstraction.

Other water sources

Other sources of fresh water on small islands are rainwater collected from artificial or natural surfaces, desalination of sea water or brackish groundwater, importation,

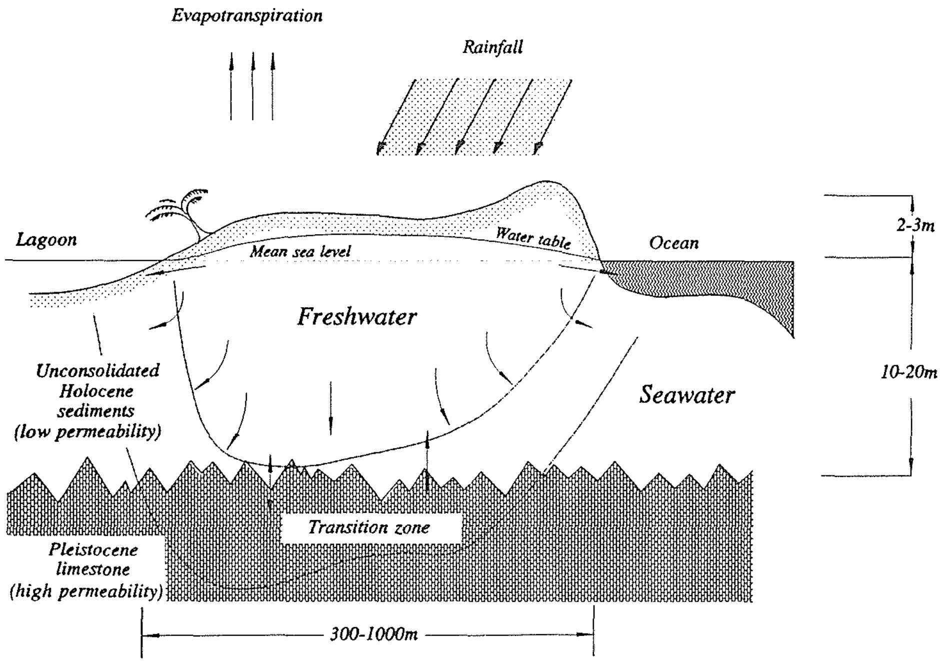

Fig. 1 Small island fresh-water lens (exaggerated vertical scale).

treated wastewater, and substitution. Apart from rainwater collection, these water sources are often referred to as "non-conventional". Rainwater, surface water and groundwater are considered to be "conventional" water sources.

Factors influencing occurrence of surface water and groundwater resources

The main influences on the occurrence of these naturally occurring fresh-water resources are:

(a) physiography,
(b) climate and hydrology,
(c) geology and hydrogeology,
(d) soils and vegetation, and
(e) human impacts, including abstraction (pumping or withdrawal of water) and pollution from a variety of sources.

For low islands and low-lying areas of high islands, sea level fluctuations due to tides, pressure changes and longer term influences are also important factors.

These influences are considered in more detail in the following sections.

PHYSIOGRAPHY

The size, shape and height of a small island, are major influences on the occurrence of both surface and groundwater resources.

Larger and wider islands are more likely to have either or both types of water resources in greater quantities than smaller and narrower islands. The width of a small island is a particularly important influence on the occurrence of basal aquifers.

Small islands are often classified according to topography as either "high" or "low". This classification attempts to distinguish those with surface water resources in the form of streams and rivers from those which have no substantial surface runoff. Volcanic islands are typically high islands and coral atolls are typically low islands. Exceptions are raised coral limestone islands as they are topographically high yet generally have no surface water.

On high volcanic islands, surface water resources will mainly be in the form of ephemeral and flashy creeks. Volcanic islands with low permeability surfaces may have small perennial streams, except during extended droughts. On most islands, surface runoff occurs rapidly after rainfall and recedes to little or no flow within hours.

On low islands, surface water if it occurs at all, is likely to be in the form of shallow and often brackish lakes.

High islands can influence precipitation patterns while low ones have little or no effect. If high islands consist of predominantly low permeability rocks, surface runoff can be an important component of the water balance. Otherwise it is likely to be a low proportion.

For low islands, the height above sea level and the width of the fringing reef together with sea level movements due to tides, pressure changes and longer term influences influence the risk of overtopping by storm surges.

CLIMATE AND HYDROLOGY

Hydrological factors, determined by the prevailing climate, together with soil and vegetation conditions affect the quantity and distribution of surface runoff and/or recharge to groundwater.

Climate

The climate of small islands within tropical regions is variable according to time and location. The tropical areas of the Pacific and Indian Oceans are normally influenced by warm, moist northeast and southeast trade winds. On the equator, the "doldrums" occur which are characterised by low pressure, strong vertical movement, instability, high solar radiation and temperatures, convection and heavy precipitation, although there are anomalous dry areas. The Inter-Tropical Convergence Zone where the northeast and southeast trade winds meet occurs near the equator.

The controlling mechanisms of tropical climate are summarized by Manton & Bonell (1993). These include, at increasing time scales, diurnal convection, easterly waves, tropical cyclones, 36-day oscillations, monsoons, quasi-biennial oscillations, El Niño Southern Oscillation (ENSO) and long term climatic change including the "greenhouse effect".

An island's climate has a very large influence on its hydrological cycle and the occurrence and variability of its water resources. This influence is mainly felt through the important hydrological parameters of precipitation and evapotranspiration.

Precipitation

In tropical regions, precipitation on small islands occurs predominantly as rain. Other forms of precipitation, particularly dew condensation and fog interception, may occur in highland areas of small high tropical islands. As these are relatively minor forms of precipitation in comparison with rainfall in tropical islands, emphasis is placed on rainfall.

The important characteristics of rainfall from a water resources viewpoint for a particular island are its spatial and temporal distribution.

Spatial variation Rainfall varies considerably between small islands and can vary within a given island. As an example of inter-island variation, the distribution of mean annual rainfall in the tropical and sub-tropical regions of the Pacific is shown in Fig. 2. Data are from rainfall recording sites close to sea level.

The spatial rainfall variation on high islands is often very significant owing to orographic effects. Under the influence of moist winds, rainfall on the windward side is considerably higher than on the leeward side as the moist air currents are forced to rise over elevated terrain. On the leeward side, dry and possibly arid conditions can prevail due to a "rain-shadow" (Föhn) effect.

On high islands in the Caribbean Sea, annual rainfall of up to 8000 mm is experienced on windward slopes decreasing to less than 1500 mm on the leeward slopes (Griesinger & Gladwell, 1993). On Kauai in the Hawaiian Islands, nearly 12 000 mm of rainfall falls annually at altitude compared with 500 mm less than

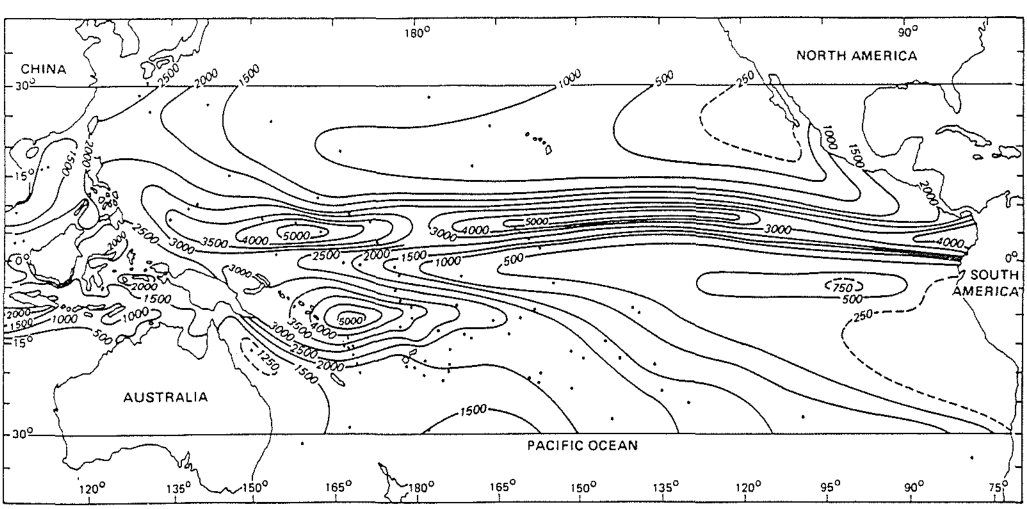

Fig. 2 Annual rainfall pattern for the Pacific Ocean (modified from Taylor, 1973).

30 km away on the leeward side of the mountains (Peterson, 1991). Similar variations are found on other small high islands (e.g. Mauritius: Rogbeer, 1984).

Rainfall gradients on small high islands are often very steep. On Kauai (area 1420 km^2 and maximum elevation 1600 m) the rainfall gradient is close to 850 mm km^{-1} (Peterson, 1991) while on Rarotonga (area 67 km^2 and maximum elevation 650 m) in the Cook Islands it reaches 1000 mm km^{-1} (Waterhouse & Petty, 1986).

On low flat islands, orographic effects are negligible and there are no significant long-term spatial rainfall variations. Minor variations, typically 10-20%, in mean annual rainfall have been observed, however, on some low islands over short distances. Examples include the limestone island of New Providence (area 208 km^2 and maximum elevation 3 m) in the Bahamas (Swann & Peach, 1992), and the South Keeling atoll (land area 12 km^2 and maximum elevation 9 m) in the Cocos (Keeling) Islands, Indian Ocean (Falkland, 1992a). Rainfall variations of these magnitudes are not considered significant given that measurement accuracy of raingauges is rarely more than 10% and that individual site conditions can account for discrepancies of a similar amount.

Temporal variation Inter-annual variability of rainfall is often high on small islands. An example is Tarawa, Kiribati where the maximum, mean and minimum annual rainfalls for the period 1948-1991 are, respectively, 3843 mm in 1987, 2029 mm and 398 mm in 1950 (Fig. 3). A more extreme example is Christmas Island, Kiribati where the maximum, mean and annual minimum rainfalls for the period 1939-1991 are, respectively, 3373 mm (1987), 903 mm and 177 mm (1954). The coefficient of variations (standard deviation/mean) of annual rainfall are 0.45 and 0.7 for Tarawa

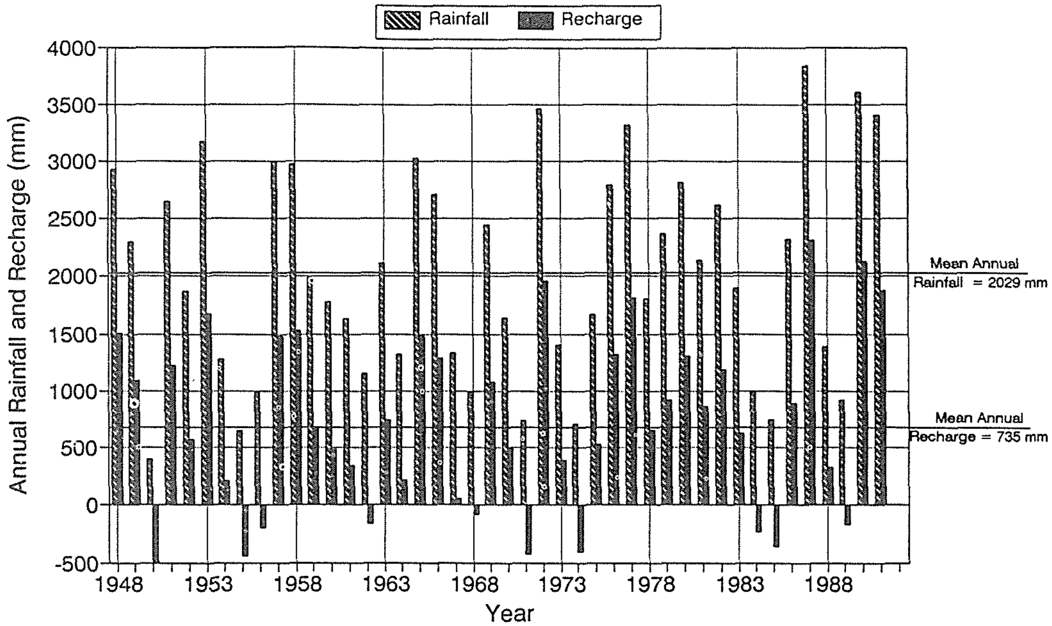

Fig. 3 Annual rainfall and recharge for Tarawa, Kiribati, 1948-1991.

and Christmas Island, respectively, which are considerably higher than on many other tropical islands (normally between about 0.2 and 0.4).

Mean monthly rainfall statistics are a useful guide to seasonal variability. For detailed water balance studies, mean values of rainfall are of little use and a time series of actual rainfall should be used.

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 before significant rainfall occurs. This was particularly evident during the major 1982-1983 ENSO event. During the first six months of 1983 the rainfalls on Saipan and Guam in the Pacific Ocean were less than 30% of the long-term mean. Similarly, in the first five months of the same year, the rainfalls on a number of islands in Micronesia were only 13% of the long-term mean (van der Brug, 1986). Conversely, the rainfall on other islands such as Christmas Island was well above average during the 1982-1983 ENSO event. For the 12 month period, August 1982-July 1983, the rainfall on Christmas Island was 4312 mm or about 4.8 times the mean annual rainfall.

On many Pacific Ocean islands there is a strong relationship between rainfall and ENSO. The Southern Oscillation Index, SOI, (relating pressure at Darwin, Australia with pressure at Tahiti) is used as a measure of ENSO activity. A high negative value is associated with the presence of strong ENSO activity and *vice versa*. Figure 4 shows the relationship between SOI and annual rainfall for Tarawa (correlation coefficient of 0.82, indicating a good correlation).

ENSO events have effects other than on precipitation. They cause sea level rise due to elevated sea surface temperatures and consequent thermal expansion of the ocean. This can add to the problems of small low islands. 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 (Falkland & Brunel, 1993).

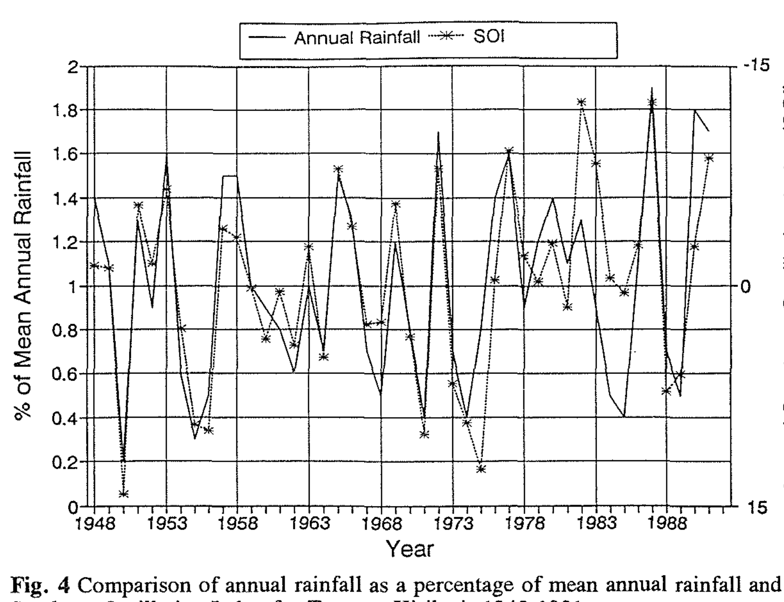

Fig. 4 Comparison of annual rainfall as a percentage of mean annual rainfall and the Southern Oscillation Index for Tarawa, Kiribati, 1948-1991.

The climates of many islands are also influenced by random cyclonic events. Cyclones are a major problem for small island communities, often causing major wind damage. On high islands they can result in floods, hillside erosion with consequent downstream damage and sedimentation. Resultant storm surges have inundated low lying areas and even whole islands, as in the case of sand islands in the Bay of Bengal. Partial inundation as a result of storms has occurred on a number of Pacific Ocean atolls in the Marshall Islands, Tuvalu and Tokelau. Fresh-water lenses suffer as they receive considerable input of sea water. Many months may be required to naturally "flush" the salt-water from fresh-water lenses and restore them to a potable condition.

Evapotranspiration

The combined processes of evaporation and transpiration, referred to as evapotranspiration. On small tropical islands, evapotranspiration is a most important part of the hydrological cycle and can account for more than half of the rainfall on an annual basis. It often exceeds the rainfall for individual months or consecutive months during dry seasons or drought periods. Despite its importance, evapotranspiration is probably the least quantified component of the water balance on small islands (Brunel, 1989).

Actual evapotranspiration (ET_a) has been estimated for some small islands using a two stage process. Firstly, potential evapotranspiration (ET_p) is estimated and secondly ET_a is calculated from ET_p using a water balance procedure.

Potential evapotranspiration ET_p is estimated using a method based on climatic data, such as the Penman (or combination) formula, or from pan evaporation data multiplied by appropriate pan coefficient(s). The Penman equation (Penman, 1948, 1956) has been found to be generally a good ET_p estimation method in the tropics (Chang, 1993). This equation has been used to estimate ET_p on a number of small tropical islands (e.g. Tarawa, Kiribati: Fleming, 1987).

Both methods were used for water resources studies of the Cocos (Keeling) Islands (Falkland, 1988, 1992a). Using data from 1982-1987, mean monthly climatic data were used to estimate ET_p by the Penman method, after comparisons with daily and monthly data indicated that there was little difference in ET_p estimates. Daily pan data and a pan coefficient of 0.8 were used to estimate ET_p by the pan method. Mean annual ET_p estimates were 2048 mm (Penman method) and 1983 mm (pan method), indicating a small difference (3%) between the two methods.

In the tropics, the net radiation energy term dominates the aerodynamic term in the Penman equation and it has been found that the simplified Priestley-Taylor method is adequate (Chang, 1993). The Priestley-Taylor method equates ET_p to 1.26 times the energy term from the Penman equation (Priestley & Taylor, 1972). This method was used by Nullet (1987) and Giambelluca *et al.* (1988) to estimate ET_p on a number of tropical Pacific islands. Nullet produced a map with isolines of annual potential evaporation, showing typical values of 1600-1800 mm in the tropical region of the Pacific Ocean.

It has been found that the Thornthwaite method (Thornthwaite, 1948) which expresses ET_p in terms of temperature and day length tends to underestimate ET_p and is less accurate than the Penman method (Chang, 1993).

Actual evapotranspiration ET_a is usually determined via a water balance procedure taking account of the prevailing soil and vegetation conditions. Details of the water balance procedure are presented later.

An alternative approach to estimating ET_a is to carry out direct measurements using one or more techniques such as weighing lysimeters, the Penman-Monteith equation (using measured values of net radiation, wind velocity and vapour pressure deficit), and the Bowen ratio technique. These have all been used in New Caledonia (Brunel, 1989). Other direct measurement methods such as the eddy correlation method could also be used.

Direct measurement of transpiration On many low islands and in the low lying areas of high islands in the humid tropics, coconut trees are prolific. They are an important part of the water balance as they are capable of transpiring large quantities of groundwater. Transpiration from coconut trees was measured directly in the Cocos (Keeling) Islands using a "heat pulse velocity meter" during a one-week study (Bartle, 1987; Falkland, 1988). The transpiration rate was measured at 70–130 $l\ day^{-1}$, equivalent to about 400–750 mm $year^{-1}$ in areas with 100% tree cover (tree spacing of about 8 m). Although the data is limited, the results have implications for water supply management, as discussed later.

GEOLOGY AND HYDROGEOLOGY

The geology and hydrogeology of small islands have a large influence on the type and distribution of their water resources. This influence is manifested mainly through the spatial distribution of permeability and porosity of rocks and sediments. Surface water resources prevail only on islands with relatively low permeability. Groundwater resources are most abundant on small islands with moderate to high permeabilities and porosities. Where the permeability or porosity are low, exploitable groundwater is generally low. Conversely, where permeabilities are very high, mixing of fresh water and sea water are enabled and fresh groundwater resources are limited.

Geology

Small islands can be classified according to geology in a number of ways. A convenient classification, outlined in UNESCO (1991) is as follows: volcanic, limestone, coral atoll, bedrock, unconsolidated and mixed.

Volcanic islands are common in tropical regions of the Pacific Ocean (e.g. Hawaiian Islands, many islands in Micronesia and French Polynesia) and in the Caribbean Sea. They also occur in the Atlantic Ocean (e.g. Ascension Island) and the Indian Ocean (e.g. Mauritius). There are at least two sub-types of the volcanic type: the andesitic sub-type which normally forms as island arcs on the continental sides of deep trenches, and the basaltic or oceanic sub-type which rises from the ocean floor in the middle of tectonic plates.

Small limestone islands are also common in the oceans and seas within the humid tropics. Examples include old carbonate islands such as Bermuda in the Atlantic Ocean, the Bahamas in the Caribbean Sea and raised coral atolls such as Nauru, Niue and many of the islands in Tonga in the Pacific Ocean. Raised atolls are uplifted coral atolls that have undergone subsequent erosion and karstification. Some limestone islands and raised coral atolls have been subsequently tilted and may also be covered in other deposits (e.g. volcanic ash layers on limestone islands in Tonga, phosphate deposits on Nauru and Christmas Island, Indian Ocean).

The coral atoll type of island is common in the Pacific Ocean (e.g. the islands of Kiribati, Tuvalu and the Marshall Islands) and in the Indian Ocean (e.g. the Maldives, some of the islands in Seychelles and the Cocos (Keeling) Islands). There are many variants of the coral atoll type of island but typically they consist of a chain of low coral islands surrounding a shallow lagoon. The stages in the evolution of an atoll are shown in Fig. 5.

Bedrock islands are those 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.

The unconsolidated type of island typically consists of sand, silt and/or mud and is generally found in the deltas of major rivers (e.g. in the Bay of Bengal).

Islands of mixed geology are common. Amongst the oceanic islands those with a mixture of volcanic and limestone rocks occur frequently (e.g. in the Federated States of Micronesia).

The geological nature of islands can change with time. Volcanic islands can subside forming fringing reefs and eventually all traces of volcanic rock sink below

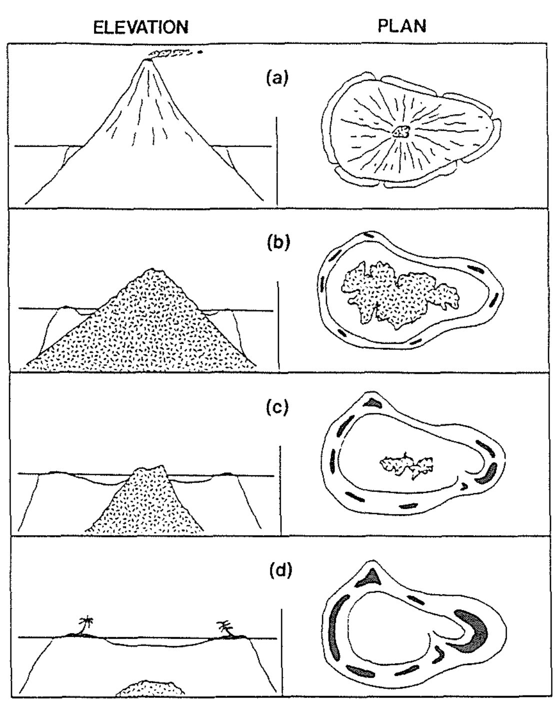

Fig. 5 Stages in the evolution of an atoll island showing (a) active volcanic island, (b) volcanic core subsiding after vulcanism ceases, (c) final stages of volcanic rock above sea level and (d) the ring-like structure of most atolls (modified from Ayers, 1984).

the surface leaving coral sands and limestone as the only rock types above sea level (Fig. 5). Young limestone islands can change markedly due to erosion and karstification.

Hydrogeology

Hydrogeological factors have a major influence on the distribution of groundwater on an island. These factors include the permeability and porosity of the rocks and sediments, and the presence and distribution of karstic features such as small cave systems and solution cavities.

Volcanic islands of the andesitic sub-type generally have low permeability and water-bearing properties (Peterson, 1984). Groundwater yields are generally low (e.g. rarely more than 1 l s^{-1} on Norfolk Island: Abell & Falkland, 1991). The basaltic sub-type of volcanic islands, where lava rather than pyroclastic rock predominates, vary in permeability and hence in exploitable groundwater. Where the lava flows are young such as found in the Hawaiian Islands, Western Samoa and French Polynesia, permeability and groundwater potential are high. In older basaltic islands with a higher degree of pyroclastic material, such as in the Federated States of Micronesia, the volcanic rock has low permeability and limited exploitable groundwater.

Limestone islands are generally karstic and weathered from alternate periods of submergence and exposure due to fluctuating sea levels. Caves and solution cavities are often found along the shoreline and within the island. The permeability of the limestone is often very high (generally greater than 1000 m day^{-1}) and, consequently, fresh-water lenses are generally no more than about 10–20 m thick, even though the islands may be quite wide. In Tongatapu, the largest island in Tonga, the fresh-water zone has been measured at 9–13 m thick (Furness & Helu, 1993) where the island is from 3-5 km wide.

Coral atolls generally consist of a layer of recent (Holocene) sediments, mainly coral sands and fragments of coral, on top of older limestone similar to that described above. An unconformity separates these two layers at typical depths below m.s.l. of 10-15 m (e.g. Enewetak atoll, Marshall Islands: Wheatcraft & Buddemeier, 1981; Kwajalein atoll, Marshall Islands: Hunt & Peterson, 1980; Tarawa and Christmas Island in Kiribati: Murphy, 1981, 1982; Cocos (Keeling) Islands: Falkland, 1988; Woodrofe *et al.*, 1991).

The presence of the uppermost unconformity and numerous other deeper unconformities is due to fluctuations in sea level causing alternate periods of emergence and submergence of the atoll. During periods of emergence, solution and erosion of the reef platform can occur while further deposition of coral limestone occurs during periods of submergence.

On South Keeling atoll in the Cocos (Keeling) Islands, uranium-series dating of the older limestone indicates that it was formed during the last inter-glacial period about 120 000 years ago (Woodroffe *et al.*, 1991). The upper sediments have been laid down in the Holocene since about 10 000 years ago. Three phases of deposition have been identified in the Holocene. From the start of the Holocene to at least 5000 years ago, sediments accumulated rapidly as sea level rose. A conglomerate platform radiocarbon dated at 3000-4000 years ago was then formed during a period of relatively stable sea level. Since then unconsolidated sands and larger sediments have been deposited to form the present reef islands. Dating of *in situ* corals has shown that the sea level was about 0.5-1.5 m higher about 3000 years ago than today (Woodroffe *et al.*, 1990).

Radiocarbon dates of the upper sediments on Tarawa have identified their age to be younger than about 8000 years of age (Marshall & Jacobson, 1985).

The upper sediments are of primary importance from a hydrogeological viewpoint as fresh-water lenses occur solely or mainly within this layer. The permeability of this layer is typically 5-10 m day^{-1} compared with a permeability in the older limestone of typically 50-100 m day^{-1}. Permeabilities greater than 1000 m day^{-1} occur in solution cavities within the limestone. Mixing of fresh water and sea water is readily facilitated in the limestone and less likely to occur in the upper sediments. The unconformity is, therefore, one of the main controlling features to the depth of fresh-water lenses.

Another hydrogeological feature of coral islands is the reef plate or beach rock around the perimeter, which may extend further inland and act as a confining layer. This can increase the available fresh-water storage (Ayers & Vacher, 1986).

SOILS AND VEGETATION

Soils

Soils play an important role in the hydrological cycle through their influence on evapotranspiration, surface runoff and groundwater recharge.

Limestone and coral islands have sandy soils of high permeability resulting in little or no surface runoff except where the surface has become compacted. Clay soils are produced by weathering on volcanic islands. These have a lower permeability than sandy soils and surface runoff is common.

Soil water retention capacity is an important determinant of evapotranspiration and recharge. Fine grained soils with high retention capacity favour evapotranspiration of infiltrated rain, thus reducing recharge. Coarse soils with low water retention capacity allow rainfall to quickly infiltrate below the root zone, thus decreasing evaporative losses and increasing recharge. During prolonged dry seasons, clay soils may develop cracks and enable similar rapid infiltration. After rain, the clay swells closing the cracks and reducing recharge.

Most islands have only a thin soil covering unless there has been some special event such as volcanic ash deposition from active volcanoes (e.g. the islands of Tonga). Thicker soils have greater water retention capacity than thinner soils.

Thick, low permeability soils can be an effective agent in preventing or minimizing groundwater pollution and, hence, in the protection of aquifers. Thin, high permeability soil layers such as the sandy soils found on coral atolls offer very little protection to underlying fresh-water lenses.

Vegetation

The native vegetation on small tropical islands consists of a variety of trees, particularly coconut trees, and a range of bushes and grasses. The coconut tree, is remarkably salt tolerant and can grow in brackish water with relatively high salinity levels. On a number of small islands, the native vegetation has been partially cleared and food crops have been planted.

The type and density of vegetation has a number of effects on the hydrological cycle and available water resources. Vegetation intercepts part of the rainfall, causes transpiration to occur, slows surface runoff and reduces erosion.

Interception and transpiration tend to decrease recharge and hence the available groundwater resources, although direct soil evaporation is decreased due to the protective vegetation cover. Depending on the depth to water table and type of vegetation, direct transpiration losses from a groundwater aquifer may be promoted. This is the case with coconut trees which are often prolific on coral atolls. These trees act as phreatophytes (i.e. draw water directly from the water table) and can lead to a reduction in groundwater resources in relatively dry periods.

Slowing surface runoff is favourable for increased infiltration of water into the ground. Reduced erosion losses are desirable for catchment management, protection of river banks and for extending the useful life of lakes and reservoirs.

Vegetation on small islands is desirable from other viewpoints. It provides food, building materials and shelter. Due to its economic, aesthetic and cultural benefits, any negative effects it may have on water resource potential tend to be outweighed.

IMPACT OF MAN

Man's activities influence both the availability of fresh water and the water quality. Humans use and often pollute water resources. Over-abstraction of water for various uses has led to the depletion of available water resources, particularly groundwater resources, on a number of small islands (e.g. Malé in the Maldives: Edworthy, 1984).

Increased development, particularly residential development, on even the smallest of islands has led to contamination of underlying or nearby aquifers and surface water. Nitrate levels in groundwater underlying unsewered urban areas on Bermuda were found to closely match population density (Thomson & Foster, 1986). Pollution from domestic animals such as pigs and dogs is also a problem on many islands.

Other islands are at risk from chemical pollution sources such as fuel storages and agricultural activities. In order to maximize food production, native vegetation is often cleared for cash crops. This is sometimes accompanied by irrigation which increases the use of available water resources and by the use of various agro-chemicals (e.g. fertilizers, herbicides and insecticides) which are potential sources of pollution to water resources. Traces of potentially hazardous organic pesticides, ethylene dibromide and dibromochloropropane have been found in water supply wells on Oahu and Maui in the Hawaiian Islands (Lau & Mink, 1987). There is a potential problem with the direct spraying of insecticides onto taro which is commonly grown in pits dug down to the water table (upper surface of fresh-water lenses) on coral atolls (Brodie *et al.*, 1984).

Detay *et al.* (1989) provide a comprehensive review of pollution problems in small islands in the Federated States of Micronesia, the Marshall Islands and Belau. Similar problems are experienced on many other small islands in the humid tropics.

WATER BALANCE OF SMALL ISLANDS

General principles

Small islands provide a unique opportunity to study the full hydrological cycle within a limited domain. The main elements of the hydrological cycle are often analysed by means of a water balance equation. The water balance equates inputs to outputs, storage terms and a possible error term to account for both errors in measurement and unknown or unquantified terms. Further details are provided in UNESCO (1991).

For a small island, the water balance is normally considered at an island wide scale, although for specific problems sub areas or basins may also be considered. Once the domain is defined, the water balance can be conveniently considered within two reference zones (Chapman, 1985). These are the island's surface consisting of vegetation, soils and the unsaturated zone (above the water table) and the groundwater system (below the water table).

At the surface of the island, rainfall is the input and evapotranspiration and recharge to groundwater are outputs. Soil moisture and interception on leaves and other surfaces are storage terms.

For the groundwater system, recharge (from the surface zone) is the input with the outputs being losses to sea water (due to outflows at the perimeter and dispersion at the base of the groundwater system) and abstraction.

Water balance at the surface

The water balance equation (or recharge model) for the surface of a small island can be expressed generally as:

$$P = \mathrm{ET_a} + SR + R \pm \mathrm{d}V \tag{1}$$

where P = precipitation (most commonly rainfall), $\mathrm{ET_a}$ = actual evapotranspiration (including interception), SR = surface runoff, R =recharge to groundwater, and $\mathrm{d}V$ = change in soil moisture store.

Interception by vegetation and other surfaces can be treated as a separate term in the water balance, but here it has been included with $\mathrm{ET_a}$ since the intercepted water is evaporated.

On low islands with permeable soils and subsurface geology (typically, coral atolls and small limestone islands) there is no surface runoff and the water balance equation reduces to:

$$R = P - \mathrm{ET_a} \pm \mathrm{d}V \tag{2}$$

Figure 6 shows a water balance model used for estimating recharge on a typical low coral island with a shallow water table.

As shown in Fig. 6, $\mathrm{ET_a}$ is comprised of three terms, namely, interception losses (E_I), evaporation and transpiration from the soil zone (E_S), and transpiration of deep rooted vegetation directly from groundwater (T_L). Normally it is assumed that rainfall

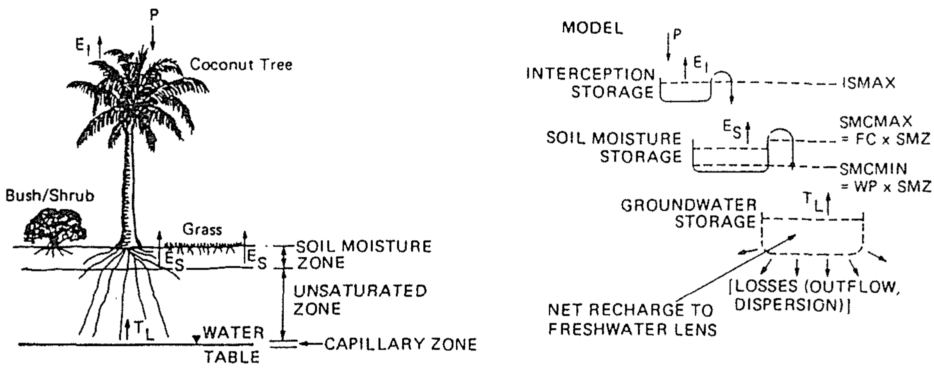

Fig. 6 Water balance model to estimate recharge for a typical coral island.

firstly fills the interception store (to a maximum value ISMAX) with the residual (or overflow) entering the soil moisture zone. Typical values of ISMAX are 1 mm for predominantly grassed areas and 3 mm for areas consisting predominantly of trees (particularly coconut trees). Evaporation is assumed to occur from this zone at the potential rate.

Roots of shallow rooted vegetation (grasses, bushes) and the shallow roots of trees can obtain water from within the soil moisture zone (SMZ), which is typically 0.3-0.5 m thick. Water requirements of vegetation from this zone are assumed to be met before any excess drains to the water table. A maximum soil moisture limit (SMCMAX, which occurs at field capacity, FC) and a minimum soil moisture limit (SMCMIN, which occurs at wilting point, WP) are set. Above the field capacity, water is assumed to drain to the water table. Below the wilting point, no further evaporation is assumed to occur and the shallow rooted vegetation wilts and possibly dies.

The amount of evaporation from the SMZ is normally assumed to be linearly related to the available soil moisture content. At WP, evaporation is assumed to be nil from the SMZ. Potential evaporation is assumed to reach full potential when the SMZ is at FC. Thus, the evaporation rate is assumed to be half that of the potential rate at a soil moisture content midway between FC and WP.

Vegetation types are assigned "crop factors" (Doorenbos & Pruitt, 1977). Crop factors of 1.0 and 0.8 were assumed in water balance studies for, respectively, shallow rooted vegetation and coconut trees (Falkland, 1983, 1988, 1992a). Thus, ET_p for coconut trees is taken as 80% of that for shallow rooted vegetation which is in turn assumed to be equal to ET_p of a "reference crop" (Doorenbos & Pruitt, 1977).

Excess water remaining after evaporative losses E_I and E_S enters the water table. This water is assumed in the model to be "gross recharge" to the fresh-water lens. A further evaporative loss (T_L) is experienced due to transpiration of trees whose roots penetrate to the water table. "Net recharge" is that water remaining after T_L is deducted from gross recharge. Observations in pits on a number of atolls reveal that a considerable number of roots penetrate to the capillary fringe just above the water table at typical depths of about 1 to 2 m below ground level. It is estimated that between 25% and 50% of the roots from mature coconut trees penetrate to the water table. Because the movement of the water table is relatively small, even during drought periods, these roots enable transpiration when the soil moisture store has been depleted. Thus, coconut trees are able to survive prolonged drought periods on coral atolls when other shallow rooted vegetation has wilted and possibly died.

The water balance procedure is more complex for raised atolls and limestone islands. Typical depths to water table are 10-100 m and extensive karstic formations often occur. These islands may have soil layers of variable thickness unlike low coral islands. Roots of trees may penetrate through fissures and reach pockets of water at different levels. Flow paths from the surface to the water table may have major horizontal components due to karstic formations (solution channels) unlike the essentially vertical flow paths with low coral islands.

The water balance procedure for islands of mixed geology is even more complex. The water table may vary considerably in elevation due to a number of perched aquifers and an underlying basal aquifer. A realistic water balance model for estimating recharge needs to account for these characteristics and for possible horizontal or inclined interface flow between limestone and underlying volcanic rock.

The time step for the surface water balance should not exceed one day because the turnover time in the soil zone is measurable on this time scale (Chapman, 1985). The use of either mean or actual monthly rainfall data rather than actual daily rainfall data will underestimate recharge. Two coral atoll studies (Kwajalein: Hunt & Peterson, 1980; Cocos (Keeling) Islands: Falkland, 1988) have shown that the assessed recharge is decreased by between 6% and 10% of rainfall if actual monthly rather than actual daily rainfall data are used. The latter study showed that the use of mean monthly evaporation estimates rather than daily evaporation data was acceptable.

Water balance within the groundwater system

The water balance within a small island groundwater system can be expressed in its simplest form as:

$$R = GF + D + Q \pm \mathrm{d}S \tag{3}$$

where R = recharge to groundwater, GF = groundwater outflow (to the sea), D = dispersion at the base of the groundwater, Q = abstraction (normally by pumping), and $\mathrm{d}S$ = change in fresh-water zone storage.

This water balance equation is particularly applicable to relatively simple groundwater systems such as fresh-water lenses on small coral islands and atolls.

In equation (3), the value of R is usually estimated from the surface water balance (equation (1)). It can also be estimated from other methods as described later.

Due to a longer turnover time within the groundwater system, a monthly time step for the groundwater balance is acceptable. Often the turnover time of the fresh groundwater on a small island is a number of years. Even for relatively small fresh-water lenses on a coral atoll, the turnover time is generally greater than 12 months.

The groundwater balance is complicated if there are perched or dyke-confined aquifers present on the island, as in the case of some volcanic islands. In mixed geology islands, the groundwater flow pattern is often characterized by subterranean streams at the interface of limestone and underlying volcanic rock. These streams may emanate as springs either above or below sea level. A generalized model is not possible for such islands and each island needs to be considered on a site-specific basis.

Fresh-water lens flow model

Flow through fresh-water lenses is influenced by hydrological (variable recharge) and geological (variable permeabilities with depth and distance) factors as well as by tidal movements and man's influence, particularly through water abstraction.

Early conceptual models and solution techniques for fresh-water lens flow assumed a sharp interface between fresh water and sea water based on the "Ghyben-Herzberg" theory (Badon Ghijben, 1889; Herzberg, 1901) and the Dupuit assumptions of horizontal flow. Observations have shown that this is not the case on atolls and wide transition zones are the norm. Sharp interface models can at best only provide an estimate of the depth to the mid-point of the transition zone, yielding no information about transition zone width. Such models also assume horizontal flow within the lens with fresh-water outflow occurring around the perimeter of the island and do not account for tidal movements. Nevertheless, sharp interface models have been used to analyse small island groundwater systems. They can at least provide qualitative information of the response of a fresh-water lens and an indication of the most important aspects to be modelled in more detail by a more realistic model. In some cases, specific sharp interface models have been developed for particular fresh-water lenses (e.g. the limestone island of Bermuda: Thomson, 1989). Other case studies include the Cayman Islands (Chidley & Lloyd, 1977) and two atolls in Kiribati, namely, Tarawa (AGDHC, 1982) and Christmas Island (Falkland, 1983).

A more realistic conceptual fresh-water lens flow model has evolved (Buddemeier & Holladay, 1977; Wheatcraft & Buddemeier, 1981; Oberdorfer *et al.*, 1990; Underwood *et al.*, 1992) based on detailed observations on atolls. The conceptual model accounts for vertical and horizontal tidal propagation through a dual aquifer system consisting of the upper (Holocene) coral sediments and lower (Pleistocene) limestone layer. This conceptual model is supported by observations on a number of atolls in the Pacific (Buddemeier & Holladay, 1977; Hunt & Peterson, 1980; Wheatcraft & Buddemeier, 1981; Ayers & Vacher, 1986; Anthony *et al.*, 1989) and in the Cocos (Keeling) Islands (Falkland, 1988). These studies have shown that tidal lags and efficiencies at water level monitoring locations within atolls are largely independent of horizontal distance from the shore. Tidal lag and efficiency (or the time difference between, and amplitude ratio of, water table movement to tidal movement) are, in fact, greatly influenced by the depth of the holes used for water level monitoring. Vertical propagation of tidal signals tends to be dominant in the middle of the island whereas both horizontal and vertical propagation are significant near the edges.

Using this conceptual model, the numerical solution of fresh-water lens flow problems can more realistically be made with "dispersion" models rather than sharp interface models. Dispersion models are available which account for a two layered hydrogeological system, flow of variable density water and the mixing of fresh water and sea water. Dispersion models are inherently more complex, requiring additional parameters to be evaluated or estimated, than sharp interface models. Both types of models can be used on micro-computers, but dispersion models take much longer to run.

One such dispersion model, SUTRA, developed by the United States Geological Survey (Voss, 1984), has been applied to the study of fresh-water lenses and coastal aquifers on a number of islands. This model uses finite elements to solve the equations rather than the finite difference method used in the sharp interface models. Case studies of atolls and small carbonate islands using the SUTRA model include Enewetak atoll, Marshall Islands (Oberdorfer & Buddemeier, 1988; Oberdorfer *et al.*, 1990), Majuro atoll, Marshall Islands (Griggs & Peterson, 1989) and Nauru, a raised atoll, (Ghassemi *et al.*, 1990). The model has also been used to analyse groundwater systems on Oahu in the Hawaiian Islands (Voss & Souza, 1987).

Kakinuma & Inouchi (1991) used both sharp interface and dispersion models to simulate island fresh-water lenses including one on Christmas Island, Kiribati. The dispersion model (based on Pinder & Gray, 1977) was able to closely match actual water table elevations while slightly underestimating depths to observed salinity levels. Further work is being undertaken on other Christmas Island fresh-water lenses.

Other approaches to modelling transition zone behaviour have been made. Volker *et al.* (1984), for instance, used an analytical model which treated the transition zone as a mixing layer similar to a laminar boundary layer between fluids moving at different velocities. The model was tested with a fresh-water lens on Tarawa, Kiribati. Analytical solutions at two cross sections indicated that the method could reasonably describe the transition zone behaviour and the effects of different pumping strategies.

SURFACE WATER RESOURCE ASSESSMENT

Rainfall, climatic, streamflow (surface runoff) and water quality data are all important in the assessment of surface water resources, particularly on high islands. This summary concentrates on the requirements for surface runoff assessment. Further details are provided in UNESCO (1991).

As small high islands are characterized by rapidly varying topography, multiple steep basins and difficult access, it is often not feasible to establish extensive data collection sites. In particular, it is not practical or economic to gauge all streamflows. Decisions need to made about optimum networks to provide representative information. Hall (1983) outlines minimum networks for small tropical islands densities as follows: streamflow (1 per 140-300 km^2), rainfall (1 per 25 km^2) and evaporation (1 per 50 000 km^2). These are guides only and individual island size, topography, access and resources need to be taken into account in applying them. Some high islands are very much less than 140 km^2 and may require more than one streamflow station to characterize the runoff of the island. This is particularly relevant on islands which have multiple small basins with varying geological, soil and vegetation characteristics. For instance on Norfolk Island (area 35 km^2 and maximum elevation 319 m), eight temporary streamgauging stations were established to quantify surface runoff from 54% of the island's area (Abell & Falkland, 1991).

The runoff coefficient (ratio of mean surface runoff to mean rainfall) varies considerably between islands and even on islands. Runoff coefficients between 0.22 and 0.6 have been obtained for the Hawaiian Islands (Wright, 1989). An average value of 0.67 was obtained from gauging stations on Pohnpei, Federated States of Micronesia (Spengler *et al.*, 1992). On Mahe, a granitic island in Seychelles, the runoff coefficient for one basin was measured as 0.12 (Cetoupe, 1992). Runoff coefficients on Norfolk Island varied between 0.05 and 0.23 (Abell & Falkland, 1991).

Standard methods of hydrological measurement (e.g. WMO, 1981/1983) have been successfully used on small islands but may need to be adapted to suit local conditions. Problems in obtaining surface runoff measurements in tropical areas are covered in WMO (1983; 1987) and Manley & Askew (1993). Streamgauging stations need to be robust and the equipment needs to be well tested in tropical environments. The flashy nature, high sediment loads and erosive power of streams on small islands mean that float wells and in-stream pressure sensors, used for stage measurement, can often be damaged or prevented from properly operating. For these reasons, non-intrusive stage measurement methods such as ultrasonic water level recorders offer significant advantages.

Modern electronic data logging devices for the recording of hydrological data provide advantages over mechanical chart recorders as there are no or limited moving parts and the data do not require digitizing to convert them to computer-compatible format. Electronic data can be retrieved from field sites by either portable computers or via telemetry systems (e.g. telephone, radio or satellite). Problems with electronic equipment do exist. These include susceptibility to damage from induced electrical currents from lightning and the need for a higher level of technician training. These problems can be overcome by effective lightning protection and appropriate training.

Data processing, archiving, analysis and reporting of hydrological (rainfall, climatic, streamflow, water quality and groundwater) data is an integral part of surface water resources assessment. A number of high quality, "user-friendly" software packages have been developed in recent years for these purposes. Some examples are HYDSYS (Australia), Micro-TIDEDA (New Zealand), HYDROM (ORSTOM, France) and HYDATA (Institute of Hydrology, UK).

Remote sensing

Remote sensing has not been widely used in small island hydrology studies. It has been used in a number of specific applications. Aerial photography is often used as a means of mapping surface and hydrogeological features. Aerial mapping of coastal springs using thermal sensors has been used on the (non-tropical) small island of Malta (Spiteri Staines, 1989).

Aerial photography was studied (Canoy, 1983) in the US Virgin Islands to assess the suitability of remotely sensed plant pigment as an indicator of soil moisture status and possible aquifers. It was concluded that this method was not suitable.

Airborne EM instruments have been used for preliminary surveys in the (non-tropical) North Sea islands (Sengpiel & Meiser, 1979; Sengpiel, 1988). Similar methods could be used on small tropical islands.

Satellite imagery (Landsat MSS) was studied for its usefulness in water resources assessment of the Belau islands (Contractor, 1982). Although surface water bodies larger than about 1-2 ha were easily identified, it was not possible to identify water bodies with lesser areas. Identification of coastal springs was found not to be accurate. While the imagery was not of great benefit, its usefulness was seen for many remote small islands and those with access difficulties to many parts of the island.

Landsat TM satellite imagery was found to be a useful and cost-effective tool for hydrogeological mapping of the islands of St Vincent and Grenada, Caribbean Sea (Burke *et al.*, 1988).

While demonstrating some practical applications and offering useful opportunities for island hydrological studies, remote sensing will not replace but rather supplement ground-based surveys and studies. *In situ* measurements of hydrological parameters on the ground are a necessary part of any remote sensing study to provide "ground-truth" for the remotely sensed data. Undoubtedly, remote sensing applications in small island studies will become more important, especially as sensor resolution is improved.

GROUNDWATER RESOURCE ASSESSMENT

Recharge estimation and groundwater aquifer evaluation are summarized in this section.

Recharge estimation

Recharge to groundwater was introduced in the section on water balance. Here the results of some of the work on recharge estimation are presented.

Nullet (1987) used the Priestley-Taylor method of determining actual evapotranspiration and a water balance procedure to estimate recharge on vegetated Pacific Ocean atolls and produce a map showing isolines of recharge.

Using the results of a number of studies of recharge to small low lying islands, Chapman (1985) prepared a graph showing the relationship between mean annual rainfall and mean annual recharge. This graph has been further extended using additional results (Fig. 7).

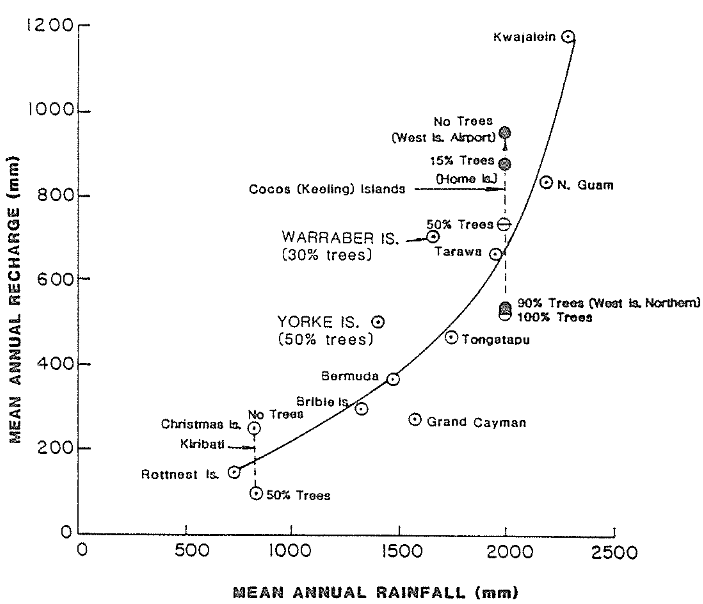

Fig. 7 Relationship between mean annual rainfall and mean annual recharge for a number of low lying islands (from Falkland, 1990).

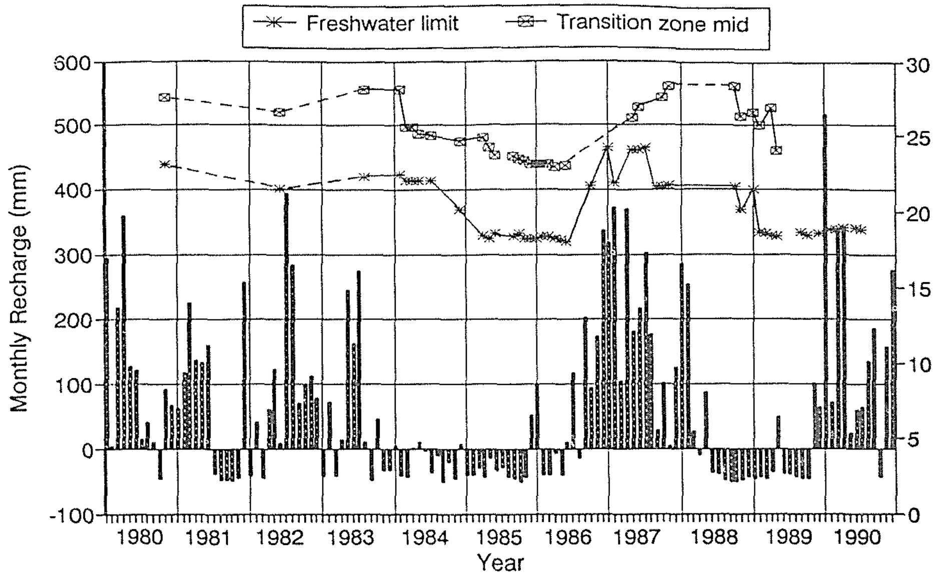

Fig. 8 Depth of fresh-water zone at a salinity monitoring borehole (BN4), Bonriki island, Tarawa atoll. The estimated monthly recharge is also shown based on a water balance procedure.

The data suggests that as the mean annual rainfall increases, the mean annual recharge exponentially increases. The influence of vegetation is shown for two atolls (South Keeling atoll in the Cocos (Keeling) Islands and Christmas Island, Kiribati) in Fig. 7. Recharge increases as vegetation decreases. Results for three fresh-water lenses with different vegetation densities in the Cocos (Keeling) Islands show that recharge can be nearly doubled by reducing the tree cover from 100% to zero.

The influence of climatic conditions is also shown in Fig. 7. The two islands, Warraber and Yorke, are located within the Torres Strait between Cape York peninsula, Australia and Papua New Guinea. There the rainfall is very seasonal with about 90% of the annual rainfall occurring in the six month monsoon or "wet" season from December to May (Falkland, 1990). Compared with small islands with similar mean annual rainfall but with less seasonal variation, these two islands receive greater recharge.

Figure 3 shows the large variation in annual recharge for Tarawa, Kiribati, based on a water balance analysis. In general, years with high annual rainfall result in high annual recharge and vice versa. The relationship is not linear as recharge is dependent not only on total rainfall but on the distribution of daily rainfall. Recharge in some years can be very low and even negative (i.e. there is a net loss of water from the fresh-water lens). The most critical times for fresh-water lenses are where there are a succession of low recharge years. Recharge is even more variable at a monthly scale than at an annual scale (Fig. 8).

Preliminary estimates of recharge can be made using a solute balance approach (e.g. chloride ion). Recharge from rainfall has a small concentration of chloride due to airborne sprays from the ocean. Evapotranspiration subsequently removes some of the water leaving the chlorides behind in the groundwater. The ratio of chloride ion in rainwater and in shallow groundwater gives an approximate value of the ratio of recharge to rainfall. Ayers (1981) used this approach for estimating recharge on Guam. Due to the many assumptions involved and the difficulty of obtaining representative values, this method is approximate. In small islands sea spray may affect samples of rainwater used for chloride balances. The groundwater may also be more saline than the recharging water due to salt water contamination where there is a thick transition zone, and this may invalidate calculations. Chapman (1985) suggests that samples for chloride ion balances should be obtained from just below the surface and just above the water table. A further problem of this method is that in low-lying areas the top phreatic water, which can more easily be sampled than water from the unsaturated zone, may not have originated locally but rather have come dominantly from the island's interior, where there is generally a lower salinity than the local recharge.

Continuous water level records can be analysed in conjunction with tidal and barometric records to estimate recharge. This method is used by Furness & Gingerich (1993) for the island of Tongatapu in Tonga. If the effects of sea level and pressure changes are removed from the water level hydrograph, recharge can be estimated from the residual trace and knowledge of the aquifer specific yield.

Other methods and examples of recharge estimation for small islands are described in UNESCO (1991).

Groundwater aquifer evaluation

The most important and prolific groundwater systems on small islands are basal aquifers, typically fresh-water lenses. Accordingly, most of this section is devoted to these, particularly those occurring on small sand, coral and limestone islands.

Volcanic islands On volcanic islands, the methods of groundwater evaluation are not dissimilar to those used on larger islands or even continents. Conventional drilling techniques and pump resting have been carried out on many small islands to assess groundwater potential. Geophysical methods are also used. Spring sources are often used to locate perched and dyke-confined aquifers (Peterson, 1984). A recent case study of the small volcanic island of Pohnpei (area 338 km^2 and maximum elevation 760 m) in the Federated States of Micronesia outlines many of the available techniques (Spengler *et al.*, 1992). Further information and references are provided in Mink (1986) and UNESCO (1991).

Fresh-water lenses There are a number of techniques which can be use to assess the location and size of fresh-water lenses. Some are relatively cheap methods and can be used for preliminary reconnaissance while other more expensive methods are suited to detailed investigations and for ongoing monitoring. The list here is by no means exhaustive. Further information and references are provided in Dale *et al.* (1986) and UNESCO (1991).

The salinity of the upper surface of a fresh-water lens can be obtained by measurements at exposed water surfaces such as existing wells and pumping galleries or additional dug or drilled holes. The lower surface of the fresh-water zone can only be accurately determined by establishing a recognizable salinity limit for fresh water and drilling through the lens to find where the limit occurs.

Apart from providing accurate data about the variation of salinity with depth (salinity profiles) in fresh-water lenses, a drilling and testing programme can provide control for geophysical soundings, provide information about permeability, porosity and depth to major hydrogeological features such as solution channels and unconformities, and enable permanent monitoring systems to be installed.

Drilling of 75 mm diameter holes up to 30 m below ground surface has been successfully undertaken with rotary rigs on Tarawa and Christmas Island and in the Cocos (Keeling) Islands (Murphy, 1981, 1982; Falkland, 1988, 1992a). An alternative to drilling holes is the driving of suitable pipes. Steel pipes have been successfully driven to 15 m below ground surface on coral atolls. On Kwajalein, 80 mm diameter pipes were driven to depths of up to 15 m using an air hammer (Hunt & Peterson, 1980) and on Majuro, 30 mm diameter pipes were driven with a manually operated drop hammer to similar depths (Hamlin & Anthony, 1987).

During drilling or driving of each hole, water samples are obtained from the base of the hole at depth intervals of typically 1-3 m and tested for salinity, normally, with an electrical conductivity meter. Vertical salinity profiles (salinity versus depth) can then be plotted.

Coring or inspection of drill cuttings provides useful information about the subsurface geology including the depth to the unconformity between upper and lower sediments.

Permeability estimates at selected depths in a number of bores, can be obtained using either falling head or constant head tests (Hvorslev, 1951). This information is essential for groundwater modelling. Permeability tests on core samples are not considered suitable as cores are not of sufficient size to be representative of the aquifer. Conventional pump tests are not appropriate as these can induce saline intrusion at the base of the borehole.

Salinity monitoring systems enable long term data to be collected about the behaviour of fresh-water lenses and for the calibration of numerical models. On coral atolls, open holes or continuously perforated casings in holes are not considered suitable for accurate determination of salinity profiles since mixing of fresh water and sea water can easily occur in the hole. This problem is known in mainland aquifers (Rushton, 1980; Kohout, 1980) and has been demonstrated in coral atolls (e.g. Enewetak; Buddemeier & Holladay, 1977). Also, contamination of the fresh-water zone by underlying saline water can be induced if this approach is used.

Two types of salinity monitoring systems for coral atolls are:

(a) Multiple holes at each location terminated at different depths with the base of each hole left open. This type of system has been used on the atolls of Kwajalein (Hunt & Peterson, 1980) and Majuro (Hamlin & Anthony, 1987), and on limestone islands in Tonga (PPK Consultants, 1992). Samples can be obtained by bailing or pumping from the base of each hole. Alternatively, a salinity probe can be lowered to the base of each hole to obtain measurements.

(b) Single boreholes with multiple tubes or pipes terminated at a number of predetermined depths, between which bentonite (sealing) layers are inserted. This system has been used in Tarawa and Christmas Island, Kiribati and in the Cocos (Keeling) Islands. Water samples are pumped to the surface using a small electric or hand operated diaphragm pump. Testing is done, as during drilling, with an EC meter and repeated until readings stabilize. The results from several years of testing are shown for Tarawa in Fig. 8 from which the response of the fresh-water lens to recharge is evident.

Geophysical methods, mainly, electrical resistivity (ER) and electromagnetics (EM), are useful for providing relatively quick and cheap assessments of fresh-water lens locations and thicknesses.

The results from ER and EM surveys are subject to differing interpretations and require independent calibration to be used with confidence. This can best be provided by vertical salinity profiles obtained from appropriately constructed boreholes. Combined with a drilling programme, these geophysical techniques offer a particularly suitable means of assessing fresh-water lenses.

ER surveys have been used, normally in conjunction with a drilling programme, for assessing fresh-water lens locations and thicknesses on many atolls and sand islands. Examples are the Cayman Islands in the Caribbean Sea (Bugg & Lloyd, 1976), Tarawa and Christmas Island, Kiribati (Jacobson & Taylor, 1981 and Falkland, 1983; 1992b), Pingelap, Federated States of Micronesia (Ayers & Vacher, 1986), the Cocos (Keeling) Islands (Falkland, 1988; 1992b) and two sand islands in Torres Strait, Australia (Falkland, 1990). Careful site selection is required to avoid known metal cables and pipes and to orient soundings parallel to the coastline to minimize violation of the horizontal layering principle on which the ER method is based (Mooney, 1980).

The use of EM surveys on small islands is outlined by Stewart (1988). EM surveys have been used on Majuro atoll, Marshall Islands (Kauahikaua, 1987), atolls in the Federated States of Micronesia (Anthony, 1992) and on the limestone islands of Tonga (Furness & Helu, 1993). In general, EM surveys are more rapid than ER surveys but give less information. The choice of method is dependent on availability of time and funds and the degree of accuracy required.

Fresh-water lens thicknesses based on salinity profiles and ER and EM soundings at borehole sites generally indicate close correlations. Exceptions are found in areas where buried conductive objects are present or where fresh-water lenses are relatively thin, such as near the coastline.

Seismic surveys have been used for analysis of subsurface geology on a number of atolls (e.g. Pingelap: Ayers & Vacher (1986) and Nukuoro, Micronesia: Ayers (1990), and the Cocos (Keeling) Islands: Creighton (1988)). Depths to water table and the unconformity can be estimated by such surveys.

Measurements of water table movements can be useful for determining mean height above mean sea level. Such data are useful for setting levels for abstraction facilities. They cannot be used, however, to determine the thickness of the fresh-water lens using the Ghyben-Herzberg ratio (approximately 40:1) because the sharp interface assumption is not correct. Rather, this approach would predict the mid-depth of the transition zone. Measurements from Christmas Island, Kiribati (Falkland, 1983) indicate that large errors can result if mean water table height above mean sea level is used to estimate fresh-water zone thicknesses. Water level measurements can also be used to determine tidal efficiencies and lags within the fresh-water lenses, which provide an indication of the relative "hydraulic connection" with the sea.

In the absence of other data, a quick assessment of the likely thickness of a fresh-water lens can be made by an empirical method. Oberdorfer & Buddemeier (1988) developed a relationship between fresh-water lens thickness (to mid-point of the transition zone), annual rainfall and island width, as follows:

$$H/P = 6.94 \log a - 14.38 \quad (4)$$

where H = lens thickness (depth from water table to sharp interface or mid-point of transition zone (m)), P = annual rainfall (m), and, a = island width (m).

Equation (4) is based on observations from nine coral islands and indicates that no permanent fresh-water lens can occur regardless of rainfall where the island width is less than about 120 m. For instance, using the mean annual rainfall of 1938 mm for the Cocos (Keeling) Islands, the minimum island width for a small fresh-water lens (say 5 m thick) to occur is about 280 m. This prediction is in reasonable agreement with observed fresh-water lenses.

It is noted that other factors which are not accounted for in equation (4) have an effect on the occurrence of fresh-water lenses (e.g. permeability of the coral sediments and the density of vegetation). Recent salinity monitoring work in the Cocos (Keeling) Islands (Falkland, 1992a) has shown that a fresh-water lens with a thickness of 11 m to the mid-point of the transition zone occurs in a location where the island is only 270 m wide. This indicates that the empirical relationship does not always give an accurate guide to lens thickness.

WATER RESOURCES DEVELOPMENT

Surface water resources

Development of surface water resources methods on small islands are generally stream intake structures, dams and other storages, or spring cappings.

Stream intake structures consist of either in-stream weirs or buried collector pipe systems laid in or near the stream bed. In-stream weirs are used in some of the high islands in the Seychelles (Wilson, 1986) and in most of the high islands in the Caribbean. Buried collector pipes are used in French Polynesia (French Polynesia country paper, 1984) and some of the Cook islands (Waterhouse & Petty, 1986).

Water retaining structures can be constructed as dams within the stream or as off-channel storages. Neither are very common on small islands due to unsuitable topography or geology and high costs. Examples of dams are found on Guam (Mink, 1976) and off-channel storages are found in the Cook Islands (Law, 1984).

A novel reservoir construction technique ("reservoirs in the sea") has been used in Hong Kong to dam sea inlets, pump out the salt water and replace it with fresh water (Chow, 1992). Two such reservoirs have been constructed with a combined capacity of just over 500 million m^3. Although not constructed on small islands, they show an innovative solution to Hong Kong's water supply problems.

Spring cappings, common in many small high islands, typically consist of an open or covered containment structure, generally constructed from concrete or masonry. Spring flows are contained by the structure and diverted to an intake pipe.

Groundwater resources

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

Dug wells are common on many small islands, particularly low islands. Fresh water is generally available in small quantities. Dug wells also provide a source of fresh water in the coastal areas of high islands. Shallow dug holes on beaches are sometimes used as a source of fresh water during low tide. Deep wells have been excavated on some islands (e.g. on the volcanic islands of Upolu and Savai'i, Western Samoa: Kear *et al.*, 1981, and on high limestone islands in Tonga: Furness & Helu, 1993).

Boreholes are a common means of developing groundwater resources on islands. These are particularly useful in high islands where depths to water table are excessive or rocks are too hard for surface excavation. Increases in salinity due to over pumping from boreholes have been experienced on a number of islands, especially where fresh-water lenses are thin. Single boreholes and arrays of boreholes have been used to extract water from relatively thin fresh-water lenses on the island of New Providence in the Bahamas but these are gradually being replaced by horizontal collection systems because the latter have less risk of inducing local sea-water upconing (Swann & Peach, 1992). Where fresh-water lenses are relatively thick, borehole abstraction systems have been used successfully.

On high islands, boreholes have been used to develop high-level or perched aquifers. For instance in Tahiti (Guillen, 1984) and in the Hawaiian Islands (Peterson, 1972), vertical and horizontal boreholes have been used to obtain water from dyke-confined aquifers contained behind impermeable volcanic rock formations called dykes.

In some limestone islands, fresh-water found in sinkholes or cave systems have been used for water supply by pumping to the surface. Examples include Christmas Island, Indian Ocean (Falkland, 1986) and the islands of Grand Bahamas and Eleuthera in the Bahamas.

In fresh-water lenses on small low islands, large-scale extraction systems have been successfully implemented using infiltration galleries or "skimming wells". These avoid the problems of excessive drawdown and consequent upconing of saline water caused by localized pumping from individual boreholes. Infiltration galleries skim water off the surface of the lens, thus distributing the pumping over a wide area.

Infiltration galleries generally consist of a horizontal conduit system which is permeable to water (e.g. slotted PVC pipe as shown in Fig. 9). The conduit system is laid in trenches dug at or close to mean sea level and allows water to be drawn towards a central pump pit.

Open trenches have been used in some islands but these are subject to surface pollution. Buried conduit systems have been installed and are successfully operating on a number of atolls including Kwajalein in the Marshall Islands (Hunt & Peterson, 1980), Diego Garcia in the Indian Ocean (Surface & Lau, 1986), Tarawa, Kiribati (AGDHC, 1986) and the Cocos (Keeling) Islands (Falkland, 1992a). On Tarawa, a yield of about 1200 m^3 day^{-1} is obtained from 17 galleries, each 300 m long, situated in two fresh-water lenses. Guidelines for the design, siting and construction of infiltration galleries are provided in UNESCO (1991).

In the Bahamas (UNDTCD, 1988) infiltration trenches have been connected to inclined pipes allowing fresh water to flow under gravity to a deep sump towards the edge of the lens. There a single pump is used to deliver the water to supply centres. This method avoids the need for multiple pumping systems, typically one per gallery or trench. Weirs at each trench must be carefully set to avoid excessive draining of fresh water from the upper surface of the lens which could cause upconing of sea water.

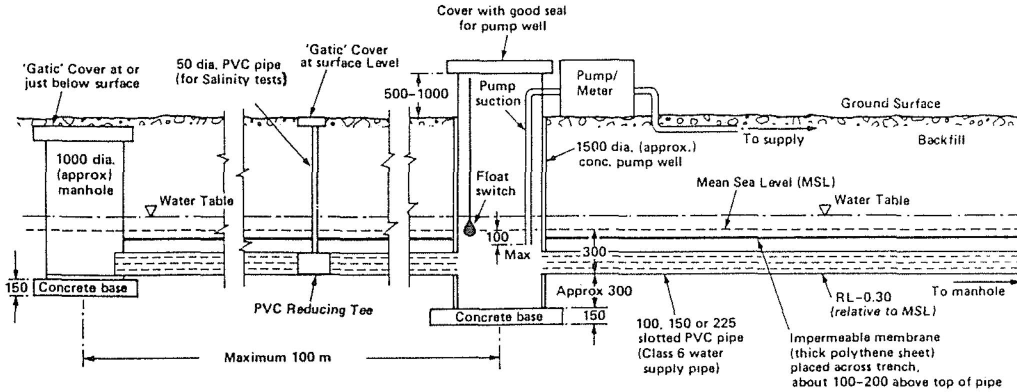

Fig. 9 Cross section through an infiltration gallery (Falkland, 1988).

The most technically difficult and least common method of groundwater development on islands is by tunnelling. Tunnels have been used in the past to develop both high-level and basal groundwater bodies on high islands. In the Hawaiian Islands, tunnels or "Maui-type wells" have been constructed to develop basal groundwater bodies 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 radiating from the pump room, allow water from a relatively large area to be abstracted. The yields from Maui-type wells are generally very good (e.g. 200 000 m^3 day^{-1} from a 500 m gallery in southern Oahu and 175 000 m^3 day^{-1} from a 200 m gallery on Maui: Peterson, 1984). Due to cheaper alternatives (boreholes), no new major Maui-type wells have been constructed since the early 1950s (Peterson, 1972).

To increase well yields, tunnels have been constructed at the base of large diameter wells or shafts at sea level. On the island of Barbados, Caribbean Sea, 60 m long tunnels have been excavated from the base of vertical shafts at a depth of about 40 m. A yield of about 95 000 m^3 day^{-1} from 14 such wells is reported (Goodwin, 1984).

Rainwater collection

Rainwater, collected from either roof or ground catchments, is one of the most common methods used for domestic water supply, particularly on small islands with relatively high rainfall. Roof catchments are most common. Examples of artificially prepared ground catchments are airport runways (e.g. on Majuro in the Marshall Islands), sealed surfaces made specifically for rainwater collection (e.g. sealed rock outcrops in Bermuda and a paved hillslope in St Thomas, US Virgin Islands), and synthetic liners (e.g. Coconut Island, Torres Strait, Australia). Storages for rainwater on islands have been made of many materials including timber, steel and other metals, clay, concrete and fibreglass.

Guidelines for the design, construction and operation of rainwater catchment systems and further references are provided in UNESCO (1991) and Gould (1991).

Desalination

While desalination plants are used on some islands for specific requirements (e.g. at tourist resorts and military installations and as a temporary measure after natural disasters), there are few small islands where desalination is used as the main source of water. In extreme cases where other water resources are exhausted it may be a necessary source of fresh water (e.g. Malé in the Maldives). On some islands, however, this technology has not been entirely successful (e.g. Diego Garcia, Funafuti in Tuvalu and Nomuka in Tonga). Problems have often been due to insufficient filtering of feed water and lack of skilled operators.

Desalination systems are based on a distillation or a membrane process. Distillation processes include 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 with varying success.

Some examples of desalination plants on islands are listed below. MSF plants with a combined capacity of a 30 000 m^3 day^{-1} operate on the island of Aruba, Netherland Antilles in the Caribbean Sea and in the US Virgin Islands there are a number of ME plants with a combined capacity of about 25 000 m^3 day^{-1}. VC plants with a combined output of 2600 m^3 day^{-1} operate in the Cayman Islands. A number of sea-water RO plants operate in the US Virgin Islands, Bermuda, and Malé in the Maldives. Further examples are provided in UNESCO (1991).

Solar stills offer a "low technology" solution in certain cases. They have been used, generally on a temporary or research basis, for the production of small quantities of fresh water from sea water. With typical daily solar radiation values in the humid tropics, fresh water yields of about 3 l m^3 day^{-1} can be produced (Eibling *et al.*, 1971). While solar stills have some major advantages such as using readily available energy and the high quality of the water produced, there are some significant problems for large scale production of fresh water by this method. They can, however, be used for emergency purposes.

Desalination is a relatively expensive and complex method of obtaining fresh water for small islands (UNESCO, 1991). It should only be considered when more conventional water sources are non-existent, fully committed or more expensive to develop. Trained operators and a reliable source of supply for chemicals and replacement parts are essential for reliable operation.

Importation

Water importation is used for a number of islands as an emergency measure during severe drought situations and in others as a supplementary source on a regular basis. Water can be imported by submarine pipeline or by sea transport (tankers or barges).

Water is imported by pipeline from adjacent mainlands to Hong Kong (Little, 1986) and Penang, Malaysia (Lee Yow Ching, 1989). Approximately 30% of New Providence's water is imported by barge from a nearby and larger island, Andros (Swann & Peach, 1992). The island of Nauru in the Pacific Ocean has received most of its water as return cargo in ships used for exporting phosphate (Jacobson & Hill, 1989). Some of the small islands of Fiji and Tonga receive water from nearby islands by barge or boat, especially during drought periods (e.g. UNESCO, 1991; Furness & Helu, 1993).

Other methods

Wastewater re-use Wastewater is sometimes used for non-potable applications such as sanitary flushing, irrigation and industrial cooling. Examples are found in Bermuda (Thomas, 1987) and Hong Kong (Chan & Chan, 1989).

In Singapore, treated stormwater is used to supplement drinking water supplies (Bingham, 1985). The scheme involves the collection of surface runoff from a number of urban catchments into ponds and subsequently into holding dams. Extensive treatment of the water then follows to ensure that it satisfies drinking water standards. The collection facilities are designed to collect about 70% of the runoff. This technology is not generally applicable for the many developing island nations.

Substitution During severe drought conditions or after natural disasters, substitutes for fresh drinking water have been used. The most notable is the water from coconuts. People on some of the smaller islands in Fiji, Kiribati and the Marshall Islands, for instance, have survived on this substitute during drought periods. The coconut tree is very salt tolerant and can continue to produce coconuts once groundwater has turned brackish.

Non-potable water systems Non-potable water sources include sea water, brackish groundwater and wastewater. There are many examples of the use of these waters in order to conserve valuable fresh-water reserves on islands. For example, sea water is used for both toilet flushing and fire-fighting on a number of islands including St Thomas and St Croix, US Virgin Islands, on Tarawa in Kiribati and on the island of Hong Kong. Sea water or brackish well water is often used for bathing and some washing purposes on small islands. Sea water is also used for cooling of electric power generation plants, for ice making, in air conditioning plants, and in 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, groundwater dams and weather modification. Most are either experimental or have not been used in humid tropical islands.

Artificial recharge increases groundwater yield by directing surface water into pits, trenches, boreholes and infiltration basins or storages. Sources of water can be streams, springs or lakes, storm runoff from impervious surfaces, wastewater and leaking pipelines. Artificial recharge schemes from naturally occurring fresh-water sources are not common on small tropical islands. Leaking pipes are known to recharge aquifers on Hong Kong (Lerner, 1986) and Bermuda (Thomson & Foster, 1986).

Subsurface, artificial sea-water intrusion barriers can be constructed to impede the outflow of fresh water, or the inflow of sea water, in basal groundwater bodies. Experimental schemes have been tried on Miyako-jima, a (non-tropical) island in the Ryukyu Archipelago of Japan (Sugio *et al.*, 1987). 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 in other islands.

Groundwater dams have been used to store water in both Africa and India. These dams are constructed under the ground surface in stream channels and are aimed at impeding and storing groundwater as it flows under the stream channel in periods when the stream has dried up. The only known example on a small (non-tropical) island is in the Cape Verde archipelago in the Atlantic Ocean (Hanson & Nilsson, 1987). They do, however, have potential application in humid tropical islands.

Weather modification, particularly "cloud-seeding", has been the subject of research in a number of continental countries but has not been applied to small islands. Until further knowledge is developed in this area, it is not very relevant.

WATER RESOURCES PLANNING AND MANAGEMENT

Planning and management issues for small islands water resources and water development projects are summarized below. Further details are presented in UNESCO (1991).

Planning

The assessment of water resources and their sustainable yields is a most important step in the planning of water resource developments. Initially, "conventional" (surface water, groundwater and rainwater) resources need to be assessed. "Non-conventional" options, including desalination and importation, may be required if conventional sources are over-utilized or where the economy can afford them.

Conjunctive use of different classes of water should be considered. Often rainwater catchments and shallow groundwater sources, either fresh or brackish, are available options even on the smallest of islands. Rainwater may be a suitable option for the most basic of needs, such as drinking and cooking, leaving higher salinity water for other uses such as bathing and washing. Where existing or potential water supplies are scarce, the use of dual or multi-quality supplies should be strongly considered (e.g. sea water for toilet flushing).

Appropriate water quality criteria should be set. Guidelines (e.g. World Health Organisation, 1984) may need to be adapted to suit local conditions. In particular, salinity criteria (e.g. chloride ion concentration) need to be carefully considered in the knowledge that island populations are often used to higher salinities in water than are specified in many guidelines. Provided there are no adverse health effects, adapting guidelines to suit local conditions is often appropriate.

In the planning and design of water resource development projects for small islands, certain basic criteria should be adopted. Simple, proven designs which have been used in similar conditions should be used. Technical criteria from other regions can only be used as guides, and should be adapted to local conditions. Locally available materials should be used where possible to minimize import costs. Materials and equipment should be standardized 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 may be necessary to specify preferred and well-tested equipment, as a prior condition to receiving aid funding. Corrosion resistant materials should be used due to the proximity to the sea and airborne salt spray. Operation and maintenance requirements should be minimized to enable village-level operation and maintenance. Renewable energy sources (e.g. solar, wind) for pumping should be considered so as to reduce operating costs.

Management

Policy and legislation Appropriate protection and management policies are essential for water resource management. Controls on abstraction must be introduced and backed by legislation to ensure that over-utilization of water resources does not occur. Water resources should be regularly monitored for quantity and quality and necessary remedial action taken to prevent over-utilization or degradation. Guidelines and case studies for water resources legislation are provided in United Nations (1986) and UNESCO (1991).

Land management Land management is very important in the protection of fresh-water lenses from contamination. This is particularly important on islands with highly permeable soils and shallow water tables which make groundwater very susceptible to pollution. Water reserves or protection zones should be established wherever possible. On atolls, it may be possible to reserve individual islands for water supply purposes (Falkland, 1991). Such reserves should disallow land uses which have the potential for polluting water resources including residential, commercial and industrial development. Where land resources are very scarce, an alternative solution is to site developments on the edge of the island or as far as practicable from the centre of the fresh-water lens.

Fresh-water maximization Where fresh-water resources are very limited, non-potable water use should be encouraged. Dual piped systems, one with potable and the other with non-potable water (e.g. salt water), can assist to limit demand for potable water. Other conjunctive use schemes are available when piped systems are not present (e.g. use of non-potable well water for bathing and washing). This is particularly appropriate in crowded areas where residential areas may be located above or adjacent to water supply sources.

To maximize fresh groundwater resources, it may be prudent to selectively clear vegetation, particularly coconut trees, to reduce transpiration. This matter should be treated cautiously as coconut trees are often a source of food and drink, shade and materials for building and other purposes. Other large trees, may also need to be assessed for their suitability in groundwater abstraction areas.

Demand management is important for water resources management on small islands. In urban areas in particular, demand management measures should include an appropriate pricing policy 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 often 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.

Pollution minimization Adequate spacing between sanitation and water supply facilities is required, and should take account of the groundwater flow direction. Guidelines from elsewhere are not necessarily applicable and need to be adapted to suit local hydrogeological conditions. Where possible on small coral islands, water supply extraction facilities should be towards the middle of the island and sanitation and solid waste disposal facilities should be near the edge of the island. It may be necessary to pipe sewage from the island via ocean outfalls where land disposal is not practical (e.g. Tarawa, Kiribati). Where environmental safeguards are paramount, extensive sewage treatment may be necessary prior to discharge (Gersekowski, 1992).

To minimize other pollution, restrictions on location of animals such as pigs and poultry may be appropriate. Potentially harmful chemicals and other substances should be sited away from water supply sources. This includes fuel depots, mechanical workshops, hospitals, laboratories and chemical stores.

Resettlement Transmigration or resettlement of people from overcrowded islands to other locations may be necessary in extremely serious situations. It has been undertaken in the past and may be necessary in the future in the event of major natural disasters such as earthquake, volcanic eruption, overtopping by waves or extreme drought. Such disasters not only affect water supplies but also most of the other aspects of a small island community infrastructure.

Training Training at technical, professional and managerial level is required as an ongoing requirement to improve the skills of local personnel in the assessment, development and management of their own water resources. Approaches to training in relation to these matters are provided by Dale (1988).

IMPACT OF SEA LEVEL RISE

It is obvious that small island nations are concerned about the possibility of sea-level rise and the impacts this would have on their communities. Long-term climatic change caused either by natural phenomena can no doubt dramatically influence the water resource situation on small islands, and in fact their very existence. The much publicised "greenhouse effect" may also cause climatic changes including changed rainfall patterns in some areas and a general increase in sea level. Average rainfall on some islands is predicted to decrease while on others it may increase. A greater influence may be caused by rising sea levels. The magnitude of these effects are, however, not well known at this stage particularly at local scales.

Earlier predictions that mean sea level by the year 2030 could rise by 0.2-1.4 m (e.g. Stark, 1988) have now been revised to smaller rises (typically 0.2-0.5 m). Potential sea level rises of these magnitudes are still of concern to many small island nations, particularly the very low-lying coral atolls and sand cays. According to Wyrtki (1990), if present trends continue the mean sea level of the oceans should not rise by more than 0.05-0.1 m in the next 50 years. This is a much lower estimate than previously presented in much of the literature.

If sea level does rise, it will have an impact on fresh-water lenses on small islands. Some scenarios have been analysed using a dispersion type model for a typical small coral island (Oberdorfer & Buddemeier, 1988). Their results show that if the rising sea does not encroach onto the land, fresh-water lens volume can actually increase. This is because the base of the fresh-water lens would rise into the upper, less permeable sediments, thus slowing the fresh-water outflow rate. The major issue, therefore, is whether potential sea level rise leads to significant loss of available land. This is dependent on the magnitude of sea level rise.

The strategy adopted for the design of infiltration galleries on a number of islands (e.g. Falkland, 1988; 1990) is to place the invert of horizontal gallery pipes at a level which is suitable under present sea level/water table conditions. If sea level rise does cause the water table to rise then these pipes will be slightly lower in the lens. This is not seen as a significant issue.

Studies of "microatolls" (large colonies of coral found in intertidal environments on coral atolls provide a natural means of tracking sea level changes. The upward growth of these corals which are normally found on reef flats are constrained by sea level and through prolonged exposure at lowest spring tides. Woodroffe & McLean (1990) have dated the growth of microatolls on a number of islands using radiometric methods and have found that there has not been any substantial net rise in sea level over the last few decades.

Because of the uncertainty of sea level rise predictions, it is imperative that present sea level monitoring programmes for small islands be encouraged and expanded. A combination of electronic/mechanical recorders and the biological microatoll "recorders" may be a sensible compromise. Current initiatives to install and operate an integrated, high resolution, sea level recording network in a number of small Pacific Ocean islands (Lennon, 1991) is a worthwhile contribution in this direction.

FURTHER RESEARCH AND DEVELOPMENT

Data collection networks for water resources 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), net solar radiation recording stations (due to its importance in evaporation studies), groundwater investigation boreholes for monitoring salinity profiles in fresh-water lenses and sea level monitoring stations.

Detailed investigations of actual evapotranspiration should be conducted using micrometeorological and other suitable techniques for selected vegetation and soil associations on small tropical islands. The interception capacity of typical vegetation found on small islands should also be studied. Existing approaches for the estimation of evapotranspiration should be re-evaluated in the light of such investigations. The use of remote sensing techniques (e.g. airborne sensing or satellite imagery) correlated with surface measurements of ET_a could considerably assist with the extrapolation of ET_a from point measurements to areal estimates.

Standardization of methods for determining of salinity profiles in observation boreholes should be developed. Recognition of the problems inherent in using single open boreholes should be highlighted. Existing methods using multiple open holes or hydraulically isolated zones should be reviewed and a suitable and economical method recommended for typical island types (e.g. low-lying coral atolls and elevated terrain on raised limestone islands).

Groundwater flow models for determining the sustainable yields of fresh-water lenses should be reviewed and simpler yet theoretically correct approaches developed for use on microcomputers by island personnel. Models which consider transition zone behaviour, rather than sharp interface models, should be used wherever possible.

Appropriate computational procedures for the design of abstraction systems in fresh-water lenses should be developed. Additional research may involve scale model studies and variable density fluids and/or construction and monitoring of a prototype on a selected island.

Further research into groundwater pollution is required. Special attention has to be given to pesticide behaviour and transport especially in terrain devoid of soil cover or with small adsorption capacity.

Guidelines for minimum distances between sanitation and water supply facilities need to be re-evaluated for island conditions with due consideration given to groundwater flow direction, the permeability of soils and underlying geological layer(s), the rate of extraction and the type(s) of sanitation disposal.

There is greater scope for technology transfer to islands in the fields of hydrology and water resources. International and regional seminars and workshops on the topics of hydrology and water resources of small islands have assisted participants from many islands in the past and these should continue on a periodic basis. Specific meetings of professional and technical experts would help to resolve ongoing practical and theoretical issues.

Training programmes of island technical and professional personnel in water sciences should be expanded. A combination of formal training in recognised institutions combined with specific in-country or regional training is an appropriate approach. Consideration should be given to further regional training workshops involving the solution of practical problems along the lines of the "REFRESHR" workshops held in the Pacific (Dale & Thorstensen, 1988).

Greater coordination is required between institutions and individuals involved with small island hydrology and water resources assessment, development and management. This could be greatly assisted by promoting a library service or information network through existing institutions involved in small island hydrology and water resources. The informal newsletter CHOC (acronym for "Contacts for Hydrogeology of Coral islands for hydrogeology") provided information on this topic for a number of years. It is now time for this role to be expanded beyond the services that can be offered by one or two individuals. The GARNET concept of applied research sharing through a network of interested institutions and individuals (Campbell *et al.*, 1992) may be an appropriate information exchange mechanism. This requires further consideration and discussion by all those interested in furthering the knowledge of small island hydrology and water resources.

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