INTERNATIONAL COLLOQUIUM ON THE DEVELOPMENT OF HYDROLOGIC AND WATER MANAGEMENT STRATEGIES IN THE HUMID TROPICS

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REGIONAL HYDROLOGY AND WATER RESOURCES PROBLEMS OF HUMID TROPICAL ISLANDS

by

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UNESCO

International Hydrological Programme

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1. Introduction

According to the adopted definition of the humid tropical region for this Colloquium (mea temperature of the coldest month is above 18°C and the number of wet months in which the rainfall greater than 100mm exceeds 4.5), many islands of the world lie in this region, particularly in the Pacif and Indian Oceans and the Caribbean Sea.

The land portion of many countries in the humid tropics consist entirely of islands. Examples (countries consisting of island archipelagos are:

- Indonesia, Phillipines (South East Asia),
- Solomon Islands, Vanuatu, Fiji, Western Samoa, Tonga, Kiribati, Tuvalu, Tokelau, Coo Islands (Pacific Ocean),
- Maldives, Seychelles (Indian Ocean),
- Bahamas, Turks and Caicos (Caribbean Sea).

Some countries consist of only one island, for example Nauru and Niue in the Pacific Ocean an Barbados and Jamaica in the Caribbean Sea. Other islands are part of larger continental countries, fc example the Hawaiian Islands (USA) and French Polynesia (France). Also, many of the islands in Sout East Asia belong to Malaysia, Vietnam, China and Japan.

Most of the island countries within the humid tropics are developing rather than develope(Hong Kong and Singapore are exceptions.

2. Island Types

Islands in the humid tropics can be classified according to their geology, topography and size. / convenient geological classification is as follows:

- volcanic type (eg. Hawaiian Islands, many islands in Micronesia and French Polynesia an some in the Caribbean). There are at least two sub-types of the volcanic type: th andesitic sub-type which normally form as island arcs on the continental sides of dee| trenches, and the basaltic or oceanic sub-type which rise from the ocean floor in th middle of tectonic plates,

- limestone type (eg. Bermuda),

- coral atoll type (eg. islands of Kiribati and Tuvalu in the Pacific Ocean and the Maldive in the Indian Ocean; a sub-type of this type is the 'raised atoll' or uplifted former cora atoll that has undergone subsequent erosion and karstification eg. Nauru and Nuie),

- bedrock type, with similar geology to adjacent continents (many examples are found oı continental shelves eg. Magnetic Island off Townsville, Australia),

- unconsolidated type (eg. sand islands which form in the deltas of major continental rivers as in Bangladesh),

- mixed type comprising a mixture of some of the above types, especially a mixture of volcanic and limestone rocks.

Islands are sometimes classified according to topography and are referred to 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 surface runoff. Volcanic islands are typical high islands and coral atolls are typical low islands.

Islands have also been classified for convenience according to size as either large or small. Although there is no exact distinction between the two sizes, an area of 5000 km^2 was selected as the upper limit for a small island at a workshop on small island hydrology (Commonwealth Science Council 1985). A smaller area of 2000 km^2 has been selected as an appropriate upper limit in the current IHP-II Project 4.6, Hydrology of Small Islands. Large islands tend to have features and problems which are similar to those found on continents whereas small islands often have additional problems. Because of this, the emphasis in this paper is placed on small rather than large islands. Some problems which relate particularly to small islands are: scarce freshwater resources, increasing urban populations with high potential for pollution of available freshwater resources (particularly groundwater) owing to close proximity to water sources, lack of trained professional and technical staff to assess and properly develop freshwater resources, logistical problems due to large distances from supply or information sources causing delays and much higher than normal costs and severe environmental conditions caused be close proximity to the sea (highly corrosive conditions and possibility of island overtopping from storm surges generated by cyclones).

Problems of the large islands are largely addressed in the other papers dealing with regional water problems in the humid tropics at this Colloquium (Asia: Chang; Africa: Ayibotele; Latin America and the Caribbean: Griesinger). Some of their problems are coincident with those outlined for small islands and will, therefore, be covered in this paper.

3. Recent Experiences with Island Hydrology and Water Resources

In recent years, there have been a number of major regional, interregional and international seminars, meetings and workshops on hydrology and water resources in islands, particularly small islands, in the humid tropics. These include the following:

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

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

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

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

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

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

Proceedings of each of the above meetings have been published and these provide a goo overview of the range of problems confronting islands and some of the solutions which have bee implemented.

As part of Project 4.6 (Hydrology of Small Islands) of Phase III of Unesco's Internation: Hydrological Programme, a review of existing knowledge regarding hydrology and the water balance c small islands was published (Diaz Arenas and Huertas, 1986). In addition, a Guide on Hydrology an Water Resources Development of Small Islands is currently being prepared under the same projec While this project is not exclusively dealing with the humid tropics, it is concerned to a large degree wit the humid tropical region because most small islands fall within this region. Unesco was also involve with two research studies on the hydrological problems of small islands. The first study involved tw small islands in Indonesia (Barang Lompo and Koding Areng near Ujung Pandang, Sulawesi) while th second was on Marinduque island in the Phillipines. Both studies were conducted by nation: organisations with the funding and review (Daniell, 1986) by Unesco.

UNDTCD has been actively involved in the last two decades with the assessment an development of water resources on small islands. Initially, projects were conducted on individual island in the early 1970's. By the end of the 1970's, a regional project was started in the Caribbean to cc ordinate activities in 11 small island countries. In 1986 a similar regional project was launched for th small island countries in the Pacific region. As part of the project, much information (eg. studies an reports) on small island hydrology and water resources has been assembled at the UNDTCD office i Fiji.

In addition to the above regional and international efforts, a number of studies and projects t assess and develop water resources on small islands have been conducted by or through other agencie such as ORSTOM (France), USAID (USA), AIDAB (Australia) and DSIR/Ministry of Works (Ne Zealand) and private consultants. Also, a number of studies have been carried out on small island which are part of mainland countries using their own national organisations.

4. Freshwater Occurrence on Islands

Freshwater occurs naturally as either or both surface or groundwater on islands. The followin factors influence the type and quantity of freshwater on islands: climate, size, topography, geology an vegetation.

Where suitable hydrological and geological conditions prevail on 'high' islands, surface wate occurs in the form of rivers, streams, springs, lakes and wetlands. Low lying or raised flat islands rarel have surface water, except as lakes or ponds where the permeability of the surface is sufficiently lov Islands with raised topography and low permeability surfaces often have small streams but these ar normally ephemeral in nature. Surface runoff often occurs rapidly after rainfall and may recede to littl or no flow within hours. On many raised islands, perennial springs are found. These often occur aroun the base of the island either slightly above or sometimes below sea level.

Groundwater on high islands can occur in the form of elevated (high level) or basal (low level aquifers. Groundwater on low islands can occur only as basal aquifers.

Elevated aquifers can either be perched aquifers or dyke-confined aquifers. Perched aquifer occur where a horizontal, low permeability layer effectively impedes the vertical movement of percolatin groundwater. Dyke-confined aquifers, found in some volcanic islands (eg. Hawaiian islands, Frenc Polynesia), are formed when vertical volcanic dykes, typically in groups, trap water in the intervenin compartments.

Basal aquifers consist of unconfined, partially confined or confined freshwater 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 freshwater body comes into contact with seawater. On many small islands, the basal aquifer takes the form of a freshwater lens which underlies the whole island. Freshwater lenses are a very important water supply source on many small islands and are generally much more economic to develop than other options such as rain water collection, importation and desalination. They are, however, a fragile resource and must be properly assessed, developed and managed in order to provide a sustainable water supply. If these essential procedures are not undertaken, there is considerable risk of inducing the intrusion of saline water, as has occurred in a number of islands.

The main natural controlling features for the formation of freshwater lenses on low lying islands, such as coral atolls, are:

- size and shape of the island (particularly the width),
- hydrogeological factors including permeability and porosity of the sediments and the presence and distribution of solution cavities,
- amount and distribution of recharge which is dependent on rainfall and evapotranspiration patterns,
- tidal patterns,
- height of island above sea level and width of reef (to provide some idea of the risk of overtopping by storm surge).

The term 'freshwater lens' can often conjure up a misconception of the true nature of groundwater bodies underlying islands. In reality, there is no distinct freshwater body floating on seawater but rather a gradual transition from the freshest water at the water table to seawater at some depth below this. A zone of freshwater can, however, be defined on the basis of an objective salinity criterion such as a chloride ion concentration of 200 (or maybe 600) mg/l. Figure 1 shows the variation of salinity with depth from boreholes drilled across a coral atoll and the determination of the freshwater zone.

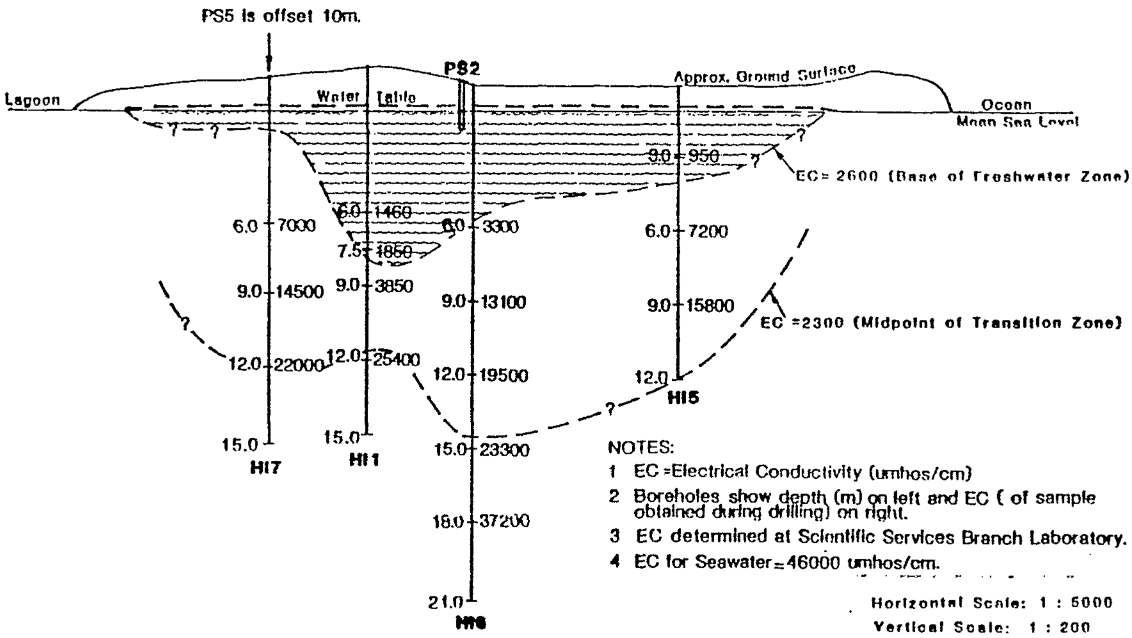


Figure 1 Cross section through Home Island freshwater lens, Cocos (Keeling) Island, Nov. 1987 (after Falkland, 1988).

It must be noted that drawings of freshwater lenses are normally shown with an exaggerated vertical scale which can often lead to a false impression of the depth of the freshwater zone: in practice, many freshwater zones are less than 5m thick although the island may be 300-500 wide. The deepest part of the freshwater zone is often displaced towards the lagoon side on coral atolls due to lower permeability sediments on that rather than the ocean side.

The Ghyben-Herzberg theory (strictly, the Badon Ghyben-Herzberg theory after works by Bado Ghyben, 1889 and Herzberg, 1901) has often been applied to the study of freshwater-saltwate relationships on islands. This theory assumes that the depth of freshwater below mean sea level i approximately 40 times the height of the water table above mean sea level, based on the differen densities of fresh and sea water. The theory is based on the concept of immiscible fluids which is no correct in practice because the two fluids do mix as a result of both mechanical and molecular dispersior The degree of mixing is a function of the freshwater flow from the aquifer to the sea. If the flow is larg as may occur from a continental coastal aquifer, a high degree of 'flushing' (of salts) occurs and th mixing or transition zone will be thin in comparison to the freshwater zone. In this case the Ghyben Herzberg theory has been found to provide a reasonable approximation to reality. However, where th freshwater outflow is small, as on a small island, the degree of flushing is correspondingly small an transition zone can be very thick. In many cases the transition zone is thicker than the freshwater zone In these cases, the Ghyben-Herzberg theory does not apply. Rather the Ghyben-Herzberg ratio of 1:4 tends to identify the midpoint of the transition zone. Serious errors in the estimation of the freshwate thickness can (and have) been caused by blindly applying the theory to small islands. This has ofte occurred because measurement of the height of water table above mean sea level is a lot easier tha obtaining borehole salinity profiles, which provide a true indication of the freshwater-seawate relationship.

In addition to natural controlling features, man can induce additional influences on groundwate systems due to abstraction. The design and operation of abstraction facilities can have a major influenc on the sustainability of fresh groundwater resources on small islands. Point abstraction at higher rate than the sustainable yield has caused the local destruction of freshwater lenses. This problem i however, reversible given sufficient recharge as exemplified in Figure 2. The recharge referred to in thi figure resulted from about 2000mm of rainfall which occurred between July 1982 and February 1983 as result of the 1982/1983 ENSO. By comparison, the average annual rainfall on Christmas Island i 840mm.

The relative importance of surface water and groundwater on islands depends on the particula nature of the island. In general, however, groundwater tends to be the more important resource of th two. Furthermore, basal aquifers tend to be more important than perched aquifers because not a 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 freshwater-seawater interactio and must be carefully managed to avoid over-exploitation with resultant seawater intrusion.

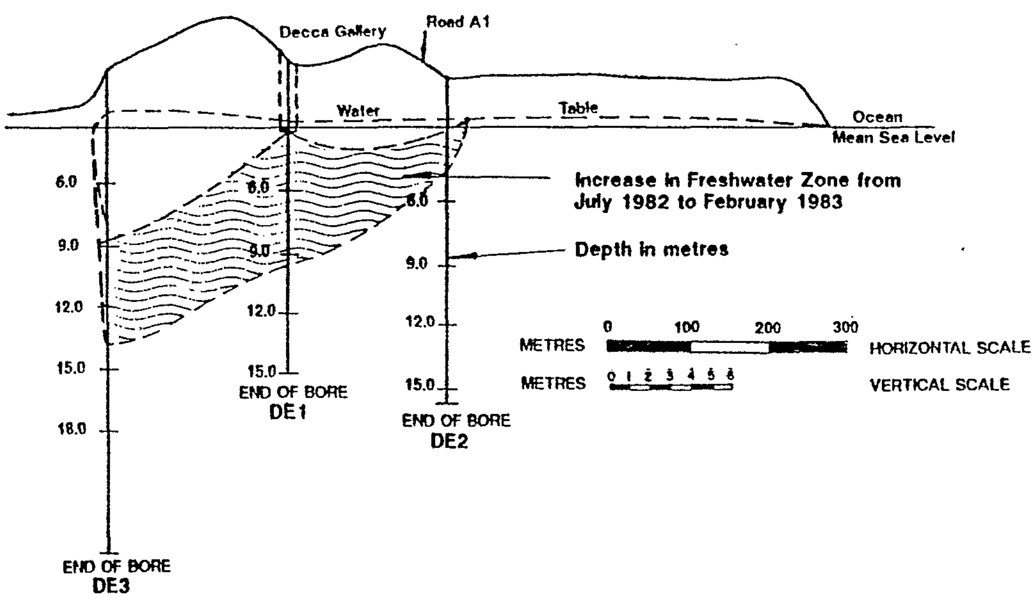


Figure 2 Increase in freshwater lens thickness following high recharge, Decca lens Christmas Island, Kiribati.

5. Water use

In general, the types of water use on small islands are similar to those experienced elsewhere in the world, for example, water supply (for domestic purposes, tourism and industry), irrigation and hydroelectric power generation. Many small islands, however, do not have sufficient water resources or adequate land resources to allow for irrigation, or suitable topographic features to allow for the development of hydroelectric schemes. Hence, most freshwater on small islands is used for water supplies. On most large islands, irrigation is the greatest use for freshwater.

5.1 Water supply

Potable water is used for drinking, cooking, bathing, washing and cleaning. Other potable water uses include toilet flushing, cooling, heating, freezing, and drinking water for domestic animals. There are many cases, however, where non-potable water supplies, such as seawater or brackish groundwater, are substituted for some of these purposes. In particular, non-potable water is used on some islands for such purposes as toilet flushing, fire-fighting, cooling water for power stations and ice-making for fishing industries. Brackish groundwater is sometimes used on very small islands, such as coral atolls, for all purposes except drinking and cooking. Seawater is sometimes used for bathing while treated sewage effluent, another source of non-potable water, is sometimes used for purposes such as watering of gardens and lawns.

The per capita consumption for freshwater varies considerably between islands and on islands depending on availability, quality, type and age of water distribution systems, cultural and socio-economic factors and administrative procedures. Examples of per capita consumption (litres per person per day) for a number of islands are:

- Male, Maldives:	59-88	(West and Arnell,1976)
- Seychelles:	180	(Rooke,1985)
- Penang, Malaysia:	265	(Harun,1988)
- Majuro, Marshall Is:	550	(Mink,1986)
- Tarawa, Kiribati:	20-40	(Bencke,1980)
- Tahiti:	1000	(French Polynesia, 1985)
- Barbados:	350	(Goodwin,1984)
- Dominica:	270	" "

Per capita tourist water use tends to be higher than per capita domestic use (for example, Barbados, 500 l/c/d: Goodwin, 1984). Tourist consumption of freshwater can represent the greatest use of water on many small islands.

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

5.2 Irrigation

Much of the natural vegetation occurring on small islands in the tropical regions of the world receives adequate rainfall for growth. The natural vegetation consists of a variety of trees, particularly coconut trees, and a range of bushes and grasses. These do not require irrigation as they have adapted to local climatic conditions. Some of the natural vegetation for example the coconut tree is remarkably salt tolerant and can grow in brackish water with relatively high salinity levels.

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

Cultivation of root and tuber crops is practised in some, mainly Pacific Ocean, islands. On important example is the cultivation of swamp taro on some coral atolls by digging a pit to the wate table. This is essentially a form of irrigation as the crops have been introduced to a source of water no naturally available.

At the higher water use end, cash crops such as sugar cane are commercially grown usin irrigation schemes on some islands. In the Hawaiian Islands and Fiji, for instance, the greatest use c water is for agriculture, primarily sugar cane cultivation. On larger islands (eg. Java, Indonesia) rice i cultivated by similar methods to those used on continents.

5.3 Hydro-power generation

There are a number of small 'high' islands where hydroelectric power generation schemes hav been implemented. These schemes tend to be on a relatively small scale but can supply significar proportions of total power requirements. Examples of islands where electricity is generated by hydrc power are Fiji, Western Samoa, Tahiti and the Marquesas Islands. Many other high islands hav potential for hydroelectric power generation.

6. Water resource development methods

Many water resource development methods are used on islands. Methods which directly exploi or produce freshwater are:

- Rainwater collection
- Surface water collection
- Groundwater abstraction
- Desalination
- Importation

In addition, other methods assist in either the conservation of freshwater by reuse or substitutior or enhancement of the available resource. These include:

- Wastewater reuse
- Direct substitution
- Non-potable water systems
- Potable water enhancement techniques

6.1 Rainwater collection

This is one of the most common methods used for domestic water supply, particularly on island with relatively high rainfall. Surfaces for rainfall collection include both roof and ground catchments witl roof catchments being the most common type. Ground catchments can be either natural or artificial Examples of artificially prepared ground catchments are:

- airport runways,
- sealed surfaces made specifically for rainwater collection (for example, sealed rocl outcrops in Bermuda and a paved hillslope in St. Thomas, US Virgin Islands),
- synthetic liners.

Storages for rainwater on islands have been made of timber, steel and other metals, clay, concret and fibreglass. Often discarded containers (eg, 200 litre drums) are used.

Numerous examples of present and past methods of rainwater systems in many countrie including some islands, are provided in the proceedings of three recent international conferences on th topic (Fujimura, 1982; Smith, 1984 and Vadhanavikkit, 1987).

6.2 Surface water collection

Surface water development methods on islands are generally of three types: stream intak structures, dams or other storages and spring cappings.

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

Water retaining structures are constructed as dams within the stream or as 'off-channel' storage Neither are very common on small islands due to a number of reasons including unsuitable topograpl or geological conditions and economic considerations. Some large dams are found, however, on son larger islands (eg. Sarawak, Malaysia).

Spring cappings typically consist of an open or covered containment structure, general constructed from concrete or masonry. Spring flows are contained by the structure and diverted to a intake pipe.

6.3 Groundwater abstraction

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

Dug wells, generally with diameters of between one and two metres are common on many sma islands. On 'low' islands, particularly coral atolls, such wells need only to be about two to three metr deep before the water table is reached. Where conditions are favourable, freshwater is available moderate quantities. Dug wells also provide a source of freshwater in some areas on 'high' islanc These areas are generally on the coastal margins in sedimentary formations.In some instances, shallo dug holes on beaches are used as a source of freshwater during low tide. These often become covered l seawater at high tide.

Water is obtained from dug wells by means of hand bailers or pumps. Hand bailers are ofte buckets or discarded food or drink containers such as steel cans or plastic bottles. Pumps range fro simple hand pumps, of which there are numerous designs, to more sophisticated mechanical pump These are driven using conventional energy sources such as diesel or electrically powered motors c where conditions are favourable, renewable energy sources such as wind or solar powered pumps ai sometimes installed.

Boreholes are also a common means of developing groundwater resources on islands, particular high islands where depths to water table are excessive or rocks are too hard for surface excavation.

On low islands, networks of boreholes have been used in the past to develop freshwater lenses. I the early 1930's, a network of boreholes was used to abstract freshwater from a freshwater lens on Ne Providence in the Bahamas. Due to over-abstraction of water, however, increasing salinity over the ne 10 years forced the closure of the borefield (Sherman, 1980). Increases in salinity due to overpumpir under similar conditions have been experienced on a number of islands. It was soon learnt that bett methods of developing fragile lenses were required, and infiltration galleries became more popular.

However, where freshwater lenses are relatively thick, borehole abstraction systems have been used successfully. The main requirements are that a network of boreholes be drilled and individual pump rates are sufficiently low to prevent the occurrence of excessive localised drawdowns and consequent upconing of underlying seawater.

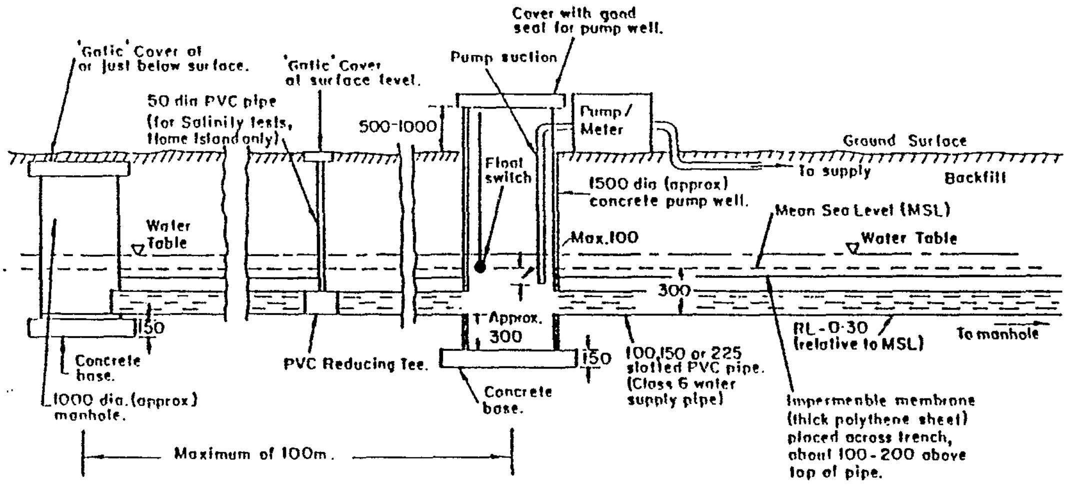
On high islands, boreholes have been used to develop both high-level and basal flow-level groundwater bodies. On Oahu in the Hawaiian islands, boreholes were drilled as early as last century to tap basal groundwater aquifers under artesian pressure (Takasaki, 1978). Often the boreholes were drilled too deep and became contaminated with seawater. Following increased knowledge of the hydrogeological conditions, boreholes were located on or near ridges where greater yields of freshwater could be obtained from the highly permeable basalt aquifers than in the alluvial valleys.

Vertical and horizontal boreholes have also been used to abstract water from dyke-confined aquifers on some high islands, including the Hawaiian Islands (Peterson, 1972) and Tahiti (Guillen, 1985).

In some islands where karstic limestone is present, sinkholes or cave systems have been developed for water supply, usually by pumping with submersible pumps. Examples include Christmas Island in the Indian Ocean (Falkland, 1986) and the islands of Grand Bahamas and Eleuthera in the Bahamas (Hadwen, 1988).

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

On coral atolls and other low limestone islands, infiltration galleries generally consist of a horizontal conduit system permeable to water (eg. slotted PVC pipe as shown in Figure 3). The conduit system is laid at or close to mean sea level and allows water to be drawn towards a central pump pit.



NOTES:

1. All joints between pipes and pump wells / manholes to be well sealed.

2. Float switch level to be as close above base of pump suction as possible (without causing vortex)

3. Optional housing over pump well and pump/meter (not shown)

DRAWING NOT TO SCALE.

Figure 3 Cross section through an infiltration gallery (after Falkland, 1988).

Infiltration galleries are generally constructed by surface excavation, using manual or mechanical methods, and subsequent laying and backfilling of a conduit system. Open trenches have been used in some islands (eg. Bahamas; Christmas Island, Kiribati) but, while these are simple to construct, they are subject to surface pollution (eg. crabs, birds and humans). Buried conduit systems have been installed and are successfully operating on a number of atolls including Kwajalein in the Marshall Islands (Hunt and Peterson, 1980), Diego Garcia in the Indian Ocean (Surface and Lau, 1986) and Tarawa, Kiribati (AGDHC, 1986). On Tarawa, a yield of about 1000 m3/day is obtained from 17 galleries, each 300m long, situated in two freshwater lenses.

An interesting and potentially very economical method of abstracting water from galleries has been trialled in the Bahamas (Golani, 1989). There, some trenches have been connected to inclined pipes allowing freshwater to flow under gravity to a deep sump towards the edge of the lens where a single pump is used to pump the water to supply centres. This method avoids the need for multiple pumping systems, typically one per gallery or trench. Care must be taken with valve or weir settings at each trench to avoid excessive draining of freshwater from the upper surface of the lens, thus causing upconing of seawater and possible local destruction of the lens.

Tunnels are probably the most technically difficult and least common method of groundwater development on islands. They have been used, however, to develop both high-level and basal groundwater bodies on high islands. In the Hawaiian Islands, for example, tunnels or 'Maui-type wells' (Chuck, 1968) have been used for many years for producing large quantities of freshwater from 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 radiate out from the pump room, allowing water from a relatively large area to be abstracted. No new major Maui-type wells have been constructed since the early 1950's (Peterson, 1972) due to cheaper alternative boreholes.

In addition to basal groundwater bodies, perched and dyke-confined aquifers have been developed in the Hawaiian Islands using tunnels. In the case of perched aquifers, tunnelling has been done along the aquifer to collect water or divert it to perched springs. These water sources constitute a relatively small amount of the available high-level groundwater. Larger water volumes are available from the dyke-confined aquifers which are saturated to levels of several hundred metres above sea-level in some cases. Horizontal or inclined tunnels penetrate one or more dyke compartments (Peterson, 1985).

Tunnels have also been constructed at the base of large diameter (2 to 3m) wells or shafts at sea level (eg. Barbados, where they have been excavated up to 60m in length: Goodwin, 1984). Other examples occur on islands outside the humid tropics (eg. Malta and the Canary Islands).

6.4 Desalination

Desalination plants are used on some islands for specific requirements such as the tourist industry. There are few islands, however, where desalination is used as the main source of water. An exception is the U.S. Virgin Islands where over 50 percent of the total requirement in 1980 was met with desalinated water (Coffin and Richardson, 1981). Also, some small islands used solely as tourist resorts utilise desalinated water for nearly all freshwater requirements.

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. For example, a 19 Ml/day MSF plant operates on the island of Aruba in the Netherland Antilles located in the Caribbean Sea (Smith, 1986). VC plants with a combined output of up to 2.6 Ml/day were operating in the Cayman Islands in 1985 (Beswick, 1987). A number of seawater RO plants operate in the U.S. Virgin Islands, Bermuda and Male in the Maldives. Bermuda has an ED plant with a capacity of 2.7 Ml/day (Thomas, 1989).

In addition to the 'high technology' desalination processes, 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 of about 5 Kwh/m^2, yields of about 3 litres/day per m^2 of solar still surface can be expected (Eibling et al, 1971). Howe (1968) provides details of experiments with both transparent plastic and glass covers on a number of islands in the Pacific Ocean. He concluded that, while the stills had some major advantages such as use of readily available energy and the high quality product, there were some significant disadvantages and further equipment development was required. They can, however, be used for emergency purposes as demonstrated by the production of 4 to 7 l/day from simple 'home-made' stills in Tarawa (Harrison, 1980).

In general, desalination is not a recommended option for most islands except where there is sufficient demand and where the users are prepared to pay for the relatively high costs of operating desalination plants. In most cases, 'conventional' methods of obtaining freshwater are preferable.

6.5 Importation

Water importation is used for a number of islands as an emergency measure during severe drought situations. In some cases, importation is used as a sole or supplementary source on a regular basis. Methods of importation include piping via fixed conduit, normally submarine pipeline, or sea transport using tankers or barges.

Hong Kong island receives about 50 percent of its potable water requirements via twin pipelines from the adjacent mainland (Little, 1986). Also, the island of Penang in Malaysia receives some of its water from the Malaysian peninsular via two submarine pipelines (Harun, 1988). Aruba in the Netherlands Antilles has received water imports by tanker from Dominica (Brewster and Buros, 1985) while approximately 30 percent of the total water supply for the island of New Providence in the Bahamas is presently imported by barge from a nearby and larger island, Andros (Swann and Peach, 1989). The island of Nauru in the Pacific Ocean has received most of its water as return cargo in ships used for exporting phosphate (Marjoram, 1983). Some of the smaller Fijian islands have received barged water from the larger islands since the early 1970's during drought periods and the service has become increasingly more routine in recent years.

6.6 Wastewater reuse

Wastewater reuse is generally used for non-potable applications such as sanitary flushing, irrigation and industrial cooling. If wastewater, which includes that discharged in either sewerage or stormwater systems, is adequately treated it can also be used as potable water.

In Singapore, treated stormwater is used to supplement drinking water supplies. 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 percent of the runoff (Bingham, 1985).

6.7 Substitution

In extreme situations, such as severe drought conditions, substitutes for fresh drinking water have been used. The most notable is the juice from coconuts. Populations on some of the smaller and drier islands in Fiji and Kiribati, for instance, have been known to survive on this substitute during drought periods. The coconut tree is remarkably salt tolerant and can produce 'fresh' juice from groundwater bodies which have high salinity levels (eg. chloride concentrations of at least one-third that of seawater: Falkland, 1983).

6.8 Non-potable water systems

Non-potable water sources include sea water, brackish ground water and wastewater. There are many examples of the use of these waters in order to conserve valuable freshwater 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 in the U.S. Virgin Islands (Coffin and Richardson, 1981), the major centres on Tarawa in the Republic of Kiribati (AGDHC, 1986) and the island of Hong Kong (Lerner, 1986). Many islands, particularly the less developed ones in the Pacific Ocean, make use of seawater or brackish well water for bathing and some washing purposes. Seawater is also used for cooling of electric power generation plants, for ice making in air conditioning plants and in swimming pools.

6.9 Potable water enhancement techniques

There are a number of methods which are aimed at increasing natural or conventional supplies. These methods, primarily directed towards increasing recharge to, or storage of, groundwater supplies include artificial recharge, seawater intrusion barriers, ground-water dams and weather modification.

Artificial recharge aims to increase the sustainable yield from aquifers by directing surface water into pits, trenches, boreholes and infiltration basins or storages. Sources of surface water could be natural occurring sources (streams, springs or lakes), storm runoff from impervious surfaces, wastewater and leaking pipelines. Examples of tropical islands where artificial recharge occurs include:

- the island of Hong Kong, where leaking water pipelines are known to contribute to groundwater recharge. This type of recharge, estimated to range from 260 to 3000 mm/year in some parts of the island, compares with an average annual rainfall of about 2000 mm (Lerner, 1986).

- Bermuda in the Caribbean Sea, where recharge in unsewered urbanised areas appears to be about twice that occurring under naturally vegetated areas (Thomson and Foster, 1986).

Subsurface, artificial seawater intrusion barriers can be constructed to impede the outflow of fresh water, or the inflow of seawater, in basal groundwater bodies. The effect is to increase groundwater storage, at least in the short-term, thus increasing the availability of fresh water. On Miyako-jima, an island in the Ryukyu Archipelago of Japan, an experimental subsurface barrier was constructed in 1978 in a small buried valley (Sugio et al, 1987). The barrier aimed to increase yield to irrigation and was designed to be semi-pervious so that seepage could occur and, hence, minimise the concentration of agricultural chemicals in the stored groundwater. The barrier was found to be successful at delaying seawater intrusion into adjacent freshwater aquifers under pumping conditions by at least 2 months.

Groundwater dams have been used to store water in both Africa and India. The only known example on a small island is in the Cape Verde archipelago, which is not actually in the humid tropics (Hanson and Nilsson, 1986). They do, however, have potential application in humid tropical islands.

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

7. Water balance

7.1 General

Islands provide an opportunity to study the full hydrological cycle over a relatively small doma For small islands, it is common for the water balance domain to be the whole island with the boundari being the ocean. For large islands, the water balance of individual catchments or basins is generally greater importance than the whole island.

The water balance for an island can, in many cases, be conveniently considered in two stages: (at the surface and (b) within the groundwater system. The surface water balance has rainfall as an inp and evapotranspiration and recharge to groundwater as outputs. The groundwater balance has rechar as an input and losses to the sea by outflow and dispersion, and abstraction by man, as outputs.

(a) The water balance at the surface depends on whether the island has suitable topographical a geological characteristics to produce surface runoff. The water balance equation at the surface of 'simple' island (eg. coral atoll) can be expressed as:

$$P = ET_a + SR + R \pm dV$$

where

P = precipitation
ET_a = actual evapotranspiration (including interception)
SR = surface runoff
R = recharge to groundwater
dV = change in soil moisture store

Interception is sometimes treated as a separate term in the water balance, but here it has be included with ET_a since the intercepted water eventually is evaporated. On low islands, for examp coral atolls, there is no surface runoff and, hence, the SR term is deleted from the above equation. (coral atolls the main interest is recharge (R) which is the input term to the second water balan equation dealing with the groundwater system. The water balance equation at the surface ('rechar model') can be simplified and rearranged to:

$$R = P - ET_a \pm dV$$

Figure 4 is one attempt to describe the water balance processes involved for a typical coral atoll.

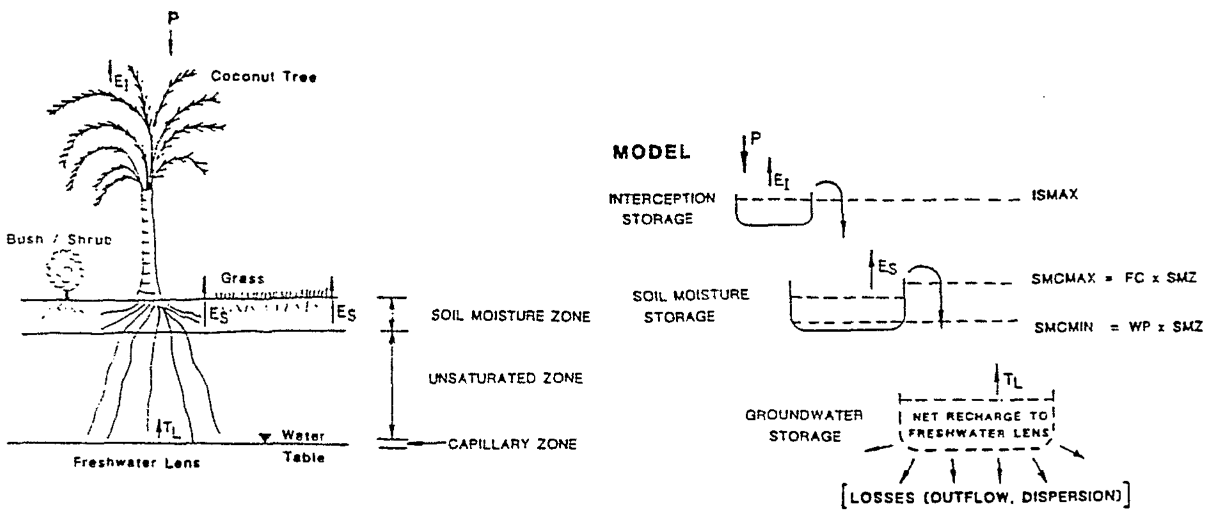


Figure 4 Recharge model for a typical coral atoll

As shown in Figure 4, actual evapotranspiration (ET_a) is comprised of interception losses (E_I) evaporation and transpiration from the soil zone (E_S), and transpiration of deep rooted vegetation directly from groundwater (T_L). The first two terms can be treated as losses from storages which have upper and lower limits. Rainfall is first used to fill up the interception store with any residual going to the soil moisture store. If this is also filled the residual becomes gross recharge. A further loss (T_L), is incurred before net recharge to groundwater is obtained. Typically, depth to water table is only one to two metres and the roots of deep rooted vegetation, such as coconut trees, can penetrate to the water table. Thus, coconut trees can act as phreatophytes and draw water directly from the water table. This helps to explain why on some drier atolls coconut trees can survive extensive droughts while shallow rooted vegetation, which draws its moisture from the soil zone, dies off.

The water balance procedure is more complex on raised atolls, which often have large depths from surface level to water table (typically 30 to 100m high) and extensive karstic formations. Unlike coral (low) atolls which usually have a thin soil layer of about 0.3 to 0.5m thick above a highly permeable unsaturated zone, typically one to two metres thick, raised atolls may have variable thickness soil layers. In places the soil layer is non-existent while in other places it can be metres thick. Roots of trees may penetrate through fissures and reach pockets of water at different levels. In addition the flow paths from the surface to the water table may not be essentially vertical as with the low atoll, but rather have major horizontal components due to karstic formations (solution channels). The situation is even further complicated in mixed type islands where the interface between limestone and underlying volcanic rock is either totally or partially above sea level. In these cases, the groundwater flow pattern is often characterised by subterranean streams at the interface, which in some parts of the island emanate as springs either above or below sea level. No general model is, therefore, possible for islands of this type and each island needs to be considered on a site-specific basis. The same comment generally applies to high volcanic islands because of their complex hydrogeological structure.

The water balance at the surface should be modelled with a time step not exceeding one day because the turnover time in the soil zone is measurable on the time scale of a day (Chapman, 1985). The use of mean monthly rather than daily data will underestimate recharge. Two atoll studies (Kwajalein: Hunt and Peterson, 1980; Cocos (Keeling) Islands: Falkland, 1988) have shown that the assessed recharge is decreased by between 6% and 10% of rainfall if monthly rather than daily data is used.

(b) The water balance for the basal groundwater system on a 'simple' small island (eg. freshwater lens on a coral atoll) can be expressed as:

$$R = GF + D + Q \pm dS$$

where

R	=	recharge to groundwater
GF	=	groundwater outflow (to the sea)
D	=	dispersion at the base of the groundwater body
Q	=	abstraction (normally by pumping)
dS	=	change in freshwater zone storage

In the above equation, the value of R has been estimated from the surface water balance. Due to a longer turnover time, a time step of a month for the groundwater system balance is suitable. Often the turnover time of the fresh groundwater on a small island is a number of years. Even for a relatively small freshwater lens 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. The equation must be modified to allow for storage in these upper aquifers in addition to storage in the lower aquifer. Obviously, the D term is only applicable in cases where a freshwater-saltwater mixing zone occurs.

The solution of the above equation has been attempted for freshwater lenses on some islands b both 'sharp interface' and 'dispersion' models. The relevant flow (and in the case of dispersion model: salt transport) equations are solved by numerical methods, expressed in either finite difference or finit element form, on a computer. Dispersion models are inherently more complex and require addition: parameters to be evaluated or estimated than sharp interface models. They are conceptually more suite to small island groundwater modelling than sharp interface models which assume that the Ghyber Herzberg theory applies, an assumption which is not correct in small islands. However, the use of sharp interface model can give some qualitative idea of the response of a freshwater lens which i subjected to selected (historical or simulated) natural stresses (droughts of varying lengths and severity and artificial stresses (different pumping strategies). They can, therefore, provide in many cases a initial indication of the most important aspects to be modelled in more detail by a dispersion model. / sharp interface model has been developed for Bermuda, which is reported to work successfull (Thomson, 1985; UNDTCD, 1989). To model the freshwater zone, a modified Ghyben-Herzberg rati was selected based on observations of the ratio of the water table above mean sea level to the depth t the limit of freshwater, as defined by some objective criterion. This approach, also used in some othe studies, has theoretical problems since the ratio should depend only on the densities of freshwater an seawater (Chapman, 1985).

To properly model the freshwater and transition zone behaviour on a small island, a dispersio model should be used. This does require a much larger effort in terms of data collection and computin resources than for a sharp interface. While sharp interface models can be easily run on micrc computers, dispersion models require much larger and faster computers to achieve reasonable run-time: One dispersion model, SUTRA (Voss, 1984), has been applied to the study of a number of islan freshwater lenses including Oahu in the Hawaiian Islands (Voss and Souza, 1987), Enewetak in th Marshall Islands (Oberdorfer and Buddemeier, 1988) and Nauru (Ghassemi et al, 1989).

One of the major requirements with the groundwater balance at present is a simpler ye theoretically correct method of describing the behaviour of freshwater lenses on small islands. Preser methods are either theoretically inadequate and need to be 'forced' to give reasonable answers or the are too complex and beyond the resources of most organisations, particularly water resources agencie on islands.

The measurement or estimation of terms in the water balance equations are now considered.

7.2 Precipitation

On islands in the humid tropics, especially small islands, precipitation is usually synonymous witl rainfall as other forms of precipitation (eg. ice, snow) are generally negligible. Hence, the term rainfa' will be used to describe total precipitation.

The controlling mechanisms for rainfall, and climate in general, in the humid tropics have bee described for this Colloquium by Manton (1989). Hence, no detailed discussion is presented here. I general terms, the rainfall patterns which influence islands in the humid tropics vary considerabl between locations. For instance, the annual rainfall pattern for the Pacific Ocean, as shown in Figure 5 indicates considerable spatial variability.

The annual rainfall pattern for the Indian Ocean, as indicated in Figure 6, also show: considerable spatial variability. Both patterns are highly interpolated owing to the limited number o data sets from island meteorological stations used in their construction. Also, the patterns do not take account of considerable variation in the rainfall on some high islands as a result of orographic effects Most raingauges are situated around the rim of high islands and thus fail to record the very high rainfall: that occur in the peaks or highlands. Where measurements have been taken in the higher altitudes annual rainfall depths exceeding 10m have been recorded. Yet, official rainfall records may show typica values of 2-3m for an island. This problem is often one of logistics: it is difficult and costly to operate anc maintain networks of raingauges in the high and often inaccessible parts of some islands. The advent o relatively cheap and robust electronic data logging equipment should gradually ease this problem. I linked to satellite telemetry (eg. ARGOS), data aquisition and monitoring from remote sites can become easier. Some islands are evaluating the use of satellite for data transfer from their hydrometric networks (eg. Solomon islands).

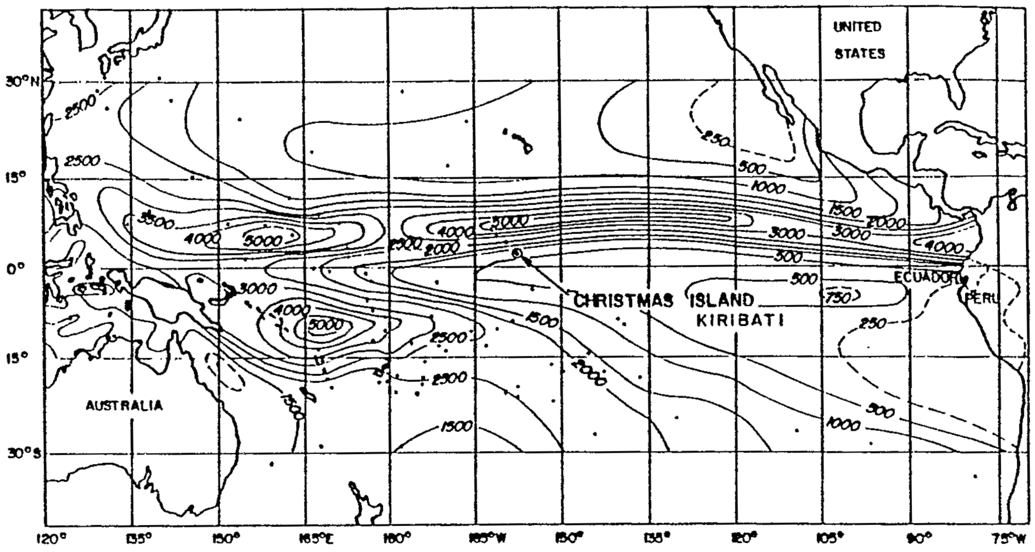


Figure 5 Annual rainfall pattern for the Pacific Ocean (modified from Taylor, 1973).

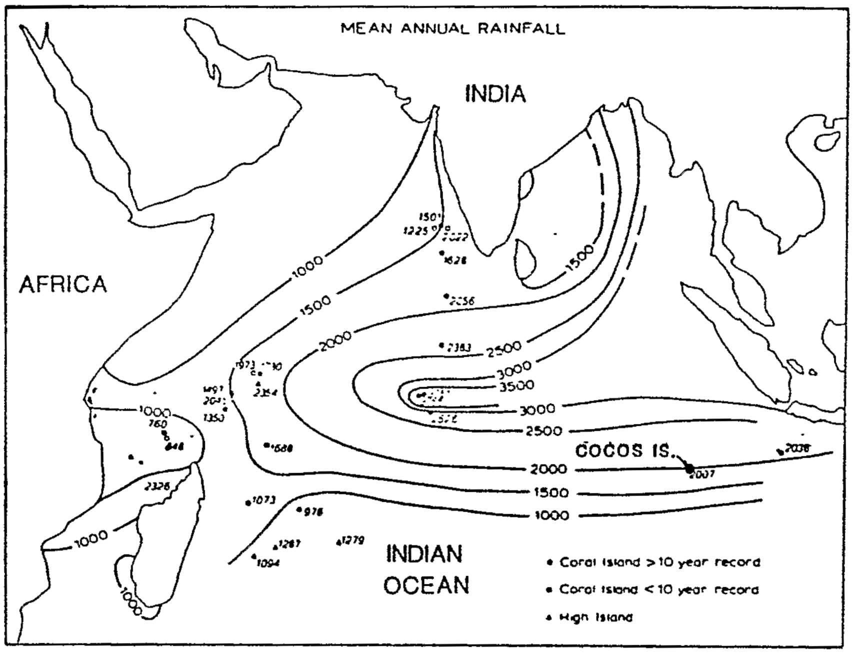


Figure 6 Annual rainfall pattern for the Indian Ocean (modified from Stoddart, 1971).

Some islands within the tropics are greatly influenced by summer monsoons and have distinct wet and dry seasons and may need to contend with seasonal fluctuations in their water resources. Extensive dry seasons can and do become critical for surface water resources with streams and springs reducing to little or zero flow. Extreme variability in rainfall for particular months from year to year is another phenomenon affecting many islands (eg. parts of New Caledonia: Brunel, 1981).

Islands are also influenced to different degrees by longer time scale mechanisms such as the El Nino Southern Oscillation (ENSO) phenomenon. The influence of ENSO on island rainfall patterns on islands in the central and eastern Pacific is very marked, as shown for an example of one island in Figure 7.

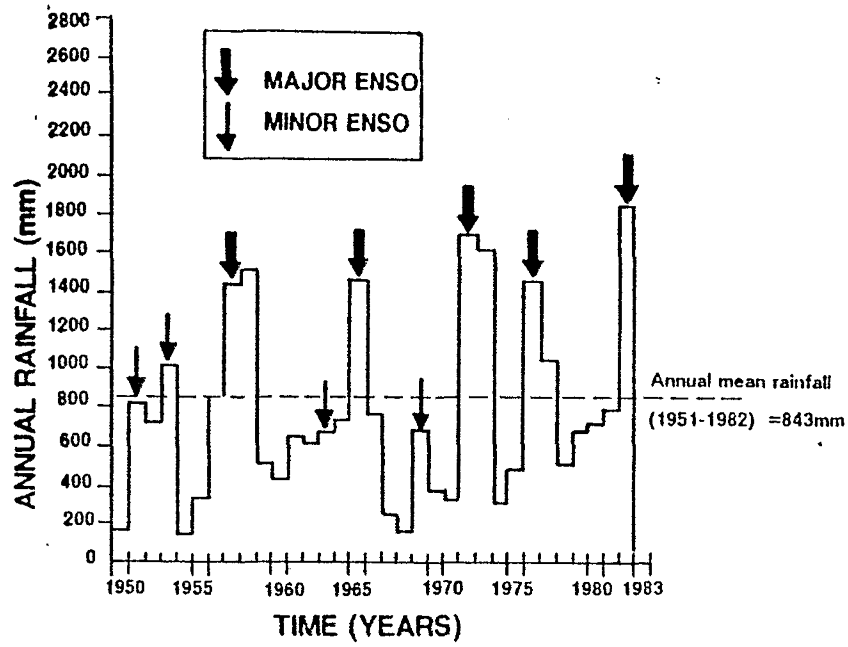


Figure 7 Effect of ENSO on annual rainfall, Christmas Island, Kiribati (after Falkland. 1983).

ENSO and anti-ENSO (also referred to as La Nina) events can produce very wet and very dry cycles to be superimposed on the normal annual cycle and, hence, exacerbate wet periods and droughts. On some islands, periods of up to 6 months may elapse before significant rainfall occurs. This was particularly evident during the major 1982-1983 ENSO event. For instance, during the first 6 months of 1983 the rainfalls on Saipan and Guam in the Pacific were less than 30% of the long-term mean. Similarly, in the first 5 months of the same year, the rainfalls on a number of islands in Micronesia was only 13% of the long-term mean (van der Brug, 1983).

In addition, the climates of many islands are influenced by random cyclonic events. Cyclones are a major problem to small islands, often causing major wind damage, large floods, massive hillside erosion and consequent sedimentation problems downstream. They have also been responsible for storm surges which have inundated low lying areas and, indeed, whole islands (eg. Funafuti in Tuvalu and some islands in the Marshall Islands and Tokelau) with seawater. Apart from any direct damage, the impact on freshwater lenses is extreme because they receive considerable input of seawater. Many months may be required to naturally flush the saltwater from freshwater lenses and restore them to a potable condition.

On low flat islands (eg. atolls), orographic effects are negligible, but there are sometimes observed variations from one side of an atoll to another. The exact reason for this is not known but may in some cases have been due to observational errors or poor siting of gauges. It is not possible to determine the exact reasons in some cases due to sites having been abandoned and subsequently changed.

While the network of rainfall gauges over the whole area of the oceans in which humid tropical islands occur is limited by the number of islands, there is a need to improve the networks on many high islands to better understand island rainfall gradients from sea level to peaks. Further studies should take advantage of technological advances to improve the access to and reliability of the data.

7.3 Evapotranspiration

The combined process of evaporation and transpiration, often referred to as evapotranspiratioı is one of the most important components of the hydrological cycle and the water balance equation. O small islands, evapotranspiration can be more than half of the rainfall on an annual basis and ofte exceeds the rainfall for individual months or consecutive months during dry seasons or drought period Despite its importance, evapotranspiration is probably the least quantified component of the wate balance on small islands. This has been emphasised in the background paper for this Colloquium by on of the authors (Brunel, 1989).

The estimation of actual evapotranspiration (ET_a) from catchments has generally been done fc small islands by a two stage process: estimation of potential evapotranspiration (ET_p) and the estimation of ET_a from ET_p using a water balance procedure. These stages are described below.

Firstly, ET_p is estimated using a method based on climatic data, such as the Penman (c Combination) formula, or from pan evaporation data multiplied by an appropriate pan coefficient. Th Penman equation has been found to be generally a good ET_p estimation method in the humid tropics, a indicated in a number of papers at this Colloquium (eg. Chang, 1989). This equation has been used t estimate ET_p on a number of small islands. For instance, Fleming (1987) used the Penman equation fc estimating ET_p for Tarawa, Kiribati. In the humid tropics, the net radiation energy term dominates th aerodynamic term in the Penman equation and it has been found that the simplified Priestly-Taylc method is adequate (where ET_p is equated to 1.26 times the energy term from the Penman equation This method was used by Nullet (1987) and Giambelluca et al (1988) to estimate ET_p on a number c tropical Pacific islands. Figure 8 shows the results of the earlier study for Pacific island atolls.

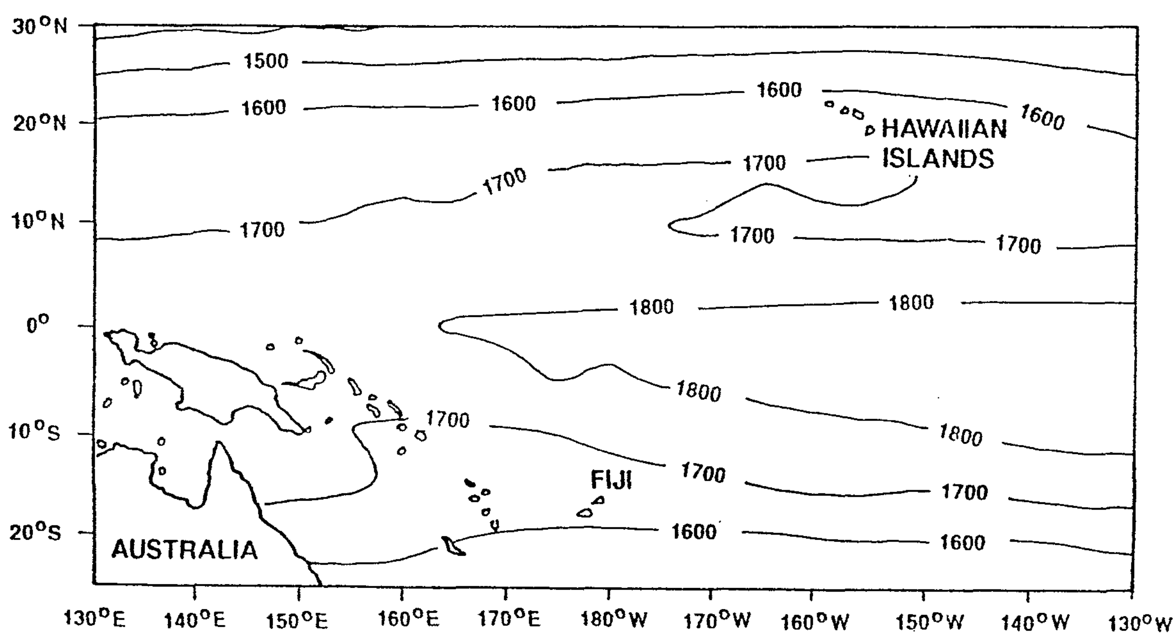


Figure 8 Isolines of annual potential evapotranspiration over atoll vegetated areas in th Pacific Ocean (after Nullet, 1987).

Secondly, actual evapotranspiration is usually determined via a water balance procedure takin into account the soil and vegetation conditions present on the island. An example for a coral atoll wa indicated in Figure 4. The components of actual evapotranspiration are direct evaporation from surface and transpiration by vegetation. Water which is intercepted by vegetation can be included in the mode The usual procedure is to subtract the volume of intercepted water from the evaporation demand an use the reduced demand as the effective value for calculating the transpiration (Chapman, 1985). Interception should be included as a component in the overall water balance. Failure to include it can lead to underestimation of ET_a and overestimation of recharge (eg. for Cocos (Keeling) Islands the difference in recharge for cases of interception stores of 3mm and zero was 5%). Problems with the water balance may occur because parameters such as depth of soil moisture store, field capacity and wilting point are not well established for tropical island soil/vegetation associations. Further problems with spatial variation arise in complex geological conditions with variable depths and types of soil. Also, with regard to vegetation on tropical islands, there is little hard data on crop coefficients which can be applied to account for the effect of different types of vegetation on the evaporation demand. Thus, estimates based on similar vegetation from other regions have been applied. For example, crop coefficients of 1.0 and 0.8 were used to adjust ET_p for shallow rooted vegetation and coconut trees, respectively, for some Pacific island water balance studies (AGDHC, 1982; Falkland, 1988). There is a need, therefore, for further basic research on typical soil and vegetation types on tropical islands.

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 (all used by ORSTOM at two sites in New Caledonia: Brunel, 1989). Other direct measurement methods such as the eddy correlation method could also be used.

Direct measurements of transpiration from coconut trees have added to the knowledge of the evapotranspiration process on small islands in the humid tropics. Transpiration from coconut trees, as measured in the Cocos (Keeling) Islands using a Heat Pulse Velocity Meter during a one-week study (Bartle, 1987), was 70-130 litres/day. Based on this limited data, the total transpiration rate due to coconut trees is about 400-750 mm/year per tree in areas with 100% tree cover, where the tree spacing is about 8m. This has implications for water supply management and it may be prudent to selectively clear coconut trees from some freshwater lens areas to maximise the supply of water.

In general, there is insufficient data available on ET_a from typical small islands. While micrometeorological techniques are available and have been used with success in a number of continental countries to study this basic process, there is yet to be a co-ordinated study for small islands, despite their very fragile freshwater resources. It is, therefore, recommended that emphasis be placed on more detailed investigations of the actual evapotranspiration process. Existing approaches for the estimation of evapotranspiration should be re-evaluated in the light of such investigations. As outlined by Brunel (1989), the study of ET_a for islands could be attempted by a two stage process. Firstly, a database of typical soil/vegetation/sub-climate associations, including relevant hydrological parameters, should be made for islands of the humid tropics and, secondly, measurements of ET_a should be made at selected sites to develop relationships between ET_a and typical associations. Some associations worth detailed study are coconut tree/coral sand and open grass/coral sand in the drier parts of the humid tropics where soil water deficit is prevalent in dry periods. The use of remote sensing techniques (eg. 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. As the spatial scale on many small islands is not large, the problem of spatial extrapolation to an island scale is not as great a problem as on continents, except where large diversity of soils and vegetation occur.

7.4 Surface Runoff

Surface runoff, as already described, only occurs on high islands with favourable topographical and geological conditions. Such islands are generally characterised by many small sized catchments with steep slopes in which runoff occurs very rapidly. As a result flash floods can occur. Also, due to the erosive power of the streams, erosion and sedimentation problems are prevalent. Soil and vegetation loss, high turbidity problems in streams and damage to water intake and other on-stream structures have occurred on a number of islands.

Stream gauging stations need to be robust and the equipment needs to be well tested in tropical environments. Electronic data logging devices offer some distinct advantages over the more conventional mechanical chart recorders: there are no moving parts, data does not require digitising, thus saving costs and the data can be retrieved by a variety of methods including telemetry systems (notably radio or satellite). The major disadvantage with electronic data logging systems appears to be a reluctance on the part of field staff to deal with data aquisition systems where the recording is not immediately visible (except via a portable computer). This problem is not unique to the tropics and is only solved by proper training and education of field staff to improve their confidence and ability in the use of the equipment.

The aquisition of data from remote sites via satellite telemetry should be encouraged. While this may appear to be a 'high tech' solution for small islands it has considerable advantages, as data can be regularly recovered and processed at a base station, thus saving time and costs. Site visits for maintenance can be restructured to some extent to respond to known problems at stations, rather than being done solely on a periodic basis. Of course, telemetry has an additional and even more important part to play when 'real time' information is required for flood warning or forecasting. It should be remembered that there is widespread acceptance of telecommunications via satellite systems, even from small islands. The use of satellites for data collection should, therefore, not be viewed as unusual. Unfortunately, this problem is fundamental in the thinking of some organisations and governments because of the low priority given to water resources assessment programmes.

Problems in obtaining surface runoff measurements on small islands in the humid tropics have largely been covered in the paper dealing with operational hydrology for this Colloquium (Manley and Askew, 1989) and there is no need to reiterate them here.

The question of minimum networks for small tropical islands is an important one for streamflow, rainfall and evaporation stations. Hall (1983) outlines minimum densities as given by WMO (1981): streamflow (1 per 140-300 km2), rainfall (1 per 25 km2) and evaporation (1 per 50,000 km2). However these are guides only and individual island size, topography and morphology need to be taken into account in applying them. For instance, some high islands are very much less than 140 km2 and may require not only one but more than one streamflow station to characterise the runoff of the island. This is particularly relevant on islands which have multiple small catchments with varying geological, soil and vegetation characteristics. As with many other aspects of hydrology in small islands, generalisations are not possible and each island or, at least group of similar islands should be assessed on its own merits.

In dealing with hydrological data (including streamflow, rainfall and other data), it is necessary to consider data processing, archiving and reporting as well as data collection activities. The widespread use of micro-computers in recent years has resulted in the development and use of some high quality, 'user friendly' packages for these tasks. Some examples are HYDROM (ORSTOM, France), HYDATA (Institute of Hydrology, UK), Micro-TIDEDA (New Zealand) and HYDSYS (Australia). With an amount of training matched to the computer literacy of the user(s), packages of this nature offer considerable flexibility and power to process and analyse data. There is good justification for the increased use of such packages for small island hydrology (as well as mainland hydrology) both within and outside the humid tropics. Some small islands have insufficient personnel trained in the use of computers but this problem can also be solved with appropriate training.

7.5 Recharge

The results of water balance studies on some small islands indicate the large influence of vegetation type and density on recharge to groundwater. This is confirmed by preliminary volumetric comparisons of freshwater zones beneath parts of atoll islands supporting different vegetation types. For instance on West Island in the Cocos (Keeling) Islands, observations of salinity profiles showed that the freshwater zone below an area supporting dense coconut trees had less volume and showed greater seasonal fluctuations than below an area supporting only grass. The width of the island and the permeability of sediments at different depths at both locations were similar, thus indicating the controlling factor was the variation in ETa between coconut trees and grass. The results of a water balance study indicated that the ETa, and hence the recharge, varied according to the density of deep rooted trees over an a freshwater lens area. The relationship between recharge and the percentage area covered with coconut trees derived from water balance studies on Cocos (Keeling) Island is shown in Figure 9.

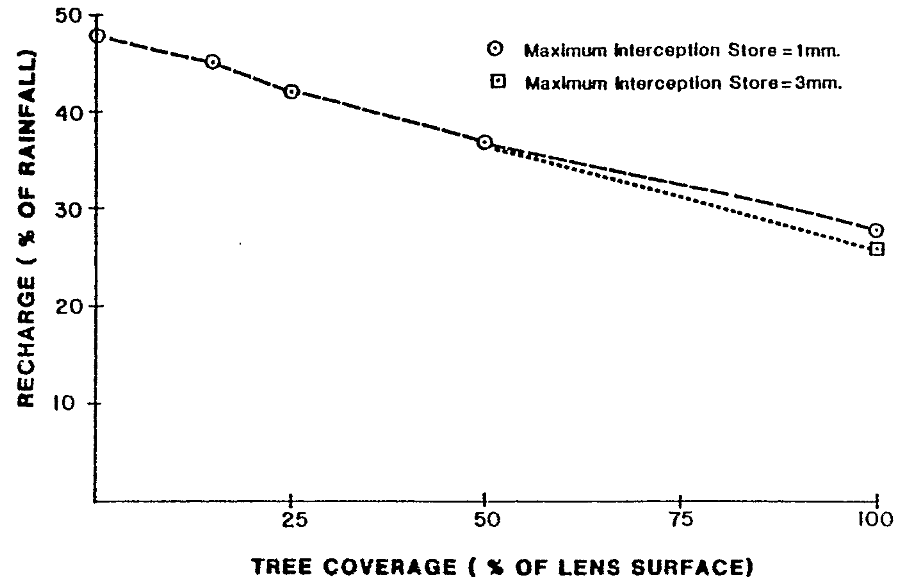
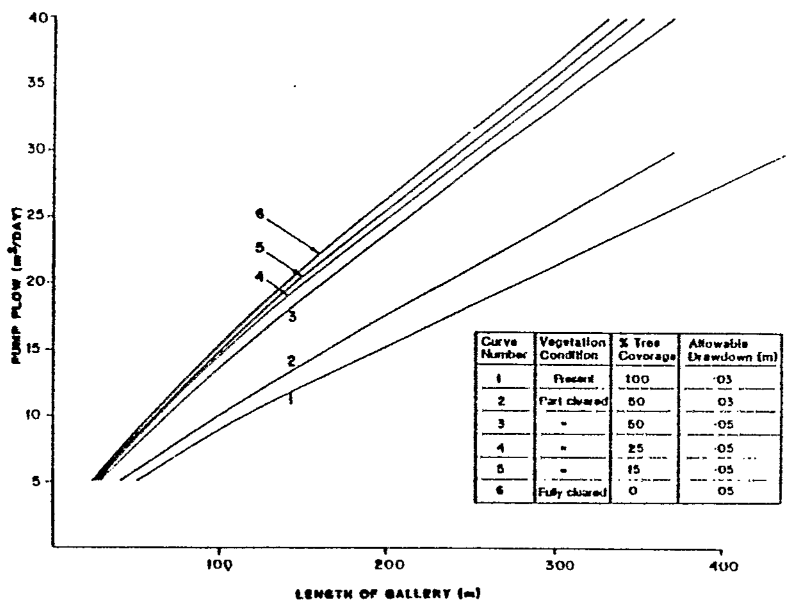


Figure 9 Recharge versus coconut tree coverage, Cocos (Keeling) Islands (after Falkland, 1988).

Vegetation can have a direct effect on the design of abstraction facilities on small coral islands. Since deep rooted vegetation effectively competes with abstraction by pumping for the limited freshwater resource under a small island, infiltration gallery lengths for a given pump flow rate need to be longer in areas where coconut trees are dense than where they are sparse or non-existent. This is shown in Figure 10.



Curve Number	Vegetation Condition	% Tree Coverage	Allowable Drawdown (m)
1	Recent	100	·03
2	Part cleared	60	03
3	"	60	·05
4	"	25	·05
5	"	15	·05
6	Fully cleared	0	05

Figure 10 Pump flow rate versus infiltration gallery length for different vegetation coverage, Northern lens, West Island, Cocos (Keeling) Islands (after Falkland, 1988).

In the absence of data on ET_a, recharge to groundwater can be approximated for small low islands from results of water balance studies on other islands. Figure 11 summarises annual rainfall versus annual recharge data derived from a selection of small islands. Once again, the effect of vegetation cover can be seen from the range of estimates of recharge for two islands with varying coverage of coconut trees. Also, a preliminary assessment of recharge can be made from the ratio of chloride ion in rainwater to that in shallow groundwater (Vacher and Ayers, 1980). Care must, however be exercised with this method to avoid erroneous results (Daniell,1983; Chapman, 1985).

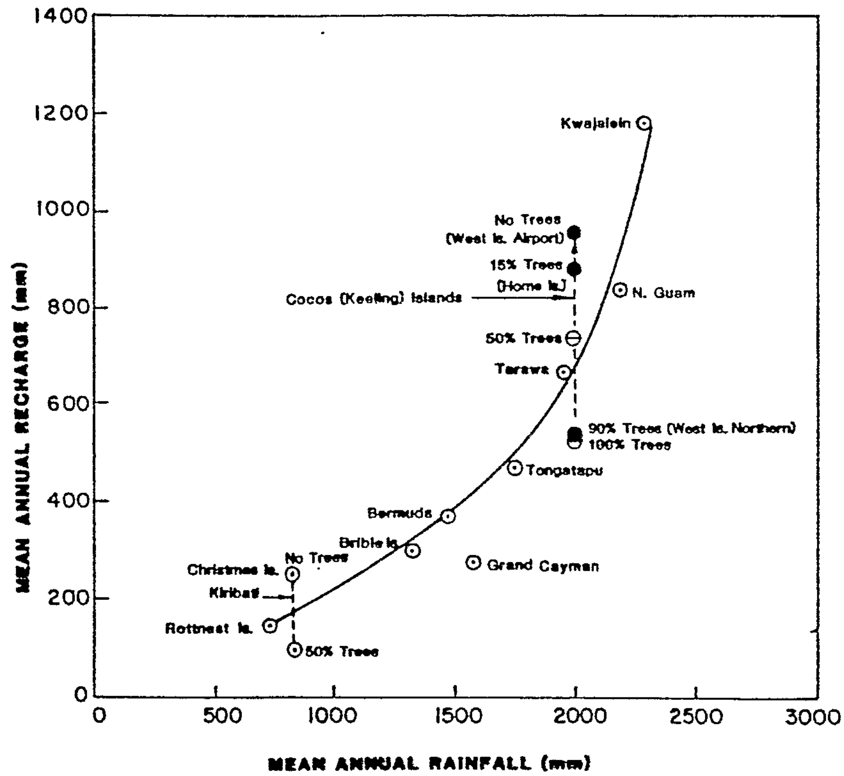


Figure 11 Annual rainfall versus annual recharge for some low islands (after Falkland, 1988 modified from Chapman, 1985).

7.6 Groundwater

One of the main problems on many small islands is the lack of accurate knowledge of the extent and sustainable yield of freshwater lenses. Some detailed studies (eg. Kwajalein, Marshall Islands: Hunt and Peterson, 1980; Tarawa, Kiribati: AGDHC, 1982; Christmas Island, Kiribati: Falkland, 1983; Diego Garcia, Chagos Archipelago: Surface and Lau, 1986; Majuro, Marshall Islands: Hamlin and Anthony, 1987; South Keeling, Cocos (Keeling) Islands: Falkland, 1988) have identified the usefulness of drilling or driving observation holes and obtaining vertical salinity profiles from water table through to seawater. The installation of simple monitoring systems inside these holes enable valuable post-drilling salinity profiles to be obtained. Single open boreholes, sometimes used for salinity monitoring, are not suitable as misleading results due to the mixing of freshwater and seawater in the borehole are likely to occur. This topic has been reported from studies on mainland aquifers (eg. Rushton, 1980; Kohout, 1980) and is just as relevant in small islands. Suitable monitoring systems are multiple open boreholes terminated at different depths (eg. Kwajalein, Majuro), or tubes within a single bore terminated at different depths and hydraulically separated by means of bentonite plugs (eg. Tarawa and Christmas Island in Kiribati, Diego Garcia, Cocos (Keeling) Islands). A limited number of islands now have close to a decade of salinity profile data which can be used to observe freshwater lens response to natural and artificial (pumping) stresses and to test and calibrate groundwater models. An example of this data is shown in Figure 12.

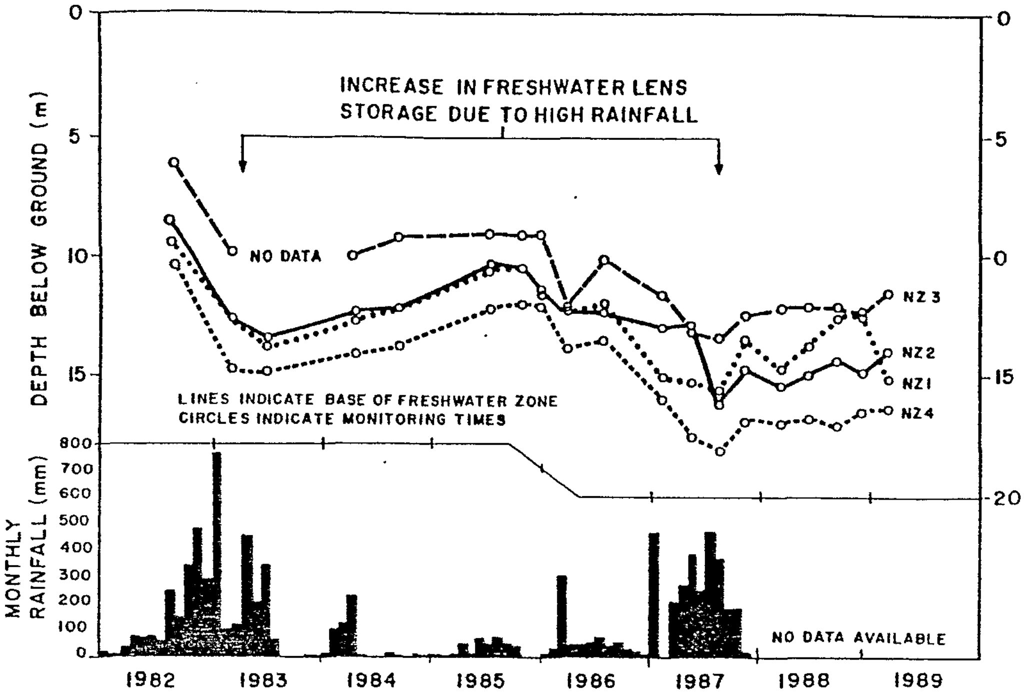


Figure 12 Borehole and rainfall data, New Zealand Airfield lens, Christmas Island, Kiribati (after Falkland, 1989).

Because of the fragile nature of freshwater lenses and the consequent acute requirement for effective monitoring systems, existing methods for obtaining salinity profiles should be critically reviewed with a view to recommending a suitable and economical method for use on small islands. This could possibly be included in the Hydrological Operational Multipurpose Subprogramme (HOMS) of the World Meteorological Organisation.

Geophysical methods are well suited to low islands with relatively small depths from surface to water table. Both electrical resistivity (ER) and electromagnetic (EM) methods have been successfully applied in a number of island studies in determining freshwater lens thickness. ER surveys, in particular, are well suited to coral atolls (Dale, 1986) and have been used on a number of atolls (eg. Falkland, 1983; van Putten, 1988). Careful site selection is required to avoid buried objects such as pipes and cables as these can give misleading readings. Also, it is necessary to ensure soundings are parallel to the coastline, particularly near the edge of a lens, to minimise violation of the horizontal layering principle on which the ER method is based (Mooney, 1980). Stewart (1988) has outlined the use of EM surveys on small islands. An EM survey is known to have been used on at least one atoll (Majuro: Kauahikaua, 1987). With both ER and EM surveys, it is necessary to provide some means of independent assessment at selected locations to prevent erroneous interpretation of geophysical results. The use of geophysics is, however, recommended for preliminary reconnaissance of freshwater resources on small islands, particularly low coral islands. The application of geophysics becomes less useful in high islands, particularly where complex geological structures are present.

Measurement of the water level fluctuations at the top of freshwater lenses (water table) cannot be used to determine freshwater zone thickness because there is no direct relationship between the height of the water table above mean sea level and the freshwater zone thickness (Ghyben-Herzberg theory does not apply). This fact has not always been realised and some incorrect assessments of freshwater storage volume have been made in the past based on water level measurements alone. These measurements are, however, useful for monitoring the drawdown effects of pumping and setting design levels for infiltration gallery and other abstraction facilities.

Although some islands have been studied in detail, there appears to be a gap in the transfer of this knowledge to other island situations. The advantages and limitations of the various groundwater investigation and monitoring techniques should be well understood by field workers assigned to assess the groundwater resources on small islands. Where major abstraction works have been built or are being designed, resources should be provided to establish proper monitoring systems, particularly properly constructed monitoring boreholes for obtaining vertical salinity profiles. This normally requires the use of a drilling rig and an experienced drilling crew. It is essential that adequate supplies and spare parts be provided for successful drilling operations, as most small islands are located well away from supply sources in both space and time.

Moreover, there is a need for the development of simple yet accurate methods of determining sustainable yield from freshwater lenses, as mentioned earlier. In the absence of detailed computer modelling for a particular island, approximate assessments of sustainable yield can be made from other studies. Based on a number of different approaches, sustainable yields of between 20% to 30% of recharge have been estimated for a number of small low lying coral islands. It is considered that, as a first approximation, a value of 25% of recharge is considered reasonable. Using the range of percentage recharge values (approx. 25-50% of rainfall), sustainable yields of 6-12% of annual rainfall are derived. Actual vegetation conditions should, however, be allowed for in the derivation of estimates for a given atoll. Higher sustainable yields than shown here may be appropriate in some islands, especially where the behaviour of lenses under drought and pumping conditions have been obtained and thoroughly studied.

The estimation of sustainable yield of an individual gallery system in a freshwater lens on small coral islands is another interesting and real problem. A number of approaches have been used for the design of gallery systems (eg. Hunt and Peterson, 1980; AGDHC, 1982; Mink, 1986; Hamlin and Anthony, 1987; Falkland, 1988). However, it is apparent that further theoretical and practical research in this area is warranted. This is particularly important given the need for simple yet effective methods for the design of gallery systems on small islands in the Pacific region as part of the current UNDTCD project operating from Fiji. At the recent UNDTCD seminar on water resources management strategies in Fiji, this matter was raised and it was recommended that further studies be initiated to develop a consistent approach for future water resource development of this nature. In the meantime, it is essential that monitoring of the behaviour of freshwater lenses using salinity profiles from properly constructed monitoring systems be continued or commenced. This will enable the response of lenses under abstraction conditions to be analysed and calibration and testing of computer models to be undertaken.

Another potential problem with freshwater lenses is rising sea level associated with the 'Greenhouse Effect'. Some scenarios have been analysed using a dispersion type model for a typical small coral island by Oberdorfer and Buddemeier (1988). If the rise of sea level does not result in seawater encroachment onto the land, freshwater lens volume can actually increase because the whole lens would not only rise at the surface to the same degree but the base would tend to move into the upper and lower permeability sediments, thus slowing the freshwater outflow rate. The major issue, therefore, is whether the water level rise will lead to loss of available land. This is dependent on the magnitude of sea level rise, an unanswered question at this stage. It is imperative that present sea level monitoring programs for small islands be encouraged and expanded.

8. Issues/problems in water resources development and management

8.1 General

The range of issues and problems related to island water resources development and management are many and varied, and are too numerous to cover in this paper. Hence, only a selection of the range of problems will be identified.

A major problem is the conflict between alternative uses for the available water resources Decisions are often required about the priorities of allocating water to various users, including th domestic, industrial, tourist, agricultural and energy sectors. In practice, these problems need to b resolved based on local economic, social and political factors. The only generalisation that can be mad is the need to satisfy the most basic requirement, that of minimum domestic water supplies, as a firs priority.

8.2 Water sources

These problems largely stem from a lack of expertise, knowledge or funds, or a combination o these factors. Often the available water resources have not been defined. This is a water resourc assessment problem requiring expert assistance to resolve it. Most commonly, sufficient local expertis and funds are not available to assess and develop water sources and external assistance must be sought.

In some situations, all local and 'conventional' water sources have been fully exploited, and othe methods such as desalination or importation are required to meet demands on either a temporary o permanent basis.

Temporary problems can arise as a result of several factors including drought, which can last fo many months, or seasonally high water demands associated with the influx of large numbers of tourists.

More permanent problems have arisen, and are emerging, on some of the smaller islands particularly atolls, with high population densities, for example Male in the Maldives. There the problen is so severe that consumption of water exceeds recharge from rainfall (Edworthy, 1984). A number o options to increase the availability of freshwater have been implemented including the installation of desalination unit.

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

Major salt water intrusion caused by the construction of waterways and boat marinas has cause the loss of freshwater lens areas in some islands (eg. Bahamas: Hadwen and Cant, 1980).

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

There are many examples of failures with desalination techniques in islands, normally indicate by production rates being far below specification. Careful selection of source water and design o appropriate pre-treatment facilities are particularly important.

8.3 Water supply distribution systems

Many problems are evident including:

- large distances to walk to sources where no communal distribution is available.
- piped systems often suffer from major leaks due to cracks, holes, poor joints and othe defects. Many water supply systems in small islands are old and in need of majo rehabilitation. Losses as high as 80% of supply have been determined in some islan water supply systems.
- where water deliveries are made, road tankers are often poorly maintained an consequently suffer from breakdowns resulting in disruptions to water supply services.

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

8.4 Water quality

Rainwater systems often suffer from water quality problems due to inferior roofing materials (eg coconut leaf thatch can lead to taste and odour problems) or inadequate filtration catchment surfaces (leading to bacteriological pollution). It is necessary that adequate roofing materials be used and, where seasonal patterns prevail, that simple systems to divert the 'first foul flush' away from storage tank(s) be used.

The quality of surface waters is often affected by heavy sediment loads and turbidity levels particularly in rivers and lakes following high intensity rainfall. This naturally occurring problem is made worse by man's activity, such as uncontrolled land clearing for agriculture causing additional sediment loads to be transported into river systems. High sediment loads cause problems such as the blockage of river or lake intakes for water supply. High turbidity levels, caused by colloidal suspensions (very fine clay particles) and often associated with high sediment loads, make water treatment more costly. These problems occur on many small 'high' islands.

Surface water quality is often affected by other pollutants such as petroleum products and general urban litter. Surface waters are particularly susceptible to pollution from toxic or other chemical spills. Concern has been expressed about the presence of timber treatment industries on some islands which use copper-chromium arsenates for preserving. A spillage involving such chemicals has occurred in a small river in the Solomon Islands leading to fish kills (Mowbray, 1984).

Groundwater quality problems include the following:

- increased salinity due to overpumping of fresh water lenses causing seawater intrusion. There are many examples of concentrated overpumping from wells, boreholes and infiltration galleries. In other cases, the problem is far more widespread and severe and is caused by general over-abstraction from many different systems.

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

- pollution from solid waste disposal areas.

- leakage of fuels from pipelines and storage tanks.

- chemical pollution associated with the return water from irrigation which may contain dissolved salts from fertilisers and residues of pesticides, insecticides and herbicides.

The fresh groundwater resources of coral atolls and low-lying limestone islands are, in general particularly susceptible to pollution owing to relatively thin and highly permeable (often greater than 100 m/day) unsaturated soil zones. As a result, normally accepted minimum distances (WHO has often mentioned 30m) from sewage disposal units (eg. pit latrines) to groundwater abstraction points are often inadequate to prevent contamination. To overcome this problem, each situation should be assessed on its own merits giving due regard to the groundwater flow direction. On very small islands, this will generally mean that sewage disposal units should be sited close to the beach and water should be abstracted from the middle of the island.

In some cases, groundwater or surface water sources may be unpolluted yet the water supplied to consumers may be polluted. This is due to contamination occurring in distribution systems which can be caused by:

- ingress of polluted groundwater through, faulty joints or defective pipes at times when the pipeline is not pressurised,
- cross connections between potable and non-potable water distribution systems,
- contaminated tools, fittings or operators during operation and maintenance activities,
- physical deterioration (eg. rust) of the internal lining of pipes leading to discoloured water.

8.5 Water legislation

Legislation dealing with water resources and supply systems in small islands varies from being almost non-existent to very complex. In the latter case, the legislation can be out-dated, redundant ambiguous or difficult to enforce. Many problems have arisen due to non-recognition of the problem of having no or inadequate legislation, difficulties in enacting new legislation and/or difficulties in enforcing existing legislation. Specific problem areas are inadequate control of quantities abstracted from wells or boreholes, inadequate protection of groundwater quality and inadequate control of the misuse or wastage of water supplied to consumers.

Even if legislation has been introduced, it is often difficult to enforce due mainly to reluctance on the part of enforcement agents to enforce legislation in small communities where they are an integral part of the community.

8.6 Administration

In many small islands water resources and supplies are administered either by a government department concerned with much broader responsibilities or by a number of departments. There is inevitably, intense competition for the very scarce funds and manpower. This phenomenon, is not unique to small island communities and is often a major concern in large communities. The fragmentation of responsibility between a number of organisations can lead to long delays in reaching decisions and the decisions may not necessarily be based on sound technical or financial grounds.

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

8.7 Project implementation

Problems in the implementation of water supply projects are often a severe impediment to the development of water resources. Examples are:

- little or no co-ordination between a multiplicity of agencies including water authorities health authorities, non-government organisations, bi-lateral and international aid agencies, and United Nations organisations.
- difficulties of transport and communications due to large distances from supply and information sources. This often results in long delays in obtaining necessary supplies Large distances between islands of an archipelago add to this problem.

- reliance, in many cases, on short-term expatriate advisory and management staff. This may lead to lack of continuity in projects with consequent wastage of resources and inefficiency.

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

- largely unskilled workforces.

8.8 Operation and maintenance

Operation and maintenance activities in relation to small island water supply systems are often very inadequate. This is due to a combination of factors such as inappropriately designed and poorly constructed facilities, inadequate funding and poorly trained personnel.

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

Common examples of the problems caused by lack of maintenance are breakdowns of equipment. As spare parts are often not available on the island, water supply interruptions are often experienced. There are many other examples which are too numerous to list here.

8.9 Natural disasters

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

Following natural disasters, emergency water supplies are often required since existing supplies may be destroyed, damaged or polluted.

8.10 Climatic change

Climatic change caused by natural phenomenon or by man (eg. 'Greenhouse Effect') can dramatically influence the water resource and supply situation on small islands. Predicted consequences of the 'Greenhouse Effect' are changing 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 (see section 7.6). It has been predicted that the sea level could rise by between about 200 mm and 1.4 m (Stark, 1988) by the year 2030.

9. Approaches to water resources development and management

9.1 Planning

There are a number of fundamental steps which have to be taken in the process of planning water resource development projects in small islands. Some important planning considerations are are:

- Evaluation of water demand including current use patterns and projected increases in demand due to increases in population or increasing requirements. Urban areas on small islands are increasing rapidly and special attention is required for these. It must be recognised that it may not be possible to economically supply water to meet all demands Satisfaction of demands must then be done on a priority basis. Minimum requirements must first be met in the case of domestic water supplies. A minimum amount of 50 l/c/d is considered appropriate in most cases, although more water is required if water-borne sewerage systems are used.

- Assessment of water resources. The assessment of water resources is generally the most technically complex step in the planning phase. It must precede any substantial water resources development. Initially, available 'conventional' resources, which include rainwater, surface water and groundwater resources, need to be assessed. An assessment of other options, including desalination and importation, may be required where the former are limited and where the economy can afford these generally more expensive options.

- Selection of water(s) source. Where a choice between alternative sources of fresh water resources is available, it should be made after an assessment of engineering, economic social, environmental, legal and administrative factors. As part of the selection process conjunctive use of different classes of water should be considered since there is often more than one source of fresh water on small islands. Often rainwater catchment and shallow groundwater sources, either fresh or brackish, are available options even on the smallest of islands. For instance, rain water may be used in minimum quantities 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 (eg. use of seawater for toilet flushing, fire fighting).

- Setting appropriate water quality criteria. Guidelines (eg. World Health Organisation 1971, 1984) need to be adapted to suit local conditions. In particular, given the heavy dependence on water supplied from freshwater lenses on small islands, criteria related to salinity (eg. chloride ion concentration) need to be carefully assessed in the knowledge that island populations are often used to higher salinities in water than are specified in many guidelines.

- Co-ordination with other sectors. Where there is potential for alternative water uses development of water resources must be viewed in the wider context of island development. For example, where there is potential for hydro-power generation development proposals have an influence on both water and energy sectors. Irrigation proposals could also have strong influences on an island's economic development and land management practices, in addition to those on the water resources. Water resources development may produce potential conflicts with other land uses. In particular, it is necessary that water supply and sanitation be seen as complementary developments. The public health of a community is strongly influenced by the level of both water supply and sanitation facilities. This aspect is particularly important on small islands where limited land area means that there is a real threat of pollution of water supplies from sewerage systems and solid waste disposal sites since human habitation is often close to water sources. The creation of water reserves separate from village areas should be considered to minimise the pollution threat.

- Appropriate technology assessment. The level of technology used in water resource development should be appropriate to the community it is intended to serve. It is particularly relevant in the case of water supplies to 'rural' communities on small islands Hence, the ability of the community to participate in implementation of water development projects and to accept responsibility for ongoing operation and maintenance are vital factors in the selection of the level of technology appropriate to the community. General principles for the selection of appropriate technology, based on a World Health Organisation list (WHO, 1987), are: minimal cost, participation by the village communities where possible in the selection process, capability for operation and maintenance by the local community, utilisation of locally available materials wherever possible, use of local labour and compatibility with local customs.

- Demand management. This aspect of water resources management is particularly important on small islands. 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 minumum levels and the use of water conserving devices.

- Leak detection and repair. 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.

- Improved training at all levels. Training at technical and professional 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 was a major topic of discussion at the recent UNDTCD seminar on small island water resources and some solutions were offered (eg. Dale, 1989).

9.2 Design Criteria

When designing water resource development projects for islands, particularly small ones, certain basic criteria should be adopted:

- simplicity of design is essential. Simple, proven designs which have been used in similar conditions should, if possible, be used. Technical criteria from other areas can only be used as guides, and should be adapted to local conditions.

- use of locally available materials, where possible, to minimise the cost of imported components and spare parts.

- standardisation, where possible, of equipment to minimise the level of knowledge or experience and the variety of spare parts required for operation and maintenance. To avoid the problem of different supplies from different aid donors it is necessary to specify requirements, which may include preferred and well-tested equipment, as a prior condition to receiving aid.

- use of corrosion resistant materials due to the proximity to the sea and airborne salt spray.

- simplification of operation and maintenance requirements to enable village-level operation and maintenance (VLOM),

- use of renewable energy sources where possible. These sources might include solar or wind energy which can reduce the operation costs of pumping systems. Imported fuels are expensive and, where possible, designs should minimise the use of these energy sources.

10. Recommendations for further action

A broad overview of hydrology and water resources development on islands, particularly small islands, within the humid tropics has been provided.

Specific recommendations for action on islands, particularly small islands, in the humid tropics are:

- 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 freshwater lenses and sea level monitoring stations. National agencies should be encouraged not only to install such monitoring stations, but provide sufficient resources to ensure their ongoing viability.

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

- detailed investigations of actual evapotranspiration using micrometeorological and/or other suitable techniques for selected vegetation/soil/sub-climate associations on small islands should be conducted. Existing approaches for the estimation of evapotranspiration should be re-evaluated in the light of such investigations. As a first stage of the investigations, a database of typical soil/vegetation/sub-climate associations, including relevant hydrological parameters, should be assembled for islands of the humid tropics. One important hydrological parameter is the interception capacity of typical vegetation found on tropical islands, including the coconut tree.

- standardisation of methods for the 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. This could possibly be included in the Hydrological Operational Multipurpose Subprogramme (HOMS) of the World Meteorological Organisation.

- groundwater flow models for determining the sustainable yields of freshwater lenses should be reviewed and simpler yet theoretically correct approaches developed for use on micro-computers. Models which allow for a transition zone, rather than sharp interface models, should be used.

- appropriate computational procedures for the design of the length of infiltration gallery systems in freshwater lenses should be developed based on past knowledge and further theoretical and/or practical research. Existing groundwater theory should be reviewed taking into account the special features of freshwater lenses. Also, existing systems on small islands should be reviewed to determine their effectiveness and/or problems. Additional research may involve scale model studies using sand boxes and variable density fluids and/or construction and monitoring of a prototype on a selected island.

- existing guidelines for separation of water supply abstraction and sanitation facilities should be re-evaluated in the context of small islands with highly permeable and thin soils. Emphasis should be placed on the need for a proper assessment of groundwater flow pattern, rate of abstraction and type of sanitation disposal method.

- greater co-ordination is required between agencies involved with small island hydrolog and water resources development. To assist in this regard, it is recommended that effort to establish a library service through existing facilities be made for the collection, storag and dissemination of technical information, data and reports dealing with, or relevant tc small island hydrology. The service could be via a network of facilities including, but nc restricted to, the UNDTCD Small Island Water Resources Project office in Fiji and th Water Resources Research Center at the University of Hawaii.

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