INTERNATIONAL HYDROLOGICAL PROGRAMME

# Fresh groundwater lens recharge, Bonriki, Kiribati

## Preliminary Report

by

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**IHP-V Project 6-1**

UNESCO, Paris, 1996

SC-96/WS/49

# FOREWORD

On many inhabited low coral islands, the groundwater lens is a vital source of freshwater for domestic consumption and for growing food. Lenses are highly vulnerable to salinization by lateral incursion of seawater, and to pollution by contaminants, primarily from human and animal wastes. Such impacts have significant effects on the health and well-being of the local communities.

The International Hydrological Programme of UNESCO commissioned in 1995 two field studies within its Humid Tropics Programme designed to enhance and disseminate understanding of groundwater lens behaviour in selected Pacific islands. These studies were recommended by Member State water resources specialists at the UNESCO-SOPAC-UN Workshop on *Pacific Water Sector Planning, Research and Training,* Honiara, Solomon Islands, 1-8 June 1994. The projects combine both technical and sociocultural investigations and are being implemented in close collaboration with the South Pacific Applied Geoscience Commission (SOPAC). They also form part of the IHP contribution to UNESCO's transdisciplinary project on *Environment and Development in Coastal Regions and Small Islands.*

In preparation for the two studies, and following a recommendation by regional experts, the IHP through the UNESCO Apia Office, commissioned literature surveys on each topic. This *Technical Document in Hydrology* by Professor Ian White presents a survey on groundwater recharge. A parallel document will present another survey on groundwater pollution in villages.

Groundwater recharge in the presence of coconut trees and other vegetation is one facet of the larger task of understanding and modelling groundwater behaviour as a basis for managing freshwater lenses. This is of great practical importance; overpumping of groundwater can cause salinization which may take decades to reverse. Conversely, lack of knowledge may prevent full use of the lens resource, and lead to expensive and unnecessary developments of alternative sources of freshwater.

It should be noted that field work on the study on Bonriki Island, Tarawa atoll, Republic of Kiribati, commenced in August 1996 and is continuing. Initial results are encouraging, and will be fully reported in due course.

# CONTENTS

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# OBJECTIVES

The objectives of this report, in connection with the proposed UNESCO IHP Pacific Field Research Study on Fresh groundwater lens recharge, Bonriki, Kirabati, are to:

1. carry out a search of the scientific literature to identify items relevant to the research study;
2. produce a bibliographic listing of relevant references;
3. assess the significance of the previous work reported in the literature for the proposed study in relation to scientific context, objectives, methods, equipment and application of results.

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## SUMMARY

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Knowledge of the recharge of the fresh groundwater lenses of small, low-lying islands in the humid tropics is essential in managing the sustainable extraction of potable water. Many studies have been undertaken on the water balance and the dynamics of fresh groundwater lenses. They range from empirical to theoretical. Of the all factors that are critical to the evolution and maintenance of water resources in shallow basal aquifers, one of the most important, total evapotranspiration, is the least well characterised.

In most approaches evapotranspiration has been estimated by empirical means such as pan evaporation or by making various estimates of potential evaporation from the Penman-Monteith or Priestley-Taylor equations, and by using almost arbitrary crop factors to estimate actual evapotranspiration. It is suggested here that equilibrium evaporation is a more appropriate upper limit for both short– and long–term water balances of small coral islands. It is also suggested that for intense convective rains on highly permeable islands, daily rainfall may underestimate recharge. Doppler radar may provide a useful method for measuring intense rainfalls reliably and at appropriate space and time scales. The International TOGA COARE is developing such techniques and has collected an impressive amount of data on tropical rainfall and evaporation. It is suggested that a liaison be established between the flux group and the UNESCO project to facilitate information and technique transfer.

Few studies have attempted to measure evapotranspiration directly. Weighing lysimeters, Bowen ratio, eddy correlation, heat pulse sap flow techniques and micrometeorological techniques have been proposed as possible measurement techniques to fill this gap. For small islands, however, these techniques are doubtful due to the limited fetch and advection from the surrounding oceans. Simple rules of thumb suggest that the fetch for many of these techniques on islands with coconut trees should be over 3 km. This means that, except for the heat pulse technique, most are inappropriate for small atolls. However, the heat pulse technique does not provide an estimate of evapotranspiration since it only measures the tree component. It is also subject to considerable tree-to-tree variation.

There are few likely candidates suitable for measuring evapotranspiration at an appropriate scale. The use of tracers and stable isotopes is worth re-examining as a method for estimating recharge. For total evaporation from highly advective, small coral islands, the recently introduced technique of long path length optical and microwave scintillometry appears extremely promising. As well, measurements from aircraft platforms maybe useful, as shown in TOGA COARE.

The use of time domain reflectometry to measure the diurnal changes of soil water content now provides the opportunity for quintifying the, at present, unknown variation in soil moisture store during rainfall and evapotranspimtion from small islands.

Stage 1 of the UNESCO project is viewed as far too ambitious, in view of the uncertainties in evapotranspiration. It is recommended that the measurement of total evapotranspiration, possibly by scintillometry, be the first priority of the UNESCO project. If this is so, both the milestones and the plan for stages 1 and 2 need to be re-visited.

# 1. INTRODUCTION

The freshwater resources of Pacific Island Nations are critical to the present and future well being of their populations. These water resources are fragile and under increasing threats from overuse and from natural and anthropogenic contamination. For small atolls, taken here as atolls with area less than 2000 km² and width less than 10 km (UNESCO 1991), groundwater is the principal freshwater resource whose quantity often represents a significant limit to growth. This groundwater exists as a subsurface freshwater ‘lens’ overlying seawater–saturated formations (Badon Ghijben, 1889; Herzberg, 1901). These atolls have a thin and highly permeable (saturated hydraulic conductivity of order 10 m $d^{-1}$) regolith with shallow watertables, of order 2 to 5 m. Groundwater is, therefore, easily contaminated by surface inputs of wastes and is also easily accessed by deep–rooted plants, especially coconut palms, which deplete the resource (Falkland, 1993).

In smaller islands, the fresh groundwater lens is only of order 20 m thick. Unlike the classical freshwater lens model (Badon Ghijben, 1889; Herzberg, 1901), the lenses in small coral atolls are subject to tidal-forced mixing at their edges and base. They do not exhibit the classical sharp interface between freshwater and seawater at its lower boundary. Rather, the change occurs over a substantial transition zone, where salinity increases with depth from fresh to seawater. In some cases this transition zone may be 25% or more of the thickness of the freshwater. Excessive extraction of the freshwater lens can lead to the intrusion of brackish water of unacceptably high salt content into the potable water supply system (Sherman, 1980; Falkland and Brunei, 1989). Severe salinisation of groundwater can also occur from surface water inputs as low islands can be inundated by the sea during cyclones.

Superimposed on the problems of contamination and overuse is the problem of variable rainfall. Many small atolls are located close to the equator and are subject to ENSO (El Niño) events. Their annual rainfalls are strongly correlated with the annual Southern Oscillation Index. This results in annual rainfalls with a high coefficient of variability, up to 0.7 in some cases (Falkland and Brunel, 1993).

The identification of sustainable rates of water extraction is essential for many small island populations in the Tropics. There have been several estimates of that rate based on limited knowledge of the hydrology of small islands, some entirely empirically based, some theoretical, and others a mixture of both (Mather, 1973; 1975; Mink, 1976; Chidley and Lloyd, 1977; Hunt and Peterson, 1980; Wheatcraft and Buddemeier, 198 1; Ayers and Vacher, 1983; Contractor, 1983; Falkland, 1983; 1988; 1992a;b;c; Chapman, 1985; Thompson, 1985; 1989; Hamlin and Anthony, 1987; Voss and Sousa; 1987; Oberdorfer and Buddemeier, 1988; Griggs and Peterson, 1989; Contractor and Srivastava, 1990; Ghassemi *et al.*, 1990; Oberdorfer *et al.* 1990; Peterson, 1991). A major problem in the application of purely theoretical approaches has been the amount of information required. On the other hand, predictions from empirical approaches, which are less data-hungry, are questionable because of their unknown generality and they tend to err on the conservative side. A key question facing water managers is whether there is sufficient information to estimate sustainable rates of water extraction from small islands in the humid tropics.

The outcomes of earlier international meetings on the hydrology of small islands have been summarised by Falkland and Brunei ( 1989). Recent reports and reviews (UNESCO, 199 1; Bonell, 1993; Falkland and Brunei, 1993) have identified areas in small island hydrology in which knowledge is incomplete. In particular they highlighted the need for increased data on climatic variables, especially rainfall and solar radiation, groundwater level and salinity profiles and sea level. They also saw the development of simpler models of the transition zone with more realistic data requirements. As well, they have identified that information on a major component of the water balance of freshwater lenses, evapotranspiration, was largely unknown. These needs have lead to a research proposal to study fresh groundwater lens recharge on a coral atoll, probably at Bonriki, Kirabati.

This report provides an assessment of the knowledge gaps which prevent water managers from achieving maximum sustainable production of freshwater without incurring brackish water intrusion. The aims, methodology and expected outcomes of the UNESCO project are examined in light of this assessment project. The report focuses on small limestone islands of low relief with basal (low level) aquifers.

## 2. FACTORS CONTROLLING THE FORMATION OF FRESHWATER LENSES

The freshwater lens beneath a coral atoll is taken to be the groundwater body which extends down to a depth at which a prescribed salinity occurs. That salinity level is dependent on what is considered a maximum permissible limit. The World Health Organisation (WHO, 1984) set that limit as a chloride concentration of 250 mg/L. For small coral atolls, with scarce water resources, whose populations are accustomed to brackish water, a limit of 600 mg/L has been suggested as being more appropriate (Falkland, 1992a). In hydrologic models the thickness of groundwater lens has often been taken to be the distance from the watertable surface to the midpoint of the transition zone, $H$ (m). This, of course, is inappropriate for estimating amounts of potable water.

The physical size of freshwater lenses and their salinity distribution are dependent on climatic, hydrologic, tidal, vegetative, geographic and geologic factors. The most important of these include (Cant and Weech, 1986; Falkland, 1992a):

- rainfall amount and its temporal and spatial distribution,
- evapotranspiration from soil and vegetation,
- vegetation type (rooting depth),
- size of the island (width from sea to lagoon),
- permeability and porosity of the aquifer formations,
- tidal range,
- extraction rate. of water and method of extraction.

For small coral islands an empirical relation between freshwater lens thickness, $H$ (m), annual precipitation, $P$ (m), and island width, W(m), has been suggested (Oberdorfer and Buddemeier, 1988):

$$\frac{H}{P} = 6.94.\log_{10}\left(\frac{W}{118}\right) \tag{1}$$

Equation (1) embodies assumptions on the dimensionality of the island and its freshwater lens, through the single dimension, $W$, and on the critical driving process for the annual water balance for atolls through $P$. There is also an implicit assumption on the permeability of the aquifer and the impact of tide, outflow to the sea and evapotranspiration which erode the lens, through the constant terms in the equation. It is known that recharge can be significantly changed if deep–rooted coconuts, which act as phreatophytes, are replaced by shallow-rooted grasses (Falkland, 1993). Equation (1) must be considered a general rule of thumb which holds in some average sense. It predicts that atolls of width less than 118 m do not have freshwater lenses. Observations indicate that equation (1) underestimates the freshwater lens thickness for islands of small width (Falkland, 1992b).

incorporation of complete descriptions of all the processes into an analytic approximation of similar utility to equation ( 1 ) have not been attempted, although numerical schemes have been used (e.g. Voss and Souza, 1987). A better long–term approximation of the water balance (see e.g. Budyko, 1974; Brutsaert, 1982) based on annual net daytime radiation and precipitation may be more useful. Such an approach has been used successfully for tropical (Vardavass, 1988) and temperate eucalypts (Dunin *et al.*, 1995) and has included impacts on shallow groundwater in tropical environments (Vardavas, 1988). In such an approximate approach, tidal influences might be represented by a permeability dependent mixing length with which island widths and outflows could be scaled. A more physically based, analytic approximation to replace equation (1) would be a useful outcome from the UNESCO project.

## 3. WATER BALANCE FOR SMALL, LOW CORAL ISLANDS

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In order to determine the maximum rates of groundwater extraction in small coral islands it is necessary to know the water balance of the freshwater lens. For coral islands, the water balance is usually treated over the island-wide domain, which may be conveniently separated into two vertical zones, the surface and groundwater regions (Chapman, 1985). The surface zone, above the watertable, comprises vegetation and soils in the unsaturated zone. Since the height of the watertable depends on recharge, this two–compartment model involves a rainfall-dependent moving boundary. Typically, depth to the watertable is between 1 to 2 m on low coral atolls and the maximum unsaturated zone water storage is of order 100 mm (Falkland and Brunei, 1989).

The freshwater balance of the entire system over the time period $t$, in volume per unit surface area, can be represented as:

$$P = E + L + Q + D + \Delta S \qquad (2)$$

where $E$ (m) is the total evapotranspiration losses from the plant–soil–groundwater system, $L$ (m) is lateral outflow, comprising surface runoff ($L_r$), subsurface unsaturated outflow ($L_u$) and saturated lateral outflow ($L_s$), $Q$ (m) is the groundwater pumping or abstraction, $D$ is the dispersion loss due to tidal forcing within the groundwater system, and $\Delta S$ (m) is the change in water store in the unsaturated ($\Delta U$) and groundwater ($\Delta G$) zones. The properties $P$, $E$, $L$, $Q$ and $D$ may be positive or zero, $\Delta S$ is positive when there is an increase and negative when there is a decrease in the water store. To be sustainable, groundwater abstraction must not cause a sustained decrease in water stored.

The high soil permeability (typically, saturated hydraulic conductivities of 5 to 10 m $d^{-1}$) and low aspect ratio of small coral atolls mean that surface runoff and unsaturated lateral flow are negligible components of $L$, so that $L = L_g$.

In the two–zone model of atoll water balance, the evapotranspiration term in equation (2) is usually considered to be the sum of three terms:

$$E = E_i + E_s + E_g \qquad (3)$$

where $E$, is evaporation from the interception store on plant surfaces during and after rainfall, $E_s$ is evapotranspiration from soil grasses and understorey supplied by the unsaturated layer, and $E_g$ is evapotranspiration supplied by the groundwater store. We note that $E_g$ encompasses both direct transpiration losses by phreatophytes, $E_p$, as well capillary rise into the unsaturated zone to supply losses there due to evapotranspiration, $E_c$. It may, in reality, be artificial to separate these two components, although, in principal, they may involve quite separate pathways. The actual magnitude of direct losses from the groundwater of small coral atolls due to phreatophytes is unknown, but appears to be substantial (Falkland, 1993). Interception losses have been crudely estimated. Their contribution to evapotranspiration losses from coral atolls remains to be quantified.

The change in groundwater store, $\Delta G$, and its recharge, $R$, are of central importance. Gross recharge, the water loss from the bottom of the unsaturated zone, is given by the surface zone water balance for negligible unsaturated zone lateral losses:

$$R - E_g = P - E_s - E_i - \Delta U \tag{4}$$

In practice, $R - E_g$ is usually taken to be net recharge, which can then be positive, under wet conditions, or negative, during dry periods. There is little information about the daily dynamics of the changes m soil moisture m the unsaturated zone. Recharge is related to the change m groundwater store through the water balance of the groundwater zone:

$$R - E_g = L_g + D + Q + \Delta G \tag{5}$$

*In* order to manage abstraction, so that $\Delta G$ is not seriously depleted over long periods, the time scale, $t$, over which the water balance is evaluated, must be considered.

## 3.1 LONG-TERM WATER BALANCE

For small coral islands, the unsaturated zone is normally small, and the maximum $\Delta U$ is typically less than 100 mm. This means that for long–term water balances ($t \sim 1$ year) $\Delta U$ is small relative to $P$ (typically 700 to 3,000 mm) and $E$ (700 to 1500 mm) and can often be ignored (Brutsaert, 1982; Dunin *et al.* 1995). Under this assumption, equation (4) becomes simply:

$$R - E_g = P - E \tag{6}$$

For short-term water balances ($t < 1$ month), however, changes in soil water store must be considered. The principal drivers for recharge, in the long term, are $P$ and $E$. These, of course, are related. The relation between $P$ and $E$ in long–term regional water balances has been examined in detail (Brutsaert, 1982). Budyko (1974) records that Russian hydrologists proposed, in 1911, that long–term regional evapotranspiration could be described by,

$$E_t = E_p \tanh\left(\frac{P}{E_p}\right) \tag{7}$$

where $E_p$ (units m) is the potential evaporation, taken here to be given by Penman's (1948) estimate of the potential evaporation rate, $E_p$ over wet surfaces,

$$E_p = E_q + E_a \gamma \,/\, (\gamma + \Delta) \tag{8}$$

Here $E_q$ *is* the equilibrium evaporation rate, $E$. the so-called "drying power of the air" (Brutsaert, 1982, p. 216), $\gamma$ is the psychometric constant ($\gamma = pC_p/[0.662\lambda]$, with $C_p$ the specific heat of the air at pressure p, $\lambda$ the latent heat of vaporisation of water at the temperature of interest) and $\Delta$ is the slope of the saturation vapour pressure versus temperature curve at the air.

There are a number methods for expressing $E_a$ in terms of vapour pressure deficit of the atmosphere, $VPD$ (kPa), measured by wet and drybulb thermometers, and the windspeed or windrun, $u$ (km/day). It is often convenient to take $E_a$ to be given by (Penman, 1948):

$$E_a = 2.6\,VPD(1 + u / 161) \tag{9}$$

The Penman equation has been found to provide good estimates of evapotranspiration for the tropics (Chang, 1993). It has been used to estimate potential evaporation from atolls (Fleming, 1987; Falkland, 1988; 1992c). The first term in equation (8), equilibrium evaporation, represents the contributions of energy supply through net radiation to evaporation, the second term contains the contributions of water vapour pressure deficit and wind speed. Because the second, atmospheric term is much less important than the energy-supply term in the tropics (Chang, 1993) simplifications based on equilibrium evaporation may be practical.

The equilibrium evaporation rate from wet surfaces over very long fetches is given by (Priestley, 1959; Slayter and McIlroy, 1961):

$$E_q = (R_n - G)\Delta / (\lambda[\gamma + \Delta]) \tag{10}$$

with $R_n$ the net radiation and G the ground heat flux. The only factors governing $E_q$ are net radiation and ground heat flux (of order 5 to 10% of $R_n$ if daytime values are used) and air temperature and pressure (through $\Delta/[\Delta+\gamma]$).

True equilibrium conditions are rare over short-time scales, however it has been proposed that equation (10) represents an instantaneous balancing act between advection, which tends to increase $E$ above $E_q$, and soil water deficit which decreases $E$ below $E_q$ and that, therefore, equation (10) may be an appropriate upper bound, even in drier, temperate regions, for evapotranspiration (Denmead and McIlroy, 1970; Dunin *et al.* 1995).

In order to use potential evaporation, equation (8), to estimate long–term evaporation, measurements of net radiation, wet and drybulb temperatures, and windspeed are required. These are often not available for small coral islands. In addition, the high humidities usually generated by the surrounding sea mean that the radiation term dominates evaporation (Fleming, 1987; Chang, 1993). Because of this, it has been suggested that the Priestley and Taylor (1972) equation is more appropriate for tropical situations with $E_p$ given by:

$$E_p = \alpha E_q \tag{11}$$

The proportionality constant, $\alpha$, in equation (11) is typically taken as $\alpha$ = 1.26 in the traditional Priestly-Taylor approach. Elsewhere, it has been suggested that $\alpha$ = 1.28 may be more appropriate (Brutsaert, 1982). This simpler Priestley-Taylor equation, (11), has been employed to estimate potential evaporation for tropical Pacific Islands (Nullet, 1987; Giambelluca *et al.*, 1988). It may be, however, that the choice of the constant term by Priestley and Taylor (1972) has been influenced by experience from advective situations from dry areas.

Denmead and McIlroy (1970) have suggested $\alpha$ = 1 was the maximum value expected even for temperate, well watered, dryland crops with a large fetch, at time scales as short as an hour. They argued that, except in oasis or desert-type situations, departures of actual evaporation from equilibrium evaporation should rarely be extreme. Brutsaert and Stricker (1979) observed over a 74–day dry period in Gelderland that the average daily $E$ was almost identical to $E_q$. For coastal regions, substantially influenced by evaporation from the sea, it seems plausible to suggest that $a = 1$, that is, equilibrium evaporation, is a reasonable daily upper bound (Dunin *et al.*, 1995).

In practice, $\alpha$ depends on soil water content and other factors. In many situations, soil moisture deficit causes $\alpha$ <1, while interception losses and advection in oasis situations produce $\alpha > 1$. Values for short-time scales have been found ranging from 0.25 to 1.26 (Priestley and Taylor, 1972; Mukammal and Neumann, 1977; Williams *et al.*, 1978). The proportionality constant $\alpha$ has been expressed as a function of soil water content, $\theta$, ($m^3 m^{-3}$) such as (Davies and Allen, 1973):

$$\alpha = 1.26[1 - \exp(-10.563\,\theta/\theta_s)] \qquad (12)$$

Here $\theta_s$ is the water content at field capacity or satiation. Davies and Allen ( 1973) took $\theta$ to be the water content in the top 50 mm of soil. Others have used simpler, linear relations and the soil water storage over the top 1 m of soil. It is not known how the depth of the vegetation's root zone, or the distribution of soil moisture within that zone, influence the perceived value of $\alpha$. Short-rooted crops, growing in the same soil water conditions as a deep rooted species, may well have a lower value of $a$, and hence $E_t$, because of drying of the top soil. It is also not known how the presence of shallow watertables, phreatophytes and understorey vegetation influence the value of $\alpha$. In the absence of such information, the assumption of $\alpha = 1$ for coral atolls seems reasonable for long term evapotranspiration estimates.

Because of the lack of availability of long–term vapour pressure deficit and wind speed data, Budyko (1974) replaced potential evaporation in equation (7) with net radiation. He postulated that, in dry periods, when $R_n >> P$, $E \rightarrow P$ and for wet periods, when $R_n << P$, he assumed that $E \rightarrow R_n$. In order to interpolate between these extremes, he used a geometric mean of two formulae due to Ol'dekop:

$$E = P\left\{\left(\frac{R_n}{P}\right)\tanh\left(\frac{P}{R_n}\right)\left[1 - \exp\left(-\frac{R_n}{P}\right)\right]\right\}^{1/2} \qquad (13)$$

Equation (13) has been shown to give a reasonable description of annual evapotranspiration from such disparate regions such as Lapland, Java and Egypt (Brutsaert, 1982).

It is unreasonable to assume that $R_n$ *is* an upper bound for evapotranspiration from moist conditions (Dunin *et al.* 1995), particularly for atolls. The potential evaporation term in equation (7) could equally be replaced with the Priestley-Taylor estimation [$\alpha = 1.26$ in equation (11)] or with equilibrium evaporation [$\alpha = 1$ in equation (11)]. If we follow the reasoning of Denmead and McIlroy (1970), then it can be suggested that for wet periods, when $P > E_q$, $E = E_q$ while for substantial dry periods, when $P < E_q$, all precipitation is extracted from the soil, so $E = P$. In order to interpolate between limiting cases, long–term evaporation is given by:

$$E = P\left[\left(\frac{E_q}{P}\right)^4 \tanh\left(\frac{P}{E_q}\right)^4\right]^{\frac{1}{4}} \qquad (14)$$

The exponent 4 in ( 14) ensures that $E$ varies rapidly from $P$ to $E_q$ as $P$ approaches and exceeds $E_q$. Similar reasoning to that embodied in equation (14) has been used to estimate the long–term water balance in tropical eucalypts with a shallow watertable during the wet season (Vardavas, 1988). The assumption that $E = P$ in dry periods, does not take into account groundwater use. The applicability of these type of approaches to small coral atolls with shallow watertables remains to be tested.

Equations (7), (13) and (14) represent a hierarchy of data requirements. All require knowledge of $P$. Equation (14) requires additional measurements of net radiation but seems to overestimate evapotranspiration for wet conditions. Equation (14) requires air temperatures as well. Equation (7) requires additional estimates of wind speed and vapour pressure deficit at some reference height, if Penman's representation of potential evaporation is used. Not all of these properties are available for small coral atolls. Moreover, the dominance of the radiation term in tropical areas may mean that wind speed and vapour pressure deficit data are not critical. If this is so, equilibrium evaporation may provide a useful method for estimating long–term evapotranspiration from small coral atolls. The apparent success of estimates of $E$ using Penman's estimate of potential evaporation may largely reflect the dominance of the radiation or equilibrium evaporation component over the atmospheric term. A comparison of the sensitivity of estimates of annual recharge when evaporation is estimated using equilibrium evaporation rather than Penman's potential evaporation remains to be carried out.

Equations (7), (13) or (14) all express long-term evaporation as a fiction of precipitation. In order to estimate long–term recharge using these measurements of $P$ and daytime $R_n$ [equation (13)] together with mean air temperature [equation (14)] and *VPD* and mean wind run [equation (7)]. It is noted that the observed relationship between mean annual recharge and mean annual rainfall (Chapman, 1985; Falkland, 1990) is consistent with the above relationships for long–term evapotranspiration.

Tests of the accuracy of predictions of long–term regional water balances, in which all components of the water balance are measured, are scarce. Dunin *et al.* (1995) have recently reported comparisons between measured annual evapotranspiration and outflow (recharge and surface runoff) for a temperate coastal eucalypt forest and those predicted from equations (14) and (6). Over a five year period they found that equation (14) underestimated annual evapotranspiration by less than 1% and equation (6) overestimated annual outflow by less than 10%. These disclosures are less than the measurement errors.

In the above we have not, thus far, defined what time period constitutes long term. The work of Dunin *et a/.* (1995), suggests that an estimate of the time scale, $t_l$, (days) for long–term water balances can be found from

$$t_l > \Delta U_{\max} / E_d \qquad (15)$$

where $\Delta U_{\max}$ is the difference in soil moisture store between field capacity and wilting point and $E_d$ is the average daily evapotranspiration rate. For small coral atolls this figure is typically of order 20 days. If this is so, it then monthly estimates of evapotranspiration may be considered long term. We note here, however, that the inequality (15) was proposed for areas which do not have a shallow watertable. It may only be applicable to coral atolls with shallow rooted plant species which do not tap the groundwater. The impact of extraction from shallow watertables on long–term evapotranspiration estimates remains to be quantified.

## 3.2 **SHORT–TERM WATER BALANCE**

While estimates of long-term water balance maybe useful in a strategic sense, their application to the management of abstraction from freshwater lenses on small coral atolls has problems (Chapman, 1985; Falkland, 1993). The high permeability of coral atoll Holocene soils and the small depth to groundwater ensure a short residence time for water in the unsaturated zone, typically a day or less. This suggests that daily water balances, at least, are required to estimate recharge from the surface layer (Chapman, 1985). Daily rainfall records are available for some low coral atolls. On the other hand, the residence time for water in the shallow groundwater system is of the order of a year, despite tidal forcing of seawater-freshwater mixing in the generally much higher permeability Pleistocene formations underlying the Holocene deposits. This longer turnover time means that monthly water balances appear adequate for characterizing the groundwater.

In the daily water balance, equation (4), evapotranspiration is somewhat conservative in that it is driven principally by the net radiation. Because of this, we do not expect that $E$ *will* exhibit large daily variations. This means that it maybe appropriate to use mean monthly estimates of daily evapotranspiration, as has been suggested (Falkland, 1988). The principal daily measurement required, therefore, is rainfall.

It has been found that the use of actual monthly rainfall data, rather than daily data, results in a 6 to 10% underestimation of recharge (Hunt and Peterson, 1980; Falkland, 1988). Because of the intense rainfall events which occur in convective storms in the tropics, and because of the high permeability of coral atoll soils, even daily estimates of rainfall may be inadequate. The error caused by the use of daily rather than higher frequency rainfall data in short-term water balances does not seem to have been explored, probably because of the general unavailability of short-term rainfall data for small coral islands. It may well be that even daily rainfall underestimates recharge.

In estimating the short-term recharge of small coral atolls, actual measurements of evapotranspiration, have not generally been used. Instead, daily average estimates of evapotranspiration, derived from monthly averaged values, have been employed. Intercepted water is treated separately from evapotranspiration from the unsaturated and groundwater zones (Chapman, 1985) [see equation (3)]. Failure to do so can result in an underestimate of evaporation and up to a 5% overestimate of recharge (Falkland, 1988). Evaporation of intercepted water is assumed to occur at the potential rate (Falkland, 1993). Essentially two methods have been used to estimate short term evapotranspiration from small coral atolls.

In the first method, the Penman equation, (8), or Priestley-Taylor equation, (11), provides an estimate of potential evaporation. The various vegetation types (usually grass and coconut trees) are assigned crop factors as proposed by Doorenbos and Pruitt (1977) and the fractional cover of each vegetation type is determined. The contribution of a particular vegetation to the actual evapotranspiration losses, $E_s$, from the unsaturated zone of a particular vegetation under well-watered conditions is taken to be the potential evaporation multiplied by the area fraction multiplied by the crop factor (Falkland, 1988).

The dependence of evapotranspiration on unsaturated zone water content has been assumed to be a linear function of reduced moisture content of the entire unsaturated zone, $\Theta = (\theta - \theta_d)/(\theta_s - \theta_d)$, with $\theta_d$ the moisture content at wilting point ( $E_s = 0$ when $\Theta = 0$). This simple linear dependence differs from the suggested exponential relation of Davies and Allen (1973), equation (12). Their relation used the water content in the top 50 mm of soil, whereas here, the water content of the entire unsaturated zone is considered. For small coral atolls, no direct measurements of unsaturated soil water content appear to have been used in estimations of $E_s$. Instead, unsaturated zone water contents are inferred from a ‘‘tipping bucket” model (Falkland, 1993).

Transpiration losses from the watertable through deep–rooted plants, such as coconuts, appear to have been assumed proportional to the fraction of roots with access to the watertable (Falkland, 1993). The latter assumes transpiration from plants with distributed root systems is essentially a simple, linear process. There appears to be no evidence for this assumption (Passioura, 1988).

In the second approach to estimating short-term evapotranspiration, measured daily pan evaporation has been used. This, when multiplied by a pan coefficient, provides an estimate of potential evaporation (Falkland, 1988; 1992c, 1993). Mean annual estimates of potential evaporation determined in this way from pan evaporation have been found to agree within 3% with that from the Penman equation. In the absence of direct evapotranspiration measurements, such agreement does not constitute validation.

In discussing long–term water balances, it was suggested that equilibrium evaporation, equation (10), rather than Penman’s equation (8) may be the appropriate upper limit for potential evaporation for small coral islands. It has been suggested that this is also so for short-term, daily, even hourly, evapotranspiration (Denmead and McIlroy, 1970; Dunin *et al.*, 1995 ). For a closed, convective boundary layer, regional evaporation from a homogeneous surface approaches $E_q$ on a daily basis (McNaughton and Jarvis, 1983). If equilibrium evaporation occurs over short time scales, a special relationship between the atmospheric and plant physiological conditions must arise:

$$r_i = \frac{\Delta}{\Delta + \gamma} r_s = 0.687 r_s \qquad (16)$$

where $r_i = pC_p VPD/(\gamma[R_n - G])$, is the climatological resistance and $r_s$ *is* the bulk stomatal resistance to the diffusive transport of water vapour at the surface. For this to occur, the minimum bulk stomatal resistance must be significant for temperate areas (about 60 s/m Dunin *et al.*, 1995). For tropical islands, where *VPD* is small, the required bulk stomatal resistance may also be correspondingly smaller. Information on the ratio $r_i/r_s$ for the plant and atmospheric conditions on small coral islands, and on the diurnal dynamics of $r_s$ for coconut trees appears not to be available. Measurements of evapotranspiration from an Amazonian rainforest (Shuttleworth, 1988) and a coastal eucalypt forest in eastern Australia indicate that equilibrium evaporation appears to be a realistic upper limit for daily evapotranspiration. Use of equilibrium evaporation rather than the Penman or Priestley-Taylor approximation for potential evaporation will result in an approximately 20% lower evapotranspiration rate with a consequent increase in the expected recharge.

There are two major problems confronting the prediction of short-term evapotranspiration from coral atolls: advection from the surrounding ocean and the use of groundwater by phreatophytes. While some progress has been made in predicting the effect of a step change in surface conditions and even one-dimensional “checker boards” on evaporation (Philip, 1996), the three-dimensional nature of small coral atolls seems beyond the scope of analytical or quasianalytical schemes. Numerical Soil Canopy Atmosphere Models (SCAM) are being developed (Raupach, 1991), but the present generation cannot deal with evapotranspiration from shallow watertables. This is largely because the partitioning of water extraction by plant roots extract from the unsaturated zone and from groundwater is unknown (Passioura, 1988).

Direct measurements of evapotranspiration using weighing lysimeters, Bowen ratios and the Penman-Monteith equation have been reported in New Caledonia (Brunel, 1989). As well, the heat pulse technique has been employed to estimate transpiration in coconut trees in the Cocos (Keeling) Islands (Falkland, 1988). Despite these limited studies, recent reviews have identified the general absence of information on evapotranspiration and soil water dynamics on coral atolls. (Brunel, 1989; Falkland, 1993; Falkland and Brunei, 1993). Since these terms account for more than 50% of the short term water balance, their importance in terms of estimation of the groundwater resources of low coral atolls cannot be underestimated. The issues relevant to the direct measurement of the short term water balance will be discussed below.

# 4. MEASUREMENT OF COMPONENTS OF THE SHORT–TERM WATER BALANCE

Critical issues influencing the measurements of components of the short-term water balance are discussed separately below.

## 4.1 PRECIPITATION

The general features of climate and rainflall in the tropics have been reviewed recently by Manton and Bonell (1993) while the climatic features of the southwest Pacific Ocean have been considered by Mullen (1991). Intense rains associated with convective instabilities and extreme temporal variability are important over short time scales. Recent radar measurements indicate a semi-diurnal cycle in convective rainfall but a diurnal cycle in stratiform rains (Bradley and Weller, 1995a). At long time scales, the critical influence of the El Niño Southern Oscillation on precipitation has been clearly demonstrated (Falkland, 1983; 1993). For low coral atolls, orographic effects are negligible and spatial variability tends to be small (10 to 20%).

A major comparison of different methods of measuring precipitation over different scales in the tropics has been carried out recently as part of the field phase of the International Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) (Lansford *et al.*, 1995; Bradley and Weller, 1995a; 1995b). This has involved a range of techniques from the point *in situ* scale; such as traditional raingauges, siphons, and optical raingauges (ORG), through to larger area techniques: such as Doppler weather radar sensing over 150 km at spatial resolutions of at least 2 km and possibly as small as 0.25 km (Lansford, 1995); regional estimations from Special Sensor Microwave/Imager (SSM/I) satellite radiometers with footprints of order 50 km; from the Geostationary Operational Environmental Satellite (GOES) Precipitation Index (GPI); and from the oceanic water balance.

### 4.1.1 Optical raingauges

ORGs have considerable potential for use in the tropics. They are extremely fast and can therefore give better estimates of “instantaneous” rainfall rates which are so important in the convective storms which are responsible for large rain events. Large discrepancies were reported, up to a factor of 2, between siphons, conventional raingauges and ORGs (Lansford *et al.*, 1995; Bradley and Weller, 1995a). It was suggested that the discrepancies may be due to the deflection of raindrops around the siphon in strong winds resulting in a lower catch (the Jevon’s effect, Koschmeier, 1934). ORGs, while not subject to catch errors, are still dependent on wind direction and have large variations in calibration bias ( 15–30%) and manufacturer’s quality control (20–30%) (Bradley and Weller, 1995a). This is an evolving technique but one which has potential for quantifying the precipitation rate on small islands.

### 4.1.2 Doppler weather radar

Doppler radar techniques appear to offer considerable promise for determiningg rainfall in tropical situations because of their reliability, useful range (120–150 km), appropriate pixel-size (0.25– km) and temporal resolution (10 min snapshots). The TOGA COARE comparison showed that different radar systems gave different rainfalls, probably due to different analysis schemes, and the mean rainfalls were about half those of oceanic mass balance and siphons. With the Doppler radar technique, different calibrations have to be used for convective and stratiform rains because of differences in the drop-size distributions. Despite these problems the radar technique appears to offer considerable promise for quantifying short term rainfall on coral atolls, particularly for intense rains (Lansford *et al.*, 1995).

### 4.1.3 Satellite radiometers

The SSM/I satellite radiometer results were shown to be very sensitive to the method of analysis used to relate brightness temperature of a column of air at a range of frequencies, covering both ice and water, to rainfall. The range of rainfalls reported was consistent with other estimates of regional average rainfall and from the range reported from GPI (Bradley and Weller, 1995a). The claimed temporal resolution for the SSM/I is of order 3 hours, but the spatial resolution appears inappropriate for short term water–balances of coral atolls.

### 4.1.4 Tropical rainfall heat flux

A major finding of TOGA COARE has been the contribution of tropical rains to the heat budget of tropical oceans. Without precipitation, models predict that the surface of the ocean is mixed down to the thermocline at 80 m every night . With precipitation, the surface of the ocean, because of the input of fresh surface water, is hydrodynamically stabilised under calm to moderate conditions. This results in the trapping of heat in less than the top 40 m of the ocean. This heat trapping in the ocean after rain has implications for the VPD over coral atolls. As well, the heat loss due to rainfall appears to be substantial in tropical areas because rainfall reaches the surface at close to the wetbulb temperature. During intense rains (several minutes at 100 mm $h^{-1}$) this loss can amount to 200 W $m^{-2}$, of the same order as the evaporative (latent heat) flux (Lansford *et al.*, 1995).

TOGA COARE is clearly generating information, particularly on the comparison of measurement techniques for precipitation in tropical areas, which is of direct relevance to quantifying the water resources of coral atolls. It is suggested that a liaison between participants in the TOGA COARE flux Working Group examining tropical rainfall and the UNESCO coral atoll project be established.

## 4.2 EVAPOTRANSPIRATION

Despite the obvious importance of evapotranspiration in determining recharge in coral islands, very few actual measurements of this dominant component of the water balance have been made. This is not just an oversight, but stems from the fact that such measurements, for small coral atolls, are far from routine. The dearth of actual evapotranspiration measurements has led to recommendations that micrometeorological techniques, used with such success in continental evapotranspiration studies, be applied to small coral atolls (Brunei, 1989; Falkland and Brunei, 1993; Falkland, 1993). Lysimeters, the Bowen ratio technique, eddy correlation and the use of the Penman-Monteith approach involving measurements of the profiles of windspeed, vapour pressure deficit and net radiation, have all been proposed. In addition the heat pulse technique (see e.g. Olbrich, 1991) has already been used to determine sap velocities in coconut trees

(Falkland, 1988). Problems involving advection and the requirement for adequate fetch must be addressed, however.

### 4.2.1 Lysimeters

Lysimeters have been used successfully in forested areas (Dunin *et al.*, 1985; 1995), however the representativeness of the sample of trees contained within the lysimeter always remains a problem. In addition, because of wind stress, the technique is usually limited to small trees (< 7 m) and, therefore, does not seem applicable to areas with coconut trees. As well, the use of lysimeters in areas where plants extract water from shallow groundwater severely compromises the technique or requires extremely elaborate procedures to account for groundwater use. Lysimeters maybe of use in determining evapotranspiration from shallow rooted grasses or understorey vegetation which only extract water from the unsaturated zone, but their general use for coral atolls seems limited.

### 4.2.2 Bowen ratio, eddy correlation, profile measurements

The major problems facing the application of these standard micrometeorological techniques to determine evapotranspiration from coral atolls are those faced by many small plot experiments, namely the adequacy of the fetch and advection from wetter or drier surrounding regions (Denmead and Raupach, 1993). All these techniques require measurements in an equilibrium boundary layer which extends to a height of about 1/100 of the fetch. Instruments need to be positioned within this boundary layer (Slatyer and McIlroy, 1961). In tall canopies it is necessary to have instruments position at least twice the canopy height. For islands containing coconut trees, a fetch of about 3 km is needed to the establish a useable boundary layer. This precludes using these standard techniques in many treed coral atolls.

In addition to this, advection from the surrounding ocean will ensure that vapour pressure gradients over a low atoll maybe small, compounding measurement problems in any profile or Bowen ratio measurements. Nullet and Giambelluca (1990) identified advection from the sea as one of the contributing factors to the disagreement between model predictions and measurements, Finally, it should be pointed out that eddy correlation is not a universal panacea. Recent measurements during the Observations At Several Interacting Scales (OASIS) experiments (Raupach *et al.*, 1994) have indicated considerable discrepancies between eddy correlation results and those of Bowen ratios and lysimeters.

### 4.2.3 Heat pulse or sap flow measurements

Heat pulse methods for determiningg the sap velocity in trees have already been used in examining transpiration in coconut trees (Falkland, 1988). While the technique can aid in elucidating the contribution of groundwater used by trees when combined with stable isotope measurements (Thorburn *et al.*, 1993a), it is not without limitations.

The heat pulse technique measures only one component, tree transpiration, of the total evapotranspiration. Understorey evapotranspiration and soil evaporation are also key components to total evapotranspiration (Denmead and Bradley, 1987). In addition, the limited number of trees which maybe sampled with the heat pulse technique, and inter– and intra-tree variability mean the areal representativeness of the technique is questionable, although agreement with other methods has been claimed (e.g. Hatton and

Vertessy, 1990). As well, wound response by trees to the insertion of heaters and temperature probes can cause problems with the technique. The technique has applications in coral atoll hydrology but only in combination with measurement of the total evapotranspiration losses.

### 4.2.4 Direct abstraction from groundwater: tracer techniques

Estimations of the rate of abstraction from and recharge to groundwater can be made from comparisons of conservative tracer compositions of groundwater and rainwater in the absence of any groundwater or soil water mixing processes (Vacher and Ayers, 1980). Chloride has been the principal tracer used, although stable water isotopes may also useful (Barnes and Allison, 1988). Care, however, must be exercised in using this technique (Daniell, 1983; Chapman, 1985). Sea spray may contaminate rainwater samples in small islands, as well as adding directly to the downward soil flux of salt. Dispersion of salt from the transition zone underlying the lens may also contaminate groundwater samples. As well, groundwater flow to lowlying areas may also complicate the use of the chloride mass balance approach. Chapman (1985) recommended the use of samples drawn from just below the surface and just above the watertable. Other seawater/freshwater tracers such as strontium (Stumm and Morgan, 1981) appear to have been used sparingly (Budd, 1988).

Analysis for stable water isotopes, in principle, would overcome sea spray problems, however, others arise. These are the extreme variability of isotopic composition of rainfall in convective storms (Gat, 1980), and the fact that root uptake by phreatophytes may not fractionate water isotopes (Thorburn *et al.*, 1993b). If the latter is so, then analysis of the stable isotope composition of groundwater may then give only the contribution of direct groundwater evaporation to total groundwater evapotranspiration. Ng and Jones (1990) obtained considerable information on the mixing and discharge properties of groundwater on Grand Cayman island using geochemical tracers and stable isotopes. In spite of the reservations about tracer techniques they appear worthwhile pursuing in conjunction with other evapotranspiration measurements.

The analysis of stable isotope composition of plants has been used to infer sources of water transpired by trees (White *et al.*, 1985; Brunei *et al.*, 1990; Thorburn *et al.*, 1993a; 1993b). Their combined use with heat-pulse sap flow measurements to determine the ii-action of transpiration derived from groundwater appears to be promising for following water use by coconuts, provided their is sufficient isotope discrimination between soil and groundwater.

### 4.2.5 Ventilated chambers

Despite problems with light interception and representativeness of area sampled, large ventilated chambers have been used successfully to measure evapotranspiration losses in eucalypt forests (Dunin and Greenwood, 1988) and for determining evaporation and groundwater losses from lower vegetation (Barrington *et al.*, 1989; 1990). While they are useful in dry periods, by their nature they cannot quantify interception losses. They are also difficult to erect in canopies with tall trees and are fragile in strong winds. Their application to coral atoll evapotranspiration measurement may be limited to understorey measurements during dry periods.

### 4.2.6 Aircraft measurements

The use of aircraft with meteorological platforms (Hacker and Schwerdtfeger, 1988, Shao *et al.*, 1991) to measure regional evapotranspiration and heat fluxes appears attractive for coral atolls. Extensive use of such aircraft have been made in the OASIS (Raupach *et al.*, 1994) and TOGA COARE (Lansford *et al.*, 1995; Bradley and Weller, 1995) experiments. In OASIS aircraft transects at various heights above heterogeneous evaporative surfaces are being used to examine the blending height above which the atmospheric boundary layer can be considered fully mixed. As well they provide transects of latent and sensible heat fluxes across heterogeneous surfaces.

In TOGA COARE, preliminary analysis of flux data from aircraft, ship and buoy sensors (Bradley and Weller, 1995b) indicate that aircraft evaporation measurements involved considerable scatter and were smaller in magnitude than ship measurements, possibly due to vertical flux divergence. Some overflights of coral atolls did occur during these ocean measurements, but the data is not yet available. Aircraft-mounted platforms are expensive to operate and cannot operate in all weathers. None-the-less the coupling of coral atoll measurements with further atmosphere-ocean exchange measurements may be fruitful, particularly for dry season evapotranspiration.

### 4.2.7 Atmospheric mass balance methods for small sources

Atmospheric mass balance methods for small sources have had considerable success in determining trace gas fluxes from plots of limited size (Denmead, 1995). If $X$ is the down wind width of the source, conservation of mass gives the flux, $F$, of any emitted gas to be:

$$F = \frac{1}{X}\int_{0}^{Z}(\overline{U}\,\overline{\rho}_d - \overline{U}\,\overline{\rho}_b + U'\rho'_d)\,dz \tag{17}$$

with Z the height of the gas cloud, $\overline{U}$, $\overline{\rho}_d$, $\overline{\rho}_b$ the mean wind speed, downwind and upwind concentrations $U'$, $\rho'_d$, $\rho'_b$ fluctuations about those means. Usually the last, turbulent diffusive term in equation (17) is ignored. This can introduce errors of between 10 to 20% unless an empirical correction is used (Denmead, 1995). This method has been used successfully for determining ammonia and methane fluxes from small source area plots.

To use this to measure evapotranspiration of small coral atolls, upwind and downwind measurements of humidity profiles, together with measurements of the mean wind profile, are required. A significant problem in the application of this technique to small coral atolls, is that the background humidity signal is large, and the additions of water vapour from the island may be very small. This would require extremely closely matched and well-calibrated upwind and downwind sensors and does not, at present. seem feasible.

### 4.2.8 Microwave and optical scintillometry

Perhaps the most promising technique for measuring evaporative fluxes from small coral atolls is the recently introduced methods of microwave and optical scintillometry (Hill, 1992; Green *et al.*, 1994; McAneney *et al.*, 1995). The twinkling of stars in the night sky is a well known phenomenon. This scintillation of starlight is caused by light scattering due to atmospheric fluctuations in the atmosphere’s refractive index. These, in turn, are due to turbulent fluctuations in heat and moisture content, which effect local air density, The use of scintillations to measure heat, momentum and moisture fluxes in the atmosphere was first examined by Weseley and Derzko (1975).

In this technique a collimated beam of incoherent radiation (infrared or microwave) is transmitted through the atmosphere to a receiver. Intensity fluctuations are recorded, which, together with measured mean wind speed and a plausible assumptions about surface roughness, provide estimates of heat, momentum and moisture fluxes. Large aperture scintillometers have a useable range of about 1.7 km when used for near–sulfate (height of 1 to 2 m) measurements. This range increases with height. Significant advantages of the large aperture scintillometers are that they have absolute calibration, have no moving or delicate parts and can operate for long periods unattended under wet and dry conditions. Optical scintillometers provide estimates of the sensible heat flux, $H$ and measurements with them show excellent agreement with traditional point measurements (McAneney *et al.*, 1995).

Two methods have been proposed to use them to find the latent heat flux. In the first, net radiation and ground heat flux are measured and the latent heat flux, $\lambda E$ is determined from the surface energy balance.

$$\lambda E = (R_n - G) - H \qquad (18)$$

In the second, the scintillometer is turned into an optical hygrometer by simultaneously measuring fluctuations in the weak absorption bands for water vapour. It has been proposed that this can be used to measure the evaporative flux directly.

Recently developed microwave scintillometers are designed to give the evaporative flux directly. These also have long path lengths but remain to be tested exhaustively.

Scintillometry appears to be the most promising of all techniques for measuring evaporative fluxes from small coral atolls. Their robustness and absolute and continuous calibration make them ideally suited for operation in the tropics. The technique is, however, still under development.

## 5. UNSATURATED ZONE MOISTURE DYNAMICS

Few measurements of soil water content changes in the unsaturated zone appear to have been made in examining the short-term water balance of islands. Instead a model based on a notional, fixed extractable water limit, based on estimates by Linsley and Franzini (1972) has been employed (Falkland, 1993). The high permeability of coral atoll soils mean that the soil moisture dynamics may need to be determined at daily or better frequency.

The most straightforward method of measuring unsaturated zone moisture content is by direct gravimetric sampling followed by determination of the loss of water at 105°C. However, this is not suitable for continuous monitoring since it involves destructive sampling. Neutron scattering is probably the next most used method of monitoring soil water content. It has several disadvantages in that it involves the use of a radioactive source, can only be used at one site at one time, is not ideal for continuous monitoring, requires *in situ* calibration, and does not perform well in sites with shallow watertables.

Recent, improved dielectric methods of measurement of water content (White and Zegelin, 1995) appear to offer the greatest advantage for studying the dynamics of coral atoll soil moisture dynamics. Of these methods, the most promising appears to be time domain reflectometry (Topp *et al.*, 1980; Topp *et al.*, 1994). In the TDR technique, a fast rise electric and magnetic pulse is sent down and reflected back from a transmission line probe inserted in the soil. The time taken for the pulse transit is proportional to the relative permittivity of the soil. Since the relative permittivity of dry soil is 3 to 5, air is 1 and water is 81, the relative permittivity is extremely sensitive to soil water content.

Original work suggested that there was a unique relation between relative permittivity and water content (Topp *et al.*, 1980). While that is approximately true for many coarser textured soils (sands, loams), it is not so for finer materials (peats, clays). A mixing law, based on the simple refractive index model for dielectric mixtures provides an excellent description of the dependence of relative permittivity of the soil-water mixture, $\varepsilon$, on the volumetric water content, $\theta$:

$$\sqrt{\varepsilon} = A\theta + B \qquad (19)$$

For sands, such as the soils found on coral atolls, the constants, $A$ and $B$, can be calculated theoretically. For clays they need to be determined empirically.

The TDR technique can be multiplexed, can operate remotely and can make measurements at time intervals as low as three seconds (Zegelin *et al.*, 1989). TDR measurements of soil moisture dynamics have been found to match lysimeter and Bowen ratio measurements to within 10% from hourly to daily time scales (Zegelin *et al.*, 1992). The technique seems ideally suited to short-term water balance studies of small coral atolls.

# 6. GROUNDWATER MIXING AND OUTFLOW

Groundwater mixing with the underlying seawater in the permeable Pleistocene formations and groundwater outflow to the sea are important factors in the water balance of small coral atolls. It has been clearly demonstrated that the sharp interface, Ghyben-Herzberg lens theory does not describe the thick transition zone that occurs in actual lenses (Falkland, 1983). Instead, dispersion due to tidal mixing must be taken into account and is best accomplished through numerical models of the lens (Pinder and Grey, 1977). The SUTRA, two dimensional finite element model, has been used to model freshwater lenses (e.g. Voss, 1984; Oberdorfer and Buddemeier, 1988; Oberdorfer *et al.;* 1990, Griggs and Peterson, 1993). Other, even more sophisticated models, such as SEPRAM, are available. They have, however, two drawbacks. Many are only two dimensional and all are data-hungry. They require intensive data about porosity and permeability distributions in the regolith and fluid properties. In addition they require that the recharge to the lens be known.

The need for simpler but nevertheless realistic models has been recognised (Volker and Rushton, 1982). Volker *et al. (1984)* produced analytical approximations for the width of the transition zone. The dynamics of the groundwater mixing can, in some situations, be modelled simply using Hele-Shaw experimental models (Demetriou *et al.*, 1989), although again this is a two–dimensional model. It is important to recognise that the outflow and inking constitute important parts of the water balance and critically influence the amount of water that can be extracted from the lens. Both are not known with any precision.

Measurements of watertable height and the depth to the transition zone are essential in determining the freshwater lens distribution and its mixing characteristics. Care has to be exercised in the placement, construction and monitoring of observation wells. Descriptions of the procedures necessary are given in Falkland (1992a). Electromagnetic induction in the frequency domain provides a useful method for interpolating between monitoring wells, however it cannot be used to extrapolate from these (Anthony, 1992).

## 7. THE UNESCO FRESHWATER LENS PROJECT

It is clear from the above that there are major gaps in our knowledge of the magnitude of the processes involved in freshwater lens recharge. Because of the extreme importance of water resources to coral atoll populations, UNESCO has initiated a project to fill those gaps.

The aims of the UNESCO project are:

> To quantify the interception and evapotranspiration in selected island vegetation and soil associations and to combine this data with soil moisture and groundwater table movement data, thereby enabling groundwater recharge to be quantified and the results to be disseminated to those involved in water balance studies/water resource assessment and management on small coral islands.

The project is planned as a staged project. Stage 1 is an ambitious stage in which rainfall, interception, sap flow, soil moisture dynamics, watertable fluctuations, groundwater salinity monitoring, climate properties and vegetation are all planned to be measured in addition to community involvement in the project. The milestones for the project seem more appropriate for a three-year rather than a one-year project.

In view of the above tidings, particularly on the difficulties in measuring evapotranspiration, it is believed that stage 1 is much too ambitious. It is clear that the highest priority should go to the development and testing of appropriate techniques for measuring total evapotranspiration over an appropriate scale for small coral islands. In my view that alone would be a three-year project and would have an extremely beneficial outcome.

The field phase in stage 1 for the first year should concentrate on the establishment of an atmospheric monitoring station (rainfall rate, net radiation, windspeed, wet and dry bulb temperatures, soil temperature), interception measurements, soil moisture and watertable monitoring, and groundwater salinity measurement as well as the community survey. This data collection could be coupled to the running and testing of simple analytic and numerical models, such as SUTRA and SEPRAM, to determine their applicability to predicting the permissible groundwater extraction rates.

Concurrently with this work should proceed on examining the usefulness of scintillometry for measurement of total evapotranspiration losses and links with TOGA COARE could be established. Stage 2 should then focus on the deployment on the scintillometer over a lengthy period. During stage 2, heat pulse measurements of sap flow could be carried out to determine the tree transpiration contribution to total evaporation. These should be coupled with groundwater and rain tracer measurements. The deployment of heat pulse measurements prior to stage 2 is not warranted.

It is clear that a detailed plan for stages 1 and 2 should be constructed as soon as possible.

## 8. CONCLUDING REMARKS

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This review has attempted to examine critically the issues in estimating the freshwater–lens groundwater resources of small coral islands It has highlighted several areas which need to be addressed in order to manage these water resources effectively. The most critical of these is that major portions of the water balance, tropical rainfall, evapotranspiration, outflow from the lens and mixing with the underlying seawater remain only plausible estimates. Actual evapotranspiration losses by may be overestimated by up to 20%. Not only is it in general unknown, but there are very few techniques available for measuring it directly. Techniques, which have been successful in continental measurements, are mostly inappropriate for the limited fetches of small coral atolls. Few of the world leading meteorologists questioned could suggest reliable schemes. One technique which does seem suited is optical and microwave scintillometry but these are only in development phase. It will be a major project to test and develop the technique for demonstration on tropical islands. It is believed, however, that that effort is a worthy goal for UNESCO.

It is important to assess how critical these gaps in our knowledge of the water balance are. If evapotranspiration is overestimated, as appears likely with current estimates, then our estimates of permissible extraction rates will be conservative and err on the side of under utilisation. This will mean that more of the water resource outflows to the sea. If optimal rates of extraction are determined through better predictions or measurements of evapotranspiration, then salt water intrusion could occur due to too small tolerances for operational errors. This seems to indicate that a year-long study of the groundwater dynamic coupled with model predictions could prove useful in identifying extraction rates.

Other issues identified in this review include:

- the appropriateness of Penman and Priestley-Taylor potential evaporation estimates;
- the applicability of equilibrium evaporation to both long and short term evapotranspiration from small coral islands;
- the adequacy of daily rainfall for determining recharge in highly permeable areas subject to convective storms;
- the appropriateness of raingauges for measuring intense rainfalls;
- the possible application of Doppler weather radar for monitoring atoll rainfall;
- the usefulness of information generated from TOGA COARE for small island hydrology;
- the establishment of links with TOGA COARE rainfall group;
- the use of aircraft platforms for measuring island evapotranspiration;
- the potential of optical and microwave scintillometry for determiningg island-scale evapotranspiration;
- a re-examination of the usefulness of tracer and stable isotope measurements in rain and groundwater for recharge estimation
- the use of stable isotopes in coconut trees to examine the source contribution of ground and soil water;
- the potential for TDR to quantify the soil water dynamics of small coral islands; and
- a re-examination of stage 1 of the UNESCO project be in light of this report.

It is clear that the UNESCO project was based on the assumption that “off-the-shelf” techniques for measuring evapotranspiration losses in the water balance equation were available. Because they are not yet at that stage it is recommended that the staging of the project be re-visited and that priority be given to developing and testing a suitable technique.

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