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Challenges in freshwater management in low coral atolls

Ian White [a,*], Tony Falkland [b], Pascal Perez [c], Anne Dray [c], Taboia Metutera [d], Eita Metai [e], Marc Overmars [f]

[a] Centre for Resource and Environmental Studies, Institute of Advanced Studies, Australian National University, Canberra, ACT 0200, Australia
[b] Ecowise Environmental, ACTEW Corporation, PO Box 1834, Fyshwick ACT 2609, Australia
[c] CIRAD Montpellier France and Resource Management in the Asia-Pacific Program, Research School of Pacific and Asian Studies, Institute of Advanced Studies, Australian National University, Canberra, ACT 0200, Australia
[d] Public Utilities Board, Betio, Tarawa, Republic of Kiribati
[e] Water Engineering Unit, Public Works Department, Betio, Tarawa, Republic of Kiribati
[f] South Pacific Applied Geoscience Commission, Suva, Fiji

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Abstract

Population centres in low atoll islands have water supply problems that are amongst the most critical in the world. Fresh groundwater, the major source of water in many atolls, is extremely vulnerable to natural processes and human activities. Storm surges and over-extractions cause seawater intrusion, while human settlements and agriculture can pollute shallow groundwaters. Limited land areas restrict freshwater quantities, particularly in frequent ENSO-related droughts. Demand for freshwater is increasing and availability is extremely limited. At the core of many groundwater management problems are the traditional water ownership rights inherent in land tenure and the conflict between the requirements of urbanised societies and the traditional values and rights of subsistence communities living on groundwater reserves. Resource limitations and geographic isolation restrict the potential for increasing wealth through crop exports. Water governance reforms and the provision of knowledge to communities are critical. Regional water organisations, fostering self-support, are a key to developing island-adopted and owned solutions.

Keywords: Groundwater; Atolls; Water pollution; Drought; Seawater intrusion; Freshwater lens

1. Introduction

Seawater intrusion is a significant threat to fresh groundwater supplies in the coastal zones of many water-stressed countries. The problem is exacerbated in small island nations. There are over 50,000 small tropical islands in the Pacific, Indian and Atlantic Oceans, of which about 8000 are inhabited. Many are classed as very small islands, with land areas less than 100 km^2 or a maximum width of less than 3 km, and formed as sand cays, coral atolls or small elevated limestone islands where surface water resources are non-existent and fresh groundwater resources are very limited.

Many small island countries have relatively high rainfalls yet face water problems that are amongst the most critical in the world [1] especially in urban and peri-urban low coral atoll communities, on which we shall concentrate here. The storage of freshwater in atolls is constrained by very small land areas, atoll geology, pressures of human settlements, agricultural activities and waste disposal [2]. Conflicts over traditional resource rights, capacity and resource limitations, frequent droughts and seawater inundation during storms add to the difficulties of freshwater management [3,4].

Traditional, subsistence crops, such as coconuts, swamp taro, breadfruit and pandanus, compete directly with humans for freshwater [5]. Rainwater harvesting from roof catchments is only practised on a small scale and in many cases is a secondary source for freshwater supply. In rapidly growing urban atoll communities, water-borne diseases are often endemic. As

* Corresponding author. Tel.: +61 2 6125 0660; fax: +61 2 6125 0757.
E-mail address: ian.white@anu.edu.au (I. White).

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a consequence protection of human health is of paramount concern. In populous atolls land is scarce and the potential to increase wealth through irrigation or tourism is restricted.

In this paper we examine the nature of freshwater in atolls, its interaction with seawater, its vulnerability, demand and management, governance, water-related wealth generation and examine mechanisms for addressing threats to atoll water supplies and island communities.

2. Freshwater in low coral atolls

2.1. Sources of freshwater

Freshwater in most low atolls is supplied from rainwater tanks, domestic groundwater wells, or, in urban areas, from reticulation systems sourced mainly from groundwater. Several islands, such as in the Maldives or Kiribati, augment these sources with seawater desalination, however desalination requires trained personnel, reliable power supplies and regular maintenance. Freshwater importation, used during droughts in Fiji and Tonga and as the main source of water in the past for Nauru, is expensive, particularly for isolated islands. Atoll soils are mostly coarse coral sands so that surface runoff is minimal with little opportunity for surface water storage. In some islands, such as Majuro in the Marshall Islands, water harvesting from impermeable surfaces such as sealed runways is used to divert runoff into tanks or shallow storages. Evaporation losses from shallow storages can be large in the tropics. Groundwater and stored rainwater are therefore the predominant sources of freshwater [4].

2.2. Fresh groundwater lenses

Groundwater occurs as a thin lens of freshwater 'floating' over seawater in coral sand and limestone aquifers (see Fig. 1). This shallow freshwater lens is fed by rainwater recharge through the coral sands. Coconut trees tap into and transpire shallow groundwater at rates of approximately 150 L/tree per day [6]. Groundwater is extracted using domestic wells and groundwater pumping schemes (see Fig. 1). Freshwater is also lost from the lens through discharge to the ocean or lagoon at the island margins. Geologically recent (<10,000 years BP) coral sands and gravels are deposited on older, karstic limestone seawater aquifers [7]. These limestone aquifers transmit tidal pressures beneath atolls and groundwater lenses rise and fall in a lagged response to the tide, mixing fresh and seawater [8,9]. Tidal mixing is another process causing freshwater loss and leads to the development of thick, brackish, transition zones between freshwater and seawater below the lenses (see Figs. 1 and 2). Fresh groundwater in low atolls is therefore balanced between episodic rainfall replenishment and continual depletion by evapotranspiration, extraction and outflow to and mixing with seawater.

2.3. Fresh groundwater quantities

Small land areas in atolls often restrict freshwater supply to mainly basic human needs. The quantity of fresh groundwater contained in lenses depends on atoll width, recharge rate and the ease of transmission of freshwater through the aquifers. Wider islands with high recharge rates and less permeable

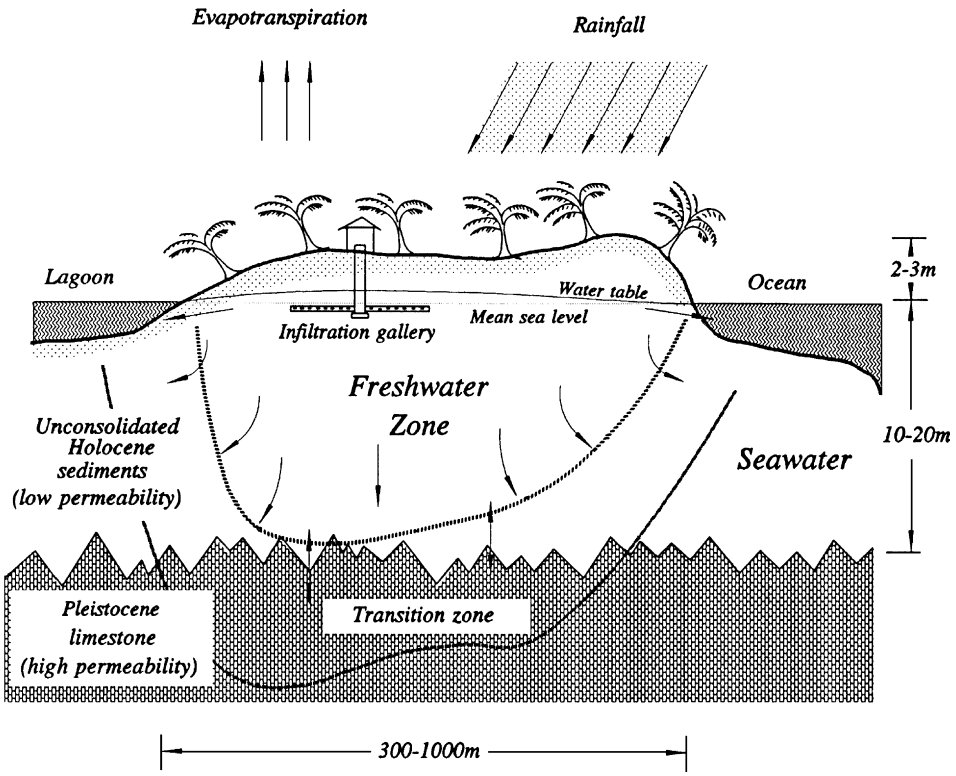

Fig. 1. Vertically exaggerated cross-section through a low coral island showing the fresh groundwater lens surrounded by seawater.

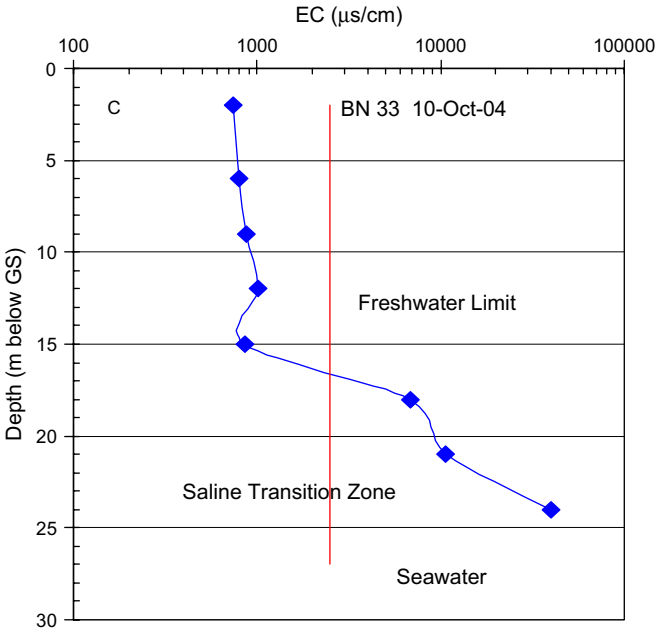

Fig. 2. Salinity (electrical conductivity, EC) profile (depth below ground surface, GS) through a fresh groundwater lens in Bonriki island, Kiribati. The limit of freshwater in atolls is usually taken as EC = 2500 µS/cm so that the thickness of freshwater at this location is around 16 m.

aquifers generally have thicker freshwater lenses, which are good sources for reticulated water supply systems. The challenge in population centres is to determine long-term sustainable groundwater extraction rates. Narrow atolls with transmissive aquifers, as in some atolls in Tuvalu, have limited potential for viable fresh groundwater. For these islands rainwater tanks and desalination appear the only viable options [4].

Sustainable groundwater extraction and use of stored rainwater to maintain freshwater supply throughout droughts is a critical issue for urban areas. Often the storage volumes of rainwater tanks are not sufficient to maintain supply in the severe droughts, which are quite frequent, especially in the central Pacific. Sustainable groundwater extraction requires data on recharge rates, demand and the response of freshwater lenses to losses. Sufficiently long monitoring records are available in only a few atolls [4]. Surrogates, such as sea temperature and rainfall inferred from coral cores, provide useful guides to past extreme events [10].

3. Vulnerability of freshwater in atolls

3.1. Natural threats

Fresh groundwater in low coral atolls is vulnerable to natural processes and human activities [11]. Drought, storms and climate change affect both quantity and quality of groundwater in atolls. Annual rainfalls in many atolls exhibit large variability due to frequent ENSO-related droughts. Droughts decrease the thickness of freshwater lenses (see Fig. 3) and increase the salinity of fresh groundwater (Fig. 4).

Roof catchments and rainwater tanks are generally small and are vulnerable during droughts. Severe droughts have

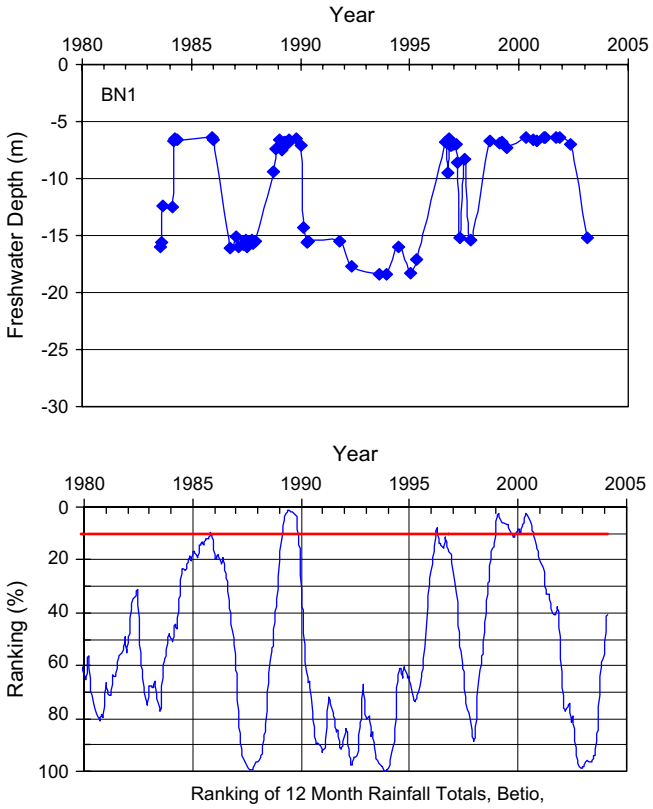

Fig. 3. Change in the freshwater depth at the edge of a large freshwater lens Bonriki island, Tarawa atoll, Kiribati. Droughts in 1984, 1989, 1996 and 1998–2002 are evident by comparison with the 12 month rainfall percentile ranking.

forced the evacuation of some atoll communities in the Pacific. The prediction of, planning for and response to droughts are priorities in small islands [11,12].

Inundation of low atolls by waves during storms can salinise shallow groundwater. Predicted climate change impacts, particularly sea level rise, therefore causes anxiety. Normal migration of the Pacific warm pool across the central Pacific in response to ENSO events already produces sea level rises of around 0.25 m. Preliminary estimates of climate change

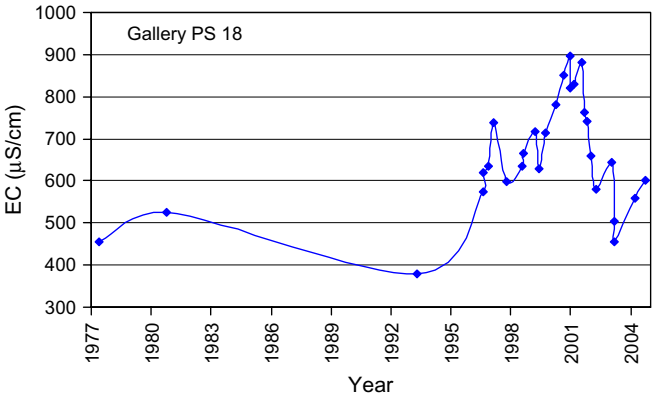

Fig. 4. Changes in shallow groundwater salinity (as electrical conductivity, EC) in an infiltration gallery pumping station near the centre of the Bonriki freshwater lens, Tarawa atoll, Kiribati.

impacts on atoll groundwater indicate that the potential change in rainfall is the most important factor. Small sea level rises with current mean rainfall may slightly increase quantities of fresh groundwater in some atolls [13].

The impacts of climate change, particularly sea level rise, have been seen by many as the greatest threat facing low, small island nations. Comparatively large commitments of human and financial resources have been devoted to exploring the vulnerability of small island communities to climate change and to developing adaptation strategies. These efforts have largely failed to recognise that, even now, mean sea level in the central Pacific can change by as much as 0.4 m in an ENSO event and that densely populated islands have not coped particularly well with past droughts and floods. Living with and managing through current climate variability are continuing challenges that need priority attention.

3.2. Threats associated with human settlement and wastes

Overpumping of fresh groundwater and inappropriate extraction wells can salinise atoll groundwater. However, biological and chemical pollution of drinking water and its impact on human health are of more concern. Groundwater contamination caused by sewerage, pigs, crop production (Fig. 5), spillage of petroleum products, and seepage from waste dumps occurs in many small islands [9].

The most critical factor influencing groundwater contamination is the depth from the surface to the watertable [14]. In atolls this depth is often less than 2 m, and surface contaminants can reach the groundwater in less than 2 h. Swamp taro pits, excavated into watertables, are significant sources of pollution. Faecal contamination of groundwater is a major source of gastroenteritis in atoll communities, causing high infant mortalities and outbreaks of diseases like hepatitis, typhoid and cholera. Domestic wells close to dwellings and pit latrines are especially vulnerable [9].

Defecation on the beach is practiced in many low-density island communities. In higher density populations pit latrines are also used. Their siting is critical as they can introduce faecal contaminants directly into groundwater. Flushing toilets can consume 30–40% of water supplies and there is little scope for freshwater sewerage systems in many small islands [4]. Majuro in the Marshalls and South Tarawa in Kiribati have saltwater sewerage systems. Leakage from saltwater systems may add to salinisation of groundwater, particularly in dry periods. Elsewhere, composting toilets have been trialed; however, there are sometimes cultural barriers to their adoption [9].

Protection of water supplies from contamination remains one of the greatest challenges for small island communities.

4. Protection of groundwater sources

4.1. Groundwater reserves

In atolls with freshwater reticulation systems, some governments have created groundwater reserves in attempts to exclude settlement, restrict land use and minimise risks of human contamination. Increasing encroachment on reserves due to population growth and population densities as high as 15,000 people/km^2, however, have forced the abandonment of groundwater reserves in some atoll islands.

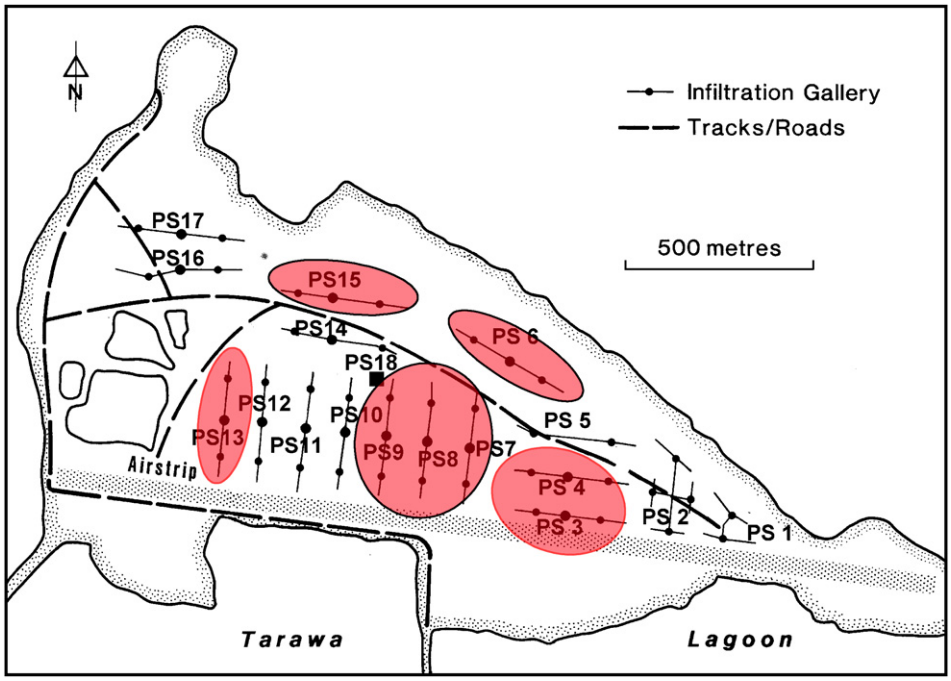

Fig. 5. *E. coli* contamination of infiltration gallery pumping stations at Bonriki water reserve, Tarawa atoll, Kiribati, which is related to agricultural and human land use.

Land ownership and traditional land use rights are central issues in the establishment of water reserves. Many island families have long-established interests in land and most rely on their lands for subsistence, even in urbanised areas. Land provides groundwater, food, attendant fishing rights and cash income from copra harvesting [15]. Traditional land ownership involves ownership of groundwater, a fact seldom appreciated when water reforms, such as state ownership of water, the introduction of water pricing regimes and the concept of water as a commodity which is separable for land are proposed by large donor agencies. This appears to be one of the fundamental reasons why many small island countries have been reluctant to introduce national water policies.

4.2. Conflicts over reserves

Given the traditional linkage between land ownerships and water rights, it is easy to appreciate why the declaration of water reserves by governments generates conflicts with landowners and users of reserves, sometimes even resulting in infrastructure vandalism [5]. Payment of adequate compensation and restricted land uses are continuing contentious issues. Wider communities regard designated water reserves as common property whose resources can be plundered. Squatting, market gardening and pig-raising also occur.

It has been suggested that governments should pay reserve landowners as custodians of reserves rather than pay rentals or compensation for groundwater reserves [5]. Also exploration of acceptable land uses on water reserves needs to be further explored. Settlements have been permitted around the perimeter of water reserves where groundwater discharges seawards (see Fig. 1) to reduce conflicts and address land shortages [3]. A novel solution for crowded atolls is the creation of solely government-owned water reserves on artificial islands formed using dredged lagoon sediments [3]. Dredging, however, may present some environmental impact problems.

Conflicts between local communities having rights over water reserves and their governments can be lengthy and debilitating. A number of proposals for addressing conflicts have been proposed. Conflict resolution and negotiation support strategies using multi agent systems are also being trialed in small island communities [16].

5. Demand and its management

Per capita consumption of freshwater in most small island countries is increasing. Past designs for freshwater reticulation systems in atolls have used 30–50 L/capita per day as the demand estimate [4]. Growing expectations in larger villages suggest 100–150 L/capita per day is a more reasonable estimate. Leakage from reticulation systems is endemic with rates over 50% not uncommon. Leakage control increases water availability and reduces costs substantially [1]. Some reticulation systems are unable to meet demands and losses so that water is supplied for only a few hours per day as *de facto* demand management. Because of uncertainty of supply in these situations, people leave taps open to intercept the supply. This greatly increases losses. Urban communities therefore often supplement water supplies using domestic wells and small rainwater tanks. During droughts these are quickly exhausted or contaminated.

Resettlement of communities to uninhabited atolls is planned in some countries to lower population pressures. Few governments, however, have sufficient resources to make this attractive for people drawn to the facilities available in towns such as schools, hospitals, and electricity. Metering and charging for water supplies, a long-recognised demand management tool is successful in some small islands [4]. Where lack of resources is significant, there is reluctance to introduce metering, or it has been abandoned in favour of flat fees, containing no conservation message. Water revenues, where collected, are mostly inadequate to cover operation and maintenance [17]. A novel approach to demand management is being trialed in Kiribati. Small, single dwelling storage tanks (500 L) are filled continually from the reticulation system by a slow trickle feed, sufficient for a family's daily demand. Conservation of water then becomes a household responsibility. Behavioural change is fundamental for conserving and protecting water and education and awareness programs have increased, particularly in the Pacific [18].

6. Policy and institutions

6.1. Water as a common pool resource

Water is usually treated as a common-pool resource in many small island nations. Property rights and responsibilities are often undefined. Over the past decade, institutional reforms have swept through the developed world water sectors, where ownership of water is usually invested in the State. There is a general reluctance in small island nations to adopt national policies and pursue developed world institutional reforms because land tenure often implies customary 'title' to water [7].

The notion of water as an environmental resource seems not in tune with water-related public-health concerns in small islands [19]. As well, water reforms such as the separation of supplier and regulator are impractical in small islands with as few as two or three water professionals. Water reforms raise constitutional, ethical and social issues, issues of community concern. Many small island governments are reluctant to entrain communities in the debate [19]. Vital local community participation in water and related land resources management and use is therefore restricted. In addition, aid donors seldom recognise the lengthy period required for adequate community consultation in atoll communities.

6.2. Institutions and capacity

Because of limitations or non-existence of national water policies or comprehensive water and sewerage laws, government agencies involved in water and wastewater management often have no clearly defined roles and responsibilities. Existing institutions frequently inherited responsibilities for water from older legislation and past administrations. Overlaps in

responsibilities and roles persist, and uncertainties in water management result. Agencies are reluctant to cooperate and share information [18]. Urban and rural water supplies are frequently under different organisations but urban water suppliers have the concentration of water expertise and resources.

Water utilities across the Pacific have identified insufficient institutional capacity, lack of government support, insufficient community support and widely scattered multiple-island states as constraints to achieving sustainable water and wastewater management [20]. Common regional concerns such as limited land area, competing land use, increasing demands, lack of resources, large distances and lack of coordination between donors and international organisations also emerged. Because of common problems and restricted national capacities in small island countries, regional water organisations such as the South Pacific Applied Geoscience Commission, the Pacific Water Association and the South Pacific Regional Environment Programme can play key roles in building self-reliance in small island countries. In the past, aid donors have overlooked or ignored the potential of such regional organisations. To be successful, regional organisations need to build long-term relationships and be adequately resourced.

There is no single reform process applicable to all small island nations in the Pacific. A number of national building blocks have been identified that may be useful [19]. These include: water sector assessment; agreement on a broadly based water vision; the development of water action agenda and plans; design of capable institutions; integrated investment plans; regional support; active initiation of dialogues with investors and donors. Awareness raising and genuine consultations with island communities are also central to any reform process. Water reform is a complex, long-term process in which Pacific-generated and locally owned solutions are required.

7. Wealth generation, water and aid

Water can play an important role in creating wealth [21]. However, benefits of increased growth from water infrastructure projects are reduced by inequitable income distribution [22]. Donor agencies in the past have funded large water infrastructure projects in small island communities resulting in the loss of householder responsibility for water conservation and protection [18]. Widespread criticism of aid projects has led to calls for 'pro-poor' growth assistance with emphasis on improved management efficiency, institutional reforms and community participation. Poverty in Asia-Pacific is claimed to stem from institutional weakness and policy failures that prevent countries from taking advantage of the opportunities of globalisation and coping with its risks [22].

Lessons from other regions in the world that rely on freshwater both for subsistence and wealth generation are pertinent. In the Mekong, six factors have been identified that could cause relative poverty to increase [22]:

- continuing deterioration of natural resources, on which the poor depend;
- the conflict between national laws and customary rights;
- spending of public resources on large infrastructure projects rather than on social investment;
- inherent inability to transfer the opportunities of globalisation to the poor and its relation to property rights;
- institutional failures, conflicting jurisdictions and agendas between government agencies; and
- reluctance to empower community participation in natural resource management.

Some of these factors are apposite to small island nations. However, in atolls, most inhabitants own land so that true poverty in the sense of landlessness is seldom encountered. Also, the potential for small island communities to participate in the benefits of globalisation through irrigation are limited by restricted land areas, acute water shortages during dry times and their isolation from markets. Some niche markets exist, such as the production of squash pumpkins in Tonga, but these are mainly confined to larger, higher, volcanic islands with fertile soils. Tourism could increase wealth generation in atolls, but it has high per capita water demands.

While the potential for high-value crop exports from atolls is limited, production of fruit and vegetables for local urban markets is an important source of cash income for the underprivileged poor. Frequent hand irrigation is required because of the permeable nature of the coral soils and the use of pig manure or mineral fertilisers threatens groundwater. Water and nutrient efficient hydroponic vegetable production is being trialed by some atoll communities. Its long term viability during dry periods when supply water salinity increases may be a problem.

Aid addressing institutional weakness, policy failure, property and customary rights, community empowerment and the deterioration of water and associated land resources together with providing the broad community with appropriate knowledge and information may provide the greatest benefits [22]. These, however, require long-term commitment and partnerships with regional and non-government organisations.

8. Conclusions

Sustainability problems faced by small island countries also occur in other developing regions. Lack of resources, deterioration of water sources, institutional failures, access to knowledge and information, restricted capacity and conflicting jurisdictions and agendas between government agencies are common. Three central issues are also shared. These are the tensions between the demands of urbanised societies and the traditional values, customs and rights of subsistence communities; land tenure and its attendant customary rights; and the lack of genuine community participation in debate and decision-making [22,23].

The extremely limited land area in atolls, their geographic isolation and hydrogeology, and the ever-present threat of seawater incursion pose unique problems that constrain sustainable development and wealth generation and threaten water supplies as populations increase. Regional pooling of expertise through partnerships with adequately resourced, long-lived regional organisations has the potential to overcome capacity

limitations in small island countries. The provision of reliable information on the quantity and quality of freshwater, demand, drought strategies, risk reduction and appropriate policies and management systems is vitally important.

The *Pacific Regional Action Plan on Sustainable Water Management* [24] addresses issues of water management, island vulnerability, awareness, technology, institutional arrangements and finance. It is an example of the strength of regional partnerships in water. Developed-world water policies and reforms that conflict with traditional rights and values of small island countries will only be adopted when the need for them is recognised and they are adopted and owned by island communities. Behavioural change at all levels is fundamentally important for conserving and protecting water in small islands but this requires appreciation of the unique cultural, social, economic and geographical contexts of small islands and long-term commitments.

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