

Aquifer vulnerability on small volcanic islands in the southwest Pacific region — an example from Norfolk Island

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Island ecosystems in the southwest Pacific region are noted for their fragility and susceptibility to degradation, particularly in regard to groundwater systems. In general, island aquifers are relatively free of major pollution problems, but human development suggests that potential long-term dangers exist. The character of groundwater resource development on small islands in this region is reviewed with regard to geologic framework, water availability, recharge, and aquifer risk. Norfolk Island serves as a case study of aquifer vulnerability on a small volcanic island. The research and training needs for the long-term protection of island water resources are briefly outlined.

Introduction

Water is the most critical of all resources on oceanic islands. In the Pacific Ocean alone there are over 30 000 small islands most of which are in tropical regions; the number of populated islands is in the order of 1000. For the purpose of this paper, the introductory material draws heavily on information given in Falkland (1991, 1992) and refers mainly to islands in the southwest Pacific Ocean region (Fig. 1). The area selected for the upper limit of a small island is 2000 km^2, but many are smaller having areas of less than a few hundred square kilometres.

On small islands, groundwater resources are generally available in limited quantities. This is evident on low-lying limestone islands and coral atolls where groundwater occurs as freshwater lenses. Many small islands have or are beginning to experience major problems with the availability, over-extraction, and pollution of their limited water resources, largely induced by increasing population. Water demand has risen significantly as living standards have improved. Competition has developed for the availability of water between urban and rural communities, tourism and small agro-industries (e.g. sugar, oils, and copra). Adverse impacts are over-pumping of groundwater leading to increases in salinity of water. Faecal contamination of groundwater by infiltration from closely located sanitation facilities is a common problem on many crowded islands. The use of biocides and fertilisers is an emerging problem.

The susceptibility of tropical islands to natural disasters (e.g. cyclones, earthquakes, and volcanic eruptions) and water supply degradation is generally higher than on continental land masses. Their isolation from sources of materials and equipment, high costs of freight, and often a lack of trained professional and technical staff make water resource development a challenging problem for island communities.

Hydrogeological framework

In general, small islands in the southwest Pacific Ocean can be topographically subdivided into *high* and *low* islands. The high islands are principally composed of an emergent or submerged volcanic core of basalt often surrounded or capped by thick coral limestone (raised atolls). These islands are older and much larger than low islands, the latter consisting mainly of coralline atolls standing only a few metres above sealevel. Further, high volcanic islands fall into two geological provinces, namely *continental* and *oceanic* (Peterson, 1984). The former are associated with island arc volcanism and lie on the continental side of deep ocean trenches (zone of plate subduction). The water-bearing properties of the volcanic rocks are generally poor since low-porosity and/or low-permeability submarine basaltic pyroclastics and deeply weathered lavas predominate. Typical examples of island groups within this province are the Solomon Islands, Vanuatu, Fiji, and Norfolk Island (Fig. 1). Islands with oceanic affinities are associated with intraplate volcanism and lie on the ocean side of the subduction zone. The volcanic rocks in this province are typically youthful basaltic lava flows which may be extremely permeable and provide important aquifers, e.g. Hawaiian Islands, French Polynesia, and Samoa (Fig. 1).

For hydrogeological purposes, islands with an emergent volcanic core may have a rugged interior, e.g. Rarotonga (Cook Islands) and Western Samoa, from which rainfall shed as surface runoff may provide viable water supplies (Dale & Waterhouse, 1985). That part of rainfall that percolates to the water table can be perched or confined to fracture systems and sedimentary interbeds which behave independently from each other because of vertical and/or horizontal low permeability barriers, such as dykes or buried soils (e.g. Hawaiian Islands.) Groundwater will move to lower levels, where it may accumulate as basal water to form for most practical purposes a freshwater lens. The highly variable geology of volcanic rocks makes it difficult to identify and manage the subsurface components that control groundwater. *Raised atolls* with a submerged volcanic core, surrounded and capped by generally thick coral limestone, are assumed to have formed in response to tectonic uplift and subsidence of the volcanic edifice, e.g. Tongapatu, Niue, and Nauru. On these islands, no streams are present and the karst topography allows rainwater to penetrate rapidly to a freshwater lens. Overpumping with consequent lowering of the lens surface to or below sealevel will induce seawater intrusion. *Coral atolls* normally occur as a ring of closely spaced coral islets encircling a shallow lagoon varying in diameter from 1–100 km. The submerged deeply buried rock core is presumed to be volcanic, e.g. Kiribati, Tuvalu, Tokelau, northern Cook Islands, and several examples in French Polynesia. A limited groundwater source may, with care, be exploited from a thin freshwater lens underlying the atoll.

Water availability

The availability of groundwater from storage is influenced by the size of the island, recharge patterns, and a wide spectrum of geological conditions. The turnover time of groundwater systems on small islands tends to be short (a

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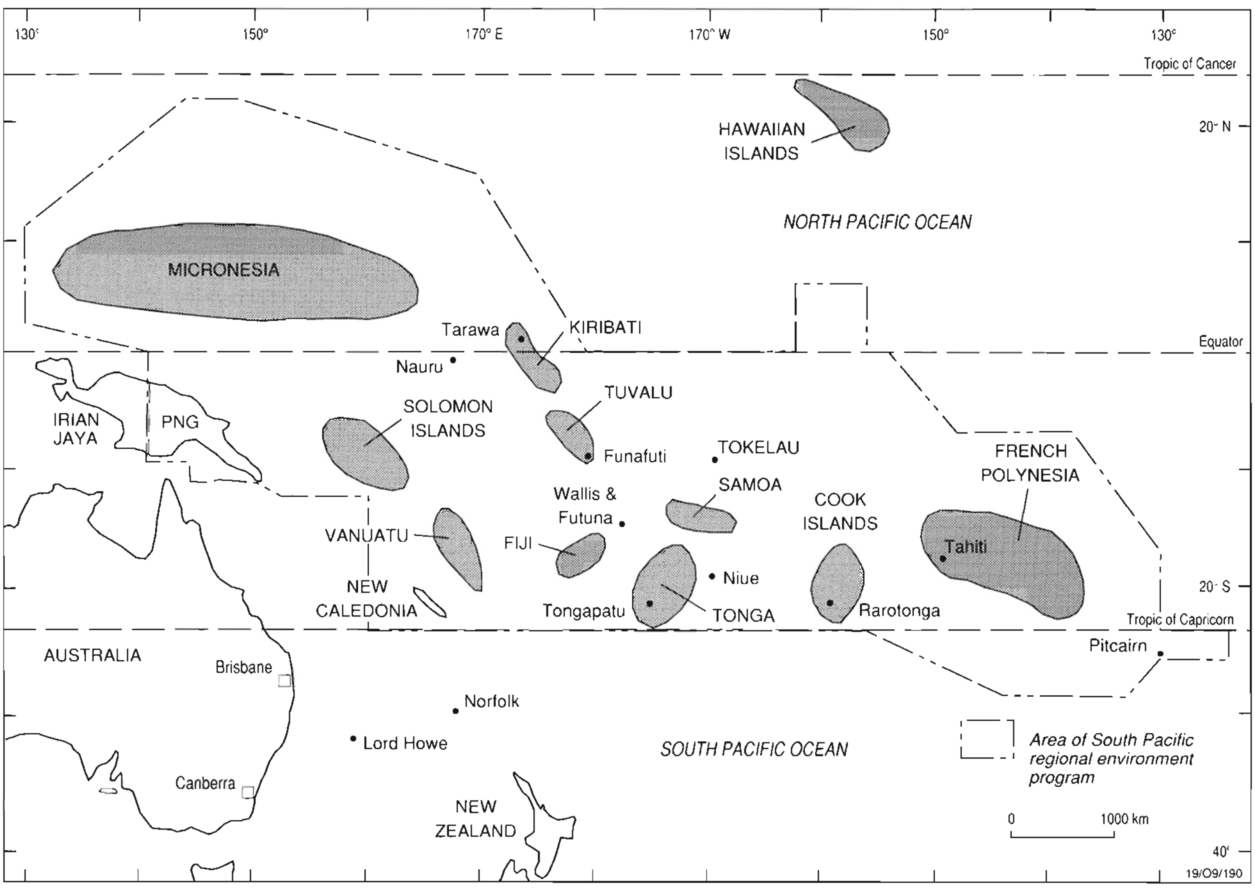


Figure 1. Island groups of the southwest Pacific Ocean.

few years at most). Thus, perched aquifers and freshwater lenses may deplete in dry seasons to a stage where there are minimal or no freshwater resources. In some cases, the rocks may be too permeable to enable a freshwater lens to form. Few high islands have topographical and hydrological conditions suited to the construction of significant water storages. Catchments are often large in number, but small in size; natural runoff of more than a few tenths of litres/second cannot be guaranteed. Other sources of freshwater are rainwater collected from roofs and other surfaces, desalination of seawater, importation, treated wastewater, and substitution (e.g. coconut juice).

Recharge

Recharge processes on small islands are largely influenced by rainfall, evapotranspiration, vegetation, and soil. The tropical areas of the Pacific Ocean are affected by warm, moist northeast and southeast trade winds, which generally result in heavy rainfall. Controlling mechanisms affecting regional variability of rainfall include tropical cyclones, El Niño Southern Oscillation (ENSO) events, and long-term climatic change including 'the greenhouse effect'. Local rainfall variations due to the orographic effect are evident on high islands. Evapotranspiration can be more than the rainfall on an annual basis and often exceeds the rainfall for individual or consecutive months during dry seasons or droughts. Despite its importance, evapotranspiration is the least-quantified component of the water balance on small islands. Vegetation affects recharge by intercepting a part of rainfall and by causing transpiration. Depending on the depth to water and the type of vegetation, direct transpiration losses may be promoted as in coconut trees on coral atolls (losses of 70–130 litres/day). In other respects, a vegetation cover is desirable for food and reduction in surface runoff and erosion. The ability of soils to hold water is important for recharge generation. High water retention (clayey) soils favours evapotranspiration, thus reducing effective rainfall while low water retention (sandy) soils allows rainfall to penetrate below roots to the water table.

Aquifer risk

Despite their limited area, small islands often have high population densities which place great stress on natural water resources. People not only create high demands for water, but also increase the risk of pollution since they often *live above* the groundwater used for potable and other purposes. The tourist industry, a major activity on small islands, demands large volumes of water with high physical, chemical, and bacteriological standards. Frequently, tourist accommodation has such a high water consumption that it can severely stress the water resource capacity of an island.

Groundwater pollution may be caused by *natural* or *artificial* processes. The commonest example of the natural process is mixing of fresh groundwater and seawater at the base of a freshwater lens to form a transitional zone of brackish water. The geometry of a lens is dependent on rainfall recharge, rock permeability, tidal fluctuations, and the size and shape of the island. However, the artificial process of overpumping in excess of recharge capacity may aggravate such a system to cause seawater upconing and a thickening of the brackish water zone. The consequences of groundwater pollution last far longer than those of surface water.

Some contaminants are conservative, i.e. they are not eliminated with time in a given environment. Examples are the chloride ion (salinity), while sulphate and nitrate are preserved under aerobic conditions. Other contaminants, such as biocides, are degradable — that is they are transformed into other substances by biochemical reactions. The sandy soils of atoll islands offer weak resistance to the free percolation of contaminants, but clay soils of volcanic islands are effective barriers until their buffering properties (exchange and adsorption) are exceeded.

Typical pollution sources are home sanitation systems (septic tanks and latrines). High bacterial counts may be noticeable in areas with scarce soil and relatively high rock permeability (e.g. coral limestone, recent volcanic rock). Domestic garbage disposal is a major problem, as good sites are hard to find because of unsuitable ground conditions and conflicting land use. Runoff from impervious roads, airport runways and leaking fuel tanks may release hydrocarbons into the groundwater. Contamination from human, animal waste, and agricultural fertilisers is forewarned by increased nitrate concentrations in shallow water table aquifers. Groundwater pollution from pesticides has been detected in small amounts in pineapple plantations on the Hawaiian Islands (Peterson, 1991). Biological contaminants (bacteria and viruses) move in groundwater, but more slowly than water due to adsorption onto solid surfaces. It is probable that island communities have tolerances to water quality levels that may not be acceptable on mainland Australia. A limited amount of published information exists on the bacteriological quality of groundwater on islands (Morrison & Brodie, 1985; Detay & others, 1989).

Norfolk Island

Norfolk Island is a territory of the Commonwealth of Australia, and with an area of 35 km^2 is the largest and only inhabited island of a remote group of three islands in the southwest Pacific Ocean, at latitude 29° S and longitude 168° E (Fig. 2). The island is a small landmass situated on the Norfolk Rise — a pronounced north-trending continental ridge between New Zealand and New Caledonia. Norfolk Island is an erosional remnant of a number of local volcanic centres that erupted several times in the Pliocene between 3.05 and 2.3 Ma ago (Jones & McDougall, 1973). The climate is subtropical with a mean annual rainfall of 1324 mm. May to August are the wettest months (monthly averages of about 140–150 mm), and November to January tend to be the driest (averaging 70–90 mm); cyclonic storms may occur in summer. Periods of low rainfall are

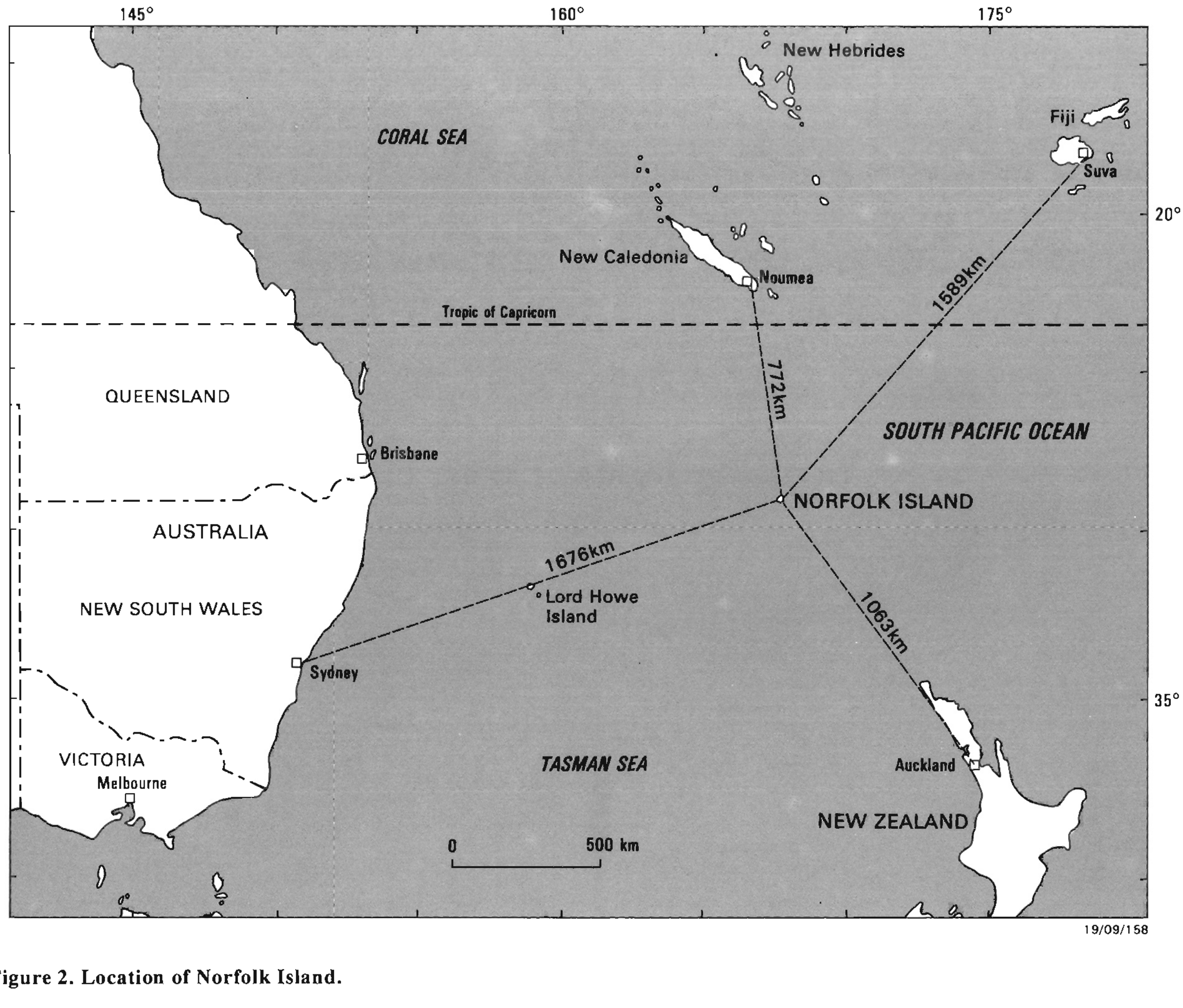


Figure 2. Location of Norfolk Island.

associated with ENSO events (Fig. 3). Mean monthly temperature fluctuates from a minimum of 12° C in winter to a maximum of 25° C in summer. As the weather is under an oceanic influence, there are no extremes of heat or cold, although humidity is generally high during summer months. There is little variation between day and night temperatures (5–6° C). At the August 1991 Census, the population on the island was 1912 (1478 permanent and 434 temporary residents). The majority live in and around the central business area of Burnt Pine–Middlegate.

Geology and geomorphology

The cliffs surrounding Norfolk Island provide a nearly continuous section of the geology (Fig. 4). Outcrop is obscured by a weathered mantle (up to 80 m thick) and in places by thick vegetation. The unweathered part of the volcanic sequence suggests a series of complex and spasmodic eruptive events in which basaltic lava and pyroclastic units were deposited on a series of weathered or eroded topographic surfaces. Hyaloclastite rocks exposed on the northern side of the island represent a lithofacies formed through quenching and fragmentation as subaerial basaltic lava flowed into seawater. Along the shore of the Kingston lowland (and also forming Nepean Island) are exposures of cross-bedded and massive calcarenite originally deposited by on-shore winds during periods of low sealevel in the Late Quaternary. Strips of alluvium occur in active creek catchments.

The geomorphology is dominated by elevated terrain in the northwest, rising to a semi-circular ridge on which Mt.Bates (318 m) is the highest point. The remainder of the island consists of a deeply incised southern plateau, about 100 m high and sloping southeast to a coastal plain at Kingston (Abell & Falkland, 1991). The drainage pattern is typical of volcanic terrain consisting of a network of dry valleys leading into perennial and intermittent streams. Radial drainage occurs around the main volcanic vent. On the southern plateau, jointing has modified the dendritic pattern (tributaries joining the main stream at right angles) developed in the headwaters of each catchment.

Groundwater occurrence

Groundwater functions as a dynamic system within the islands hydrological cycle (Fig. 5). The main agent of recharge is rainfall. An elevated water table in the weathered mantle represents the upper groundwater boundary (Abell, 1976). Groundwater moves laterally in the direction of the water table gradient, discharging either in valley floors where the ground surface intersects the water table or as high-level coastal seepages. At the base of the weathered mantle, hydraulic continuity is maintained as vertical leakage through a network of fractures and interconnected openings in fresh volcanic rock. Some groundwater moving through this system may discharge as coastal seepages close to sealevel, or it may recharge tuff beds and fragmented layers between lava flows to form local semi-confined aquifers; the remainder continues to deeper levels where it is discharged as submarine springs at and beyond the margin of the island or ultimately mixed with seawater in volcanic rocks below sealevel.

Water resource development

The heterogeneous permeability of volcanic bedrock promotes the natural mixing and formation of a brackish zone of groundwater at the base of the island. To some extent this is offset by (a) the high and well distributed annual rainfall, which guarantees rainwater storage, and (b) the clay-rich nature of the weathered mantle which supports limited catchment runoff and a high level unconfined aquifer. Exploitation of groundwater is limited to the southern and northwestern plateaux, where it is tapped by more than 450 wells and bores. Deeper semi-confined groundwater in fractured basalt and interbedded tuff is recovered from boreholes that may reach up to 35 m BSL (Fig. 6). A groundwater recharge estimate of 30% of average annual rainfall (Abell & Falkland, 1991) is based on the relationship $G = P - (E + R)$, where G = recharge, P = rainfall, E = evapotranspiration, and R = runoff. Groundwater is of the NaCl-type, with the salt derived initially from oceanic spray (Fig. 7). The water is generally of good quality and suitable for domestic use (based on a potability of <1000 mg/L). However, rainwater and most groundwaters are acidic, with low pH values (5–7). Hydrogeological factors and water balance data suggest that sufficient resources probably exist for future needs.

Aquifer vulnerability

Groundwater contamination by *natural processes* is evidenced by high salinities associated with the stable chloride ion. The classical Ghyben–Herzberg model of a fresh water lens is not considered totally applicable to Norfolk Island (Abell & Falkland, 1991). The extent of deep groundwater underlying the island is still unknown, but considering the difficult geological conditions (such as presence of fractured volcanic rocks, the effect of tidal fluctuations, and the size of the island), it is expected that the natural thickness of the brackish water transition zone may be substantial. Local pockets of topographically elevated saline groundwater (source unknown) may indicate restricted flow systems within the weathered mantle (Abell & Taylor, 1981).

Artificial pollution, particularly owing to waste disposal, presents special problems (Fig. 8). High levels of bacteriological and chemical pollution from the disposal of sanitary and livestock waste have been detected in shallow unconfined groundwater in the Burnt Pine–Middlegate area. Around the island perimeter there is evidence that localised pumping can induce seawater intrusion to bores tapping bedrock aquifers at or below sealevel (Abell & Falkland, 1991). Until recently, the treatment and disposal of sewage from private homes and communal establishments was through a septic tank system with the effluent draining to absorption trenches in the ground. Larger establishments, such as hotels and the hospital, were served by package treatment plants generally of the 'activated sludge' or 'Imhoff' types. Effluent from such plants was discharged into absorption trenches, disposed onto the ground surface with overland drainage to creeks, or in one case discharged down a borehole. Effluent discharged into or on the ground percolates through the soil into the weathered mantle, where it acts in most cases as a form of recharge to the water table. During droughts, summer months, or at times when demand is high (tourist season), the constant re-use of shallow groundwater with a component of sanitary waste tends to increase salinity levels (closed system circulation). In the past, bacteriological tests on groundwater have indicated high levels of faecal contamination (Goldfinch & Cross, 1980; DHC, 1987). A program of testing on 150 groundwater samples in 1981–83 showed that 68 exceeded the *E.Coli* guideline value (1/100 ml), while many others exceeded the total coliforms guideline value (10/100 ml). The distribution of nitrate in the groundwaters is uneven; most contain some

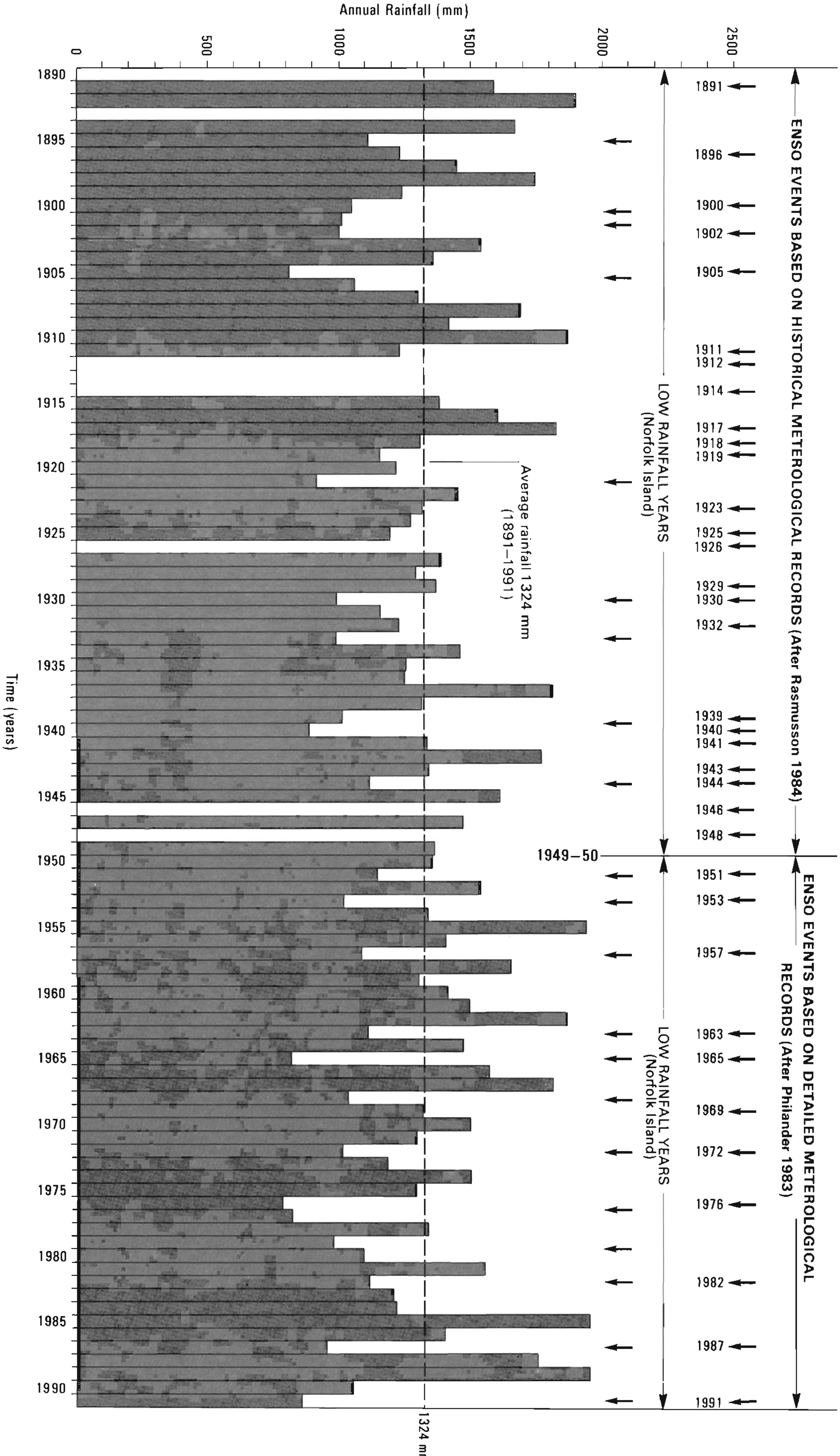


Figure 3. Annual rainfall record on Norfolk Island.

nitrate, but values of >10 mg/L and up to a limit of 45 mg/L are mainly associated with wells (uncased) which tap only the upper part of the saturated zone in the weathered mantle where groundwater moves seasonally under oxygen-rich conditions. The higher nitrate levels are attributed to domestic and livestock waste. Livestock wanders freely over the island and distributes considerable amounts of waste. High livestock densities also occur around watering points and at the dairy farm.

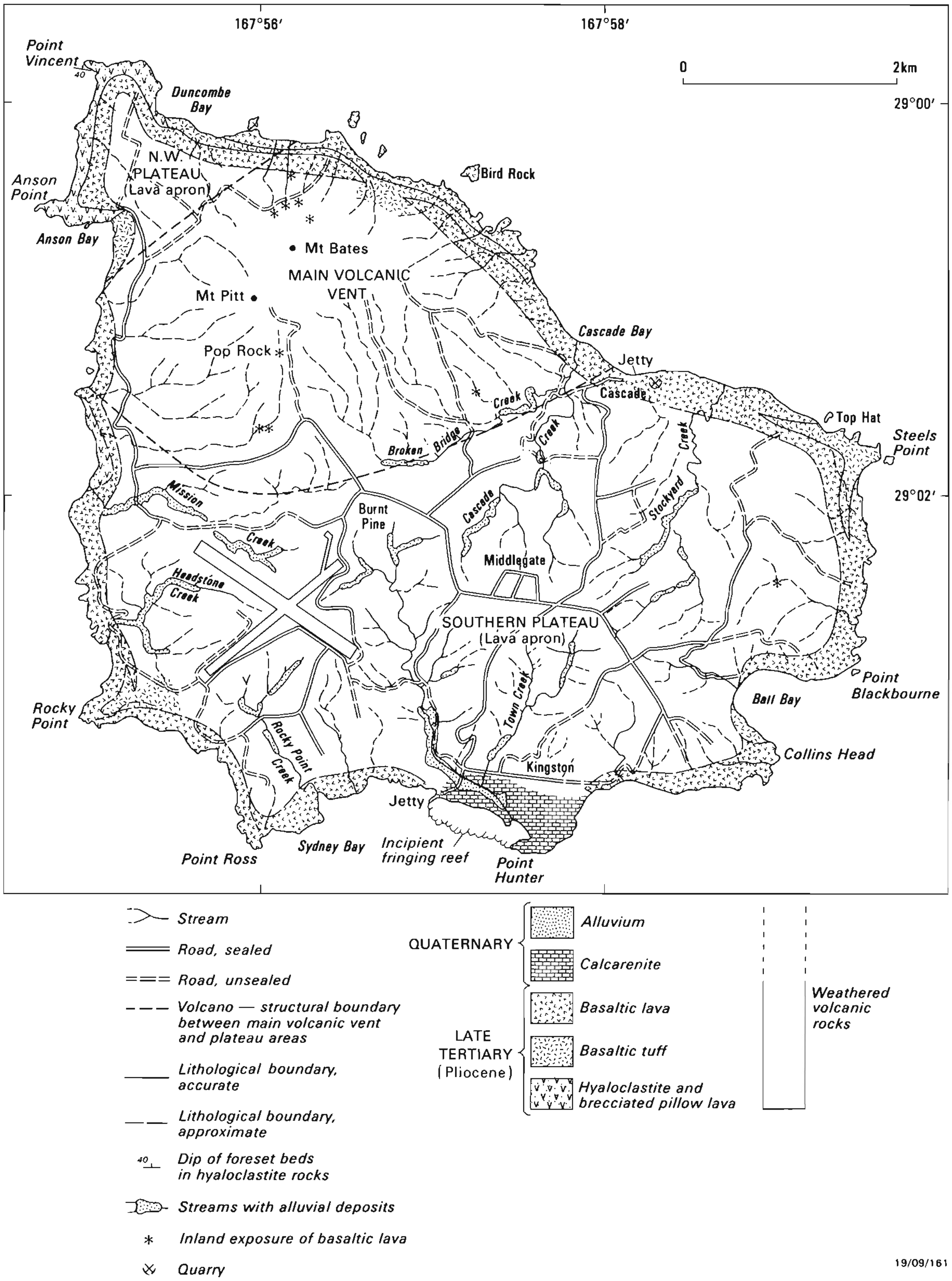


Figure 4. Geology of Norfolk Island.

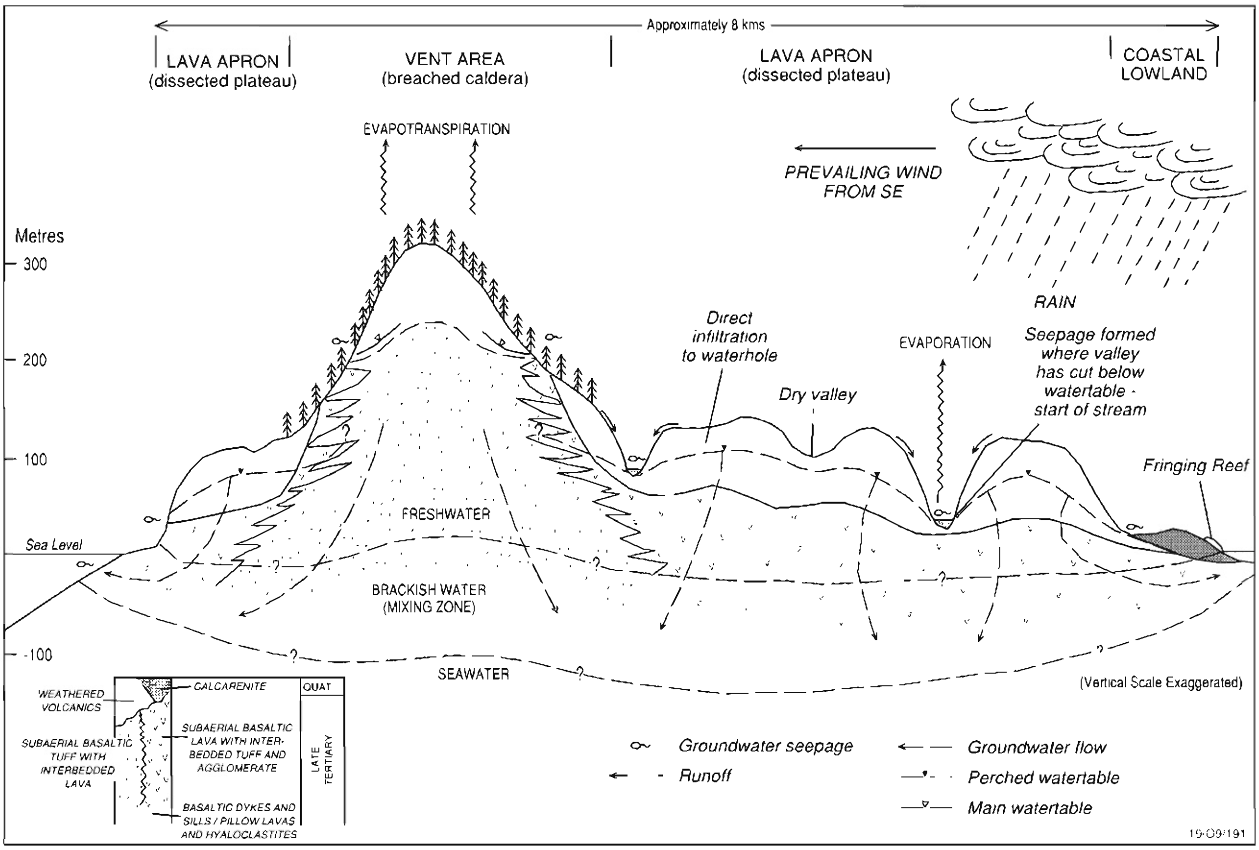


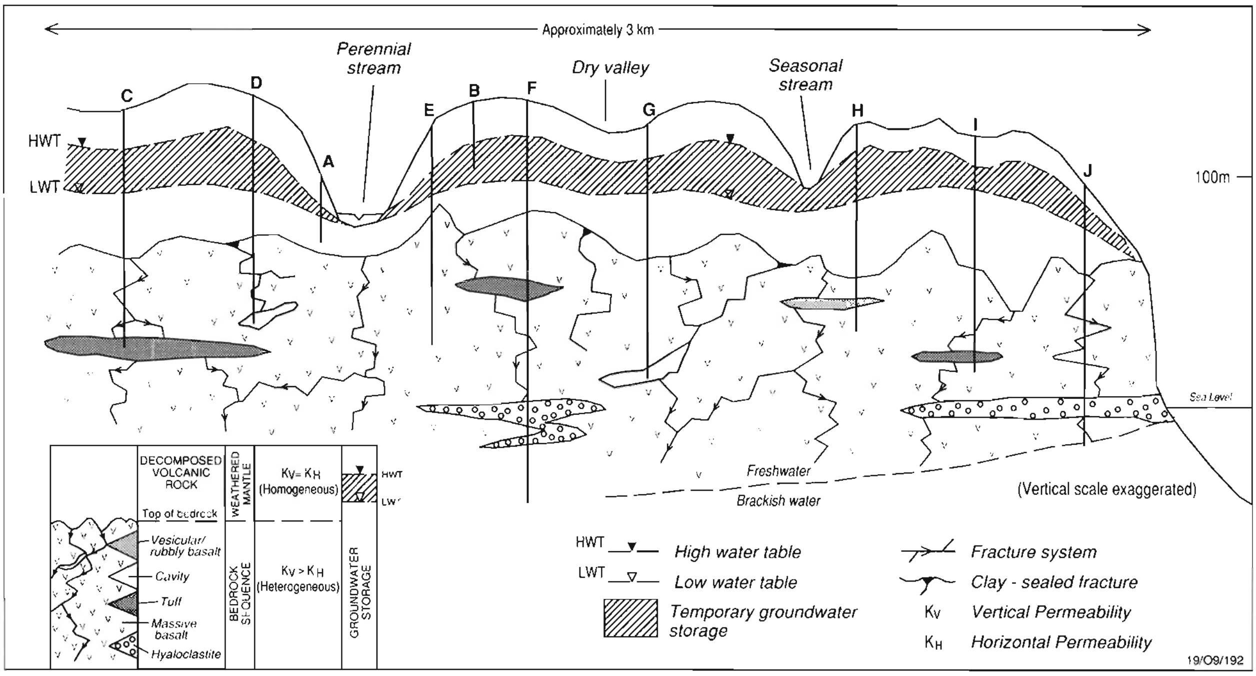
Figure 5. The hydrological cycle for Norfolk Island.

Aquifer stress may be promoted by short and long-term climatic change, in particular droughts associated with ENSO events. The annual rainfall record (Fig. 3) can assist in predicting low rainfall years and hence periods of falling water levels reflecting diminishing recharge to groundwater storage (Abell & Falkland, 1991). For instance, since 1950 there have been 11 ENSO events, the average period between events is 3–4 years. In low rainfall years, the water table aquifer may deplete to a stage where wells dry out and additional demand is placed on deeper groundwater, sometimes inducing brackish water upconing. In contrast, the elevated nature of Norfolk Island (cliffs averaging 100 m ASL) suggest that possible sealevel rise due to the 'greenhouse effect' (estimated at up to 0.5 m) is not expected to have a deleterious effect, although it may aggravate existing salinity problems in bores and wells in the low lying coastal plains at Kingston.

There is an increased demand for water (mainly groundwater) caused by an expansion of the tourist industry (Fig. 9), which has also meant a rapid development of accommodation and shops. On average, tourists represent about ⅙ of the islands population at any one time, though the figure can be as high as ⅓ during peak holiday periods. The tourist industry is a major seasonal user of groundwater. One of the peak periods of tourism (November to January) occurs during the dry season. Many tourists come from communities with plentiful water supplies, and having sufficient disposable income are accustomed to a high standard of living, and consequently high rates of water consumption, which in turn places extra pressure on waste disposal facilities.

In island environments, waste disposal should if possible be directed to areas where it cannot pollute groundwater. On Norfolk Island, a *Water Assurance Scheme* for the disposal of sewage effluent from the Burnt Pine–Middlegate area has been partially completed and was opened in December 1990 (Fig. 10). The scheme in essence removes sewage from individual establishments into the main sewerage line, which is then taken to an outfall site in an intertidal cave at the foot of Headstone cliffs. The effluent, when it reaches the treatment plant, is passed through a screen and then over large rotating drums (rotating biological contact) for oxygenation. However, the recommended legislation — making it compulsory for all premises either to be connected or have effluent holding tanks installed — has not yet been formulated.

The main issue with respect to water supply on Norfolk Island is the quality of water, and the ability to monitor and control quality on an on-going basis. At present, little is known about quality degradation in the deep groundwater system. It is expected that it is safeguarded to some extent against the contaminated shallow aquifer in the weathered mantle by intervening rock layers, although according to DHC (1983) rates of underground flow may be very rapid (up to 40 m/hr). Nevertheless, in the long-term, management of a safe water supply will depend on protecting and concentrating deep groundwater development in volcanic bedrock aquifers *above sealevel* to safeguard against seawater intrusion. There is probably some scope for development *below sealevel* provided abstraction rates are kept low. This, however, requires further deep drilling to monitor the thickness of freshwater and transition zones.



A and B	*Bore or well taps the water table in the weathered mantle. Water supplies obtained are subject to periodic drought conditions, bacteriological and chemical pollution.*
C	*Bore taps saturated tuff bed recharged by a wet fracture system and confined by impermeable basalt; gives subartesian water supply.*
D	*Bore intersects dry fracture system and bedrock cavity; lost circulation during drilling.*
E	*Bore penetrates impermeable and poorly fractured basalt; no water supply.*
F	*Deep bore supply from bedrock aquifers; gives subartesian water supply but overpumping will induce saline upconing.*
G	*Subartesian bore supply from a saturated bedrock cavity recharged from wet fractures.*
H	*Small water supply from vesicular / rubbly zone between basaltic lavas.*
I	*Safe subartesian bore water from bedrock aquifers above sea level in the coastal zone.*
J	*Unsafe subartesian water supply in the coastal zone tapping brackish water in bedrock aquifers at and below sea level.*

Figure 6. Simplified scheme for groundwater development in the weathered mantle and volcanic bedrock beneath the southern plateau.

Conclusions

Small islands in the southwest Pacific have limited fresh water resources. They are highly vulnerable to over-exploitation (resulting in seawater intrusion), pollution from human activities, and to the predicted global climatic change leading to a rise in sealevel. Water resources are threatened by increasing water demand due to demographic pressure, agricultural development, and modernisation of consumption patterns. Deterioration in quantity and quality of groundwater resources is a limiting factor in economic development and must be considered in the formulation of development programs.

Research

Effective management and protection of small island groundwater resources relies on the acquisition and integration of reliable hydrological data. Through modelling, these data can be synthesised to generate groundwater flow models and vulnerability maps as predictive tools to support ecologically sustainable development. However, there are significant gaps in knowledge that may be addressed by: (a) establishment of observation bore networks for monitoring aquifer salinity; (b) evaluation of techniques for the estimation of evapotranspiration, particularly of the interception capacity of typical vegetation; (c) research into the movement of urban and agricultural pollutants through aquifers with special attention to transport in terrain devoid of soil cover or with little adsorption capacity; and (d) simple but accurate methods for estimating groundwater resources particularly of the recharge process using limited hydrometric, soil, and vegetation data.

Training

Long-term water resource development and management on small islands have not always achieved their goal, as technologies, design, and materials have not been suitable for the environment or cultural habits of the people, or because operation and maintenance costs are excessive. The situation is further aggravated by lack of qualified personnel, financial resources, and geographical isolation. The ability of islands and island groups to manage better their water affairs will depend on: (a) legislative control, technical solutions, and community education to overcome threatening pollution hazards; (b) increased technology transfer in the form of equipment and expertise best suited to the needs of practical island management of water supplies, e.g. drilling technology, water quality analysis, and methodologies for optimising the safe yield from freshwater lenses; and (c) professional and technical training programs by way of formal training at recognised

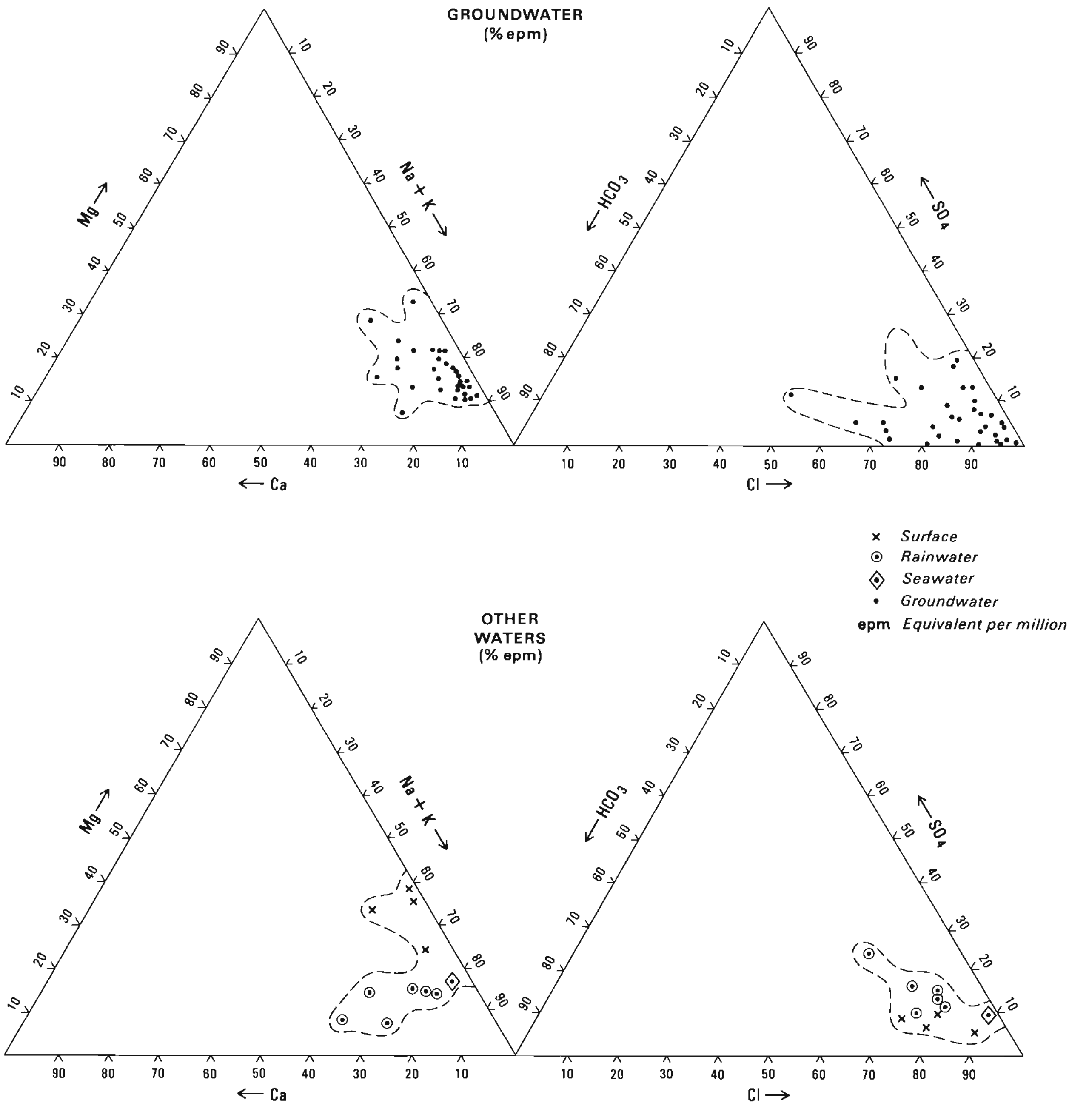


Figure 7. Trilinear plots of ground and other waters on Norfolk Island.

institutions, on-island seminars and workshops conducted by personnel from external agencies, aid agreements, and continued support for locally based monitoring and protection of groundwater resources.

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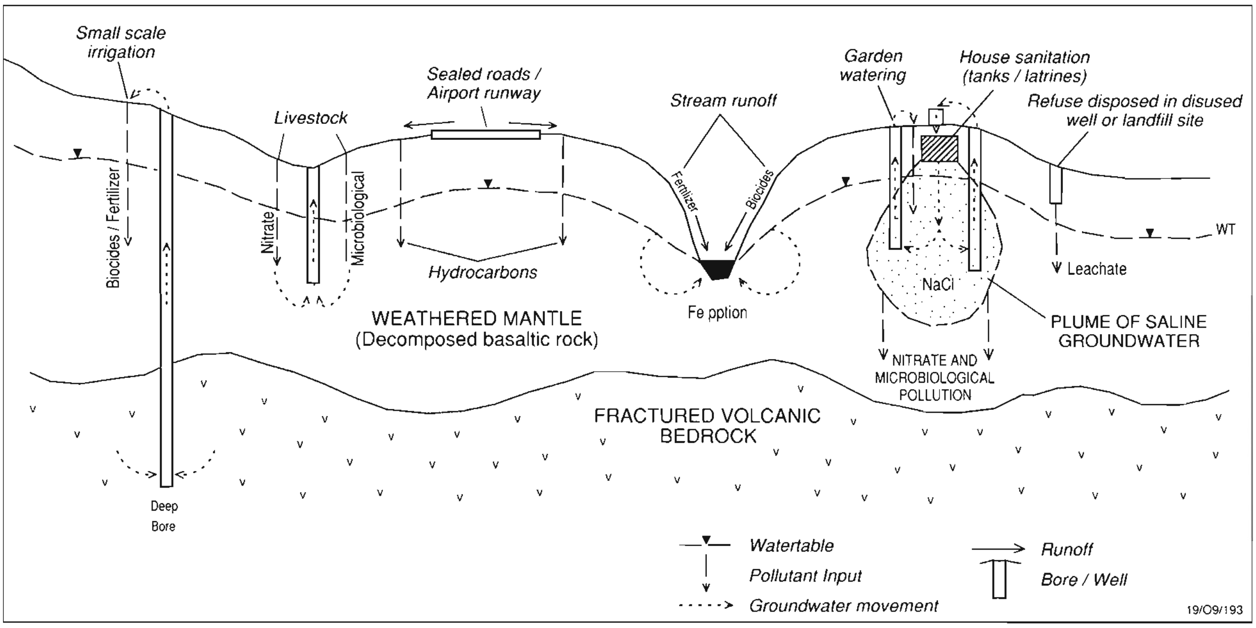

Figure 8. Sources of shallow groundwater pollution on Norfolk Island.

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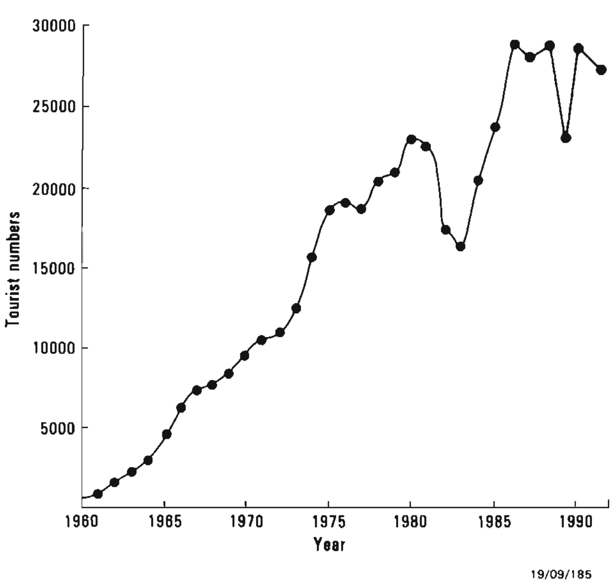

Figure 9. Annual tourist population on Norfolk Island (1960–1992).

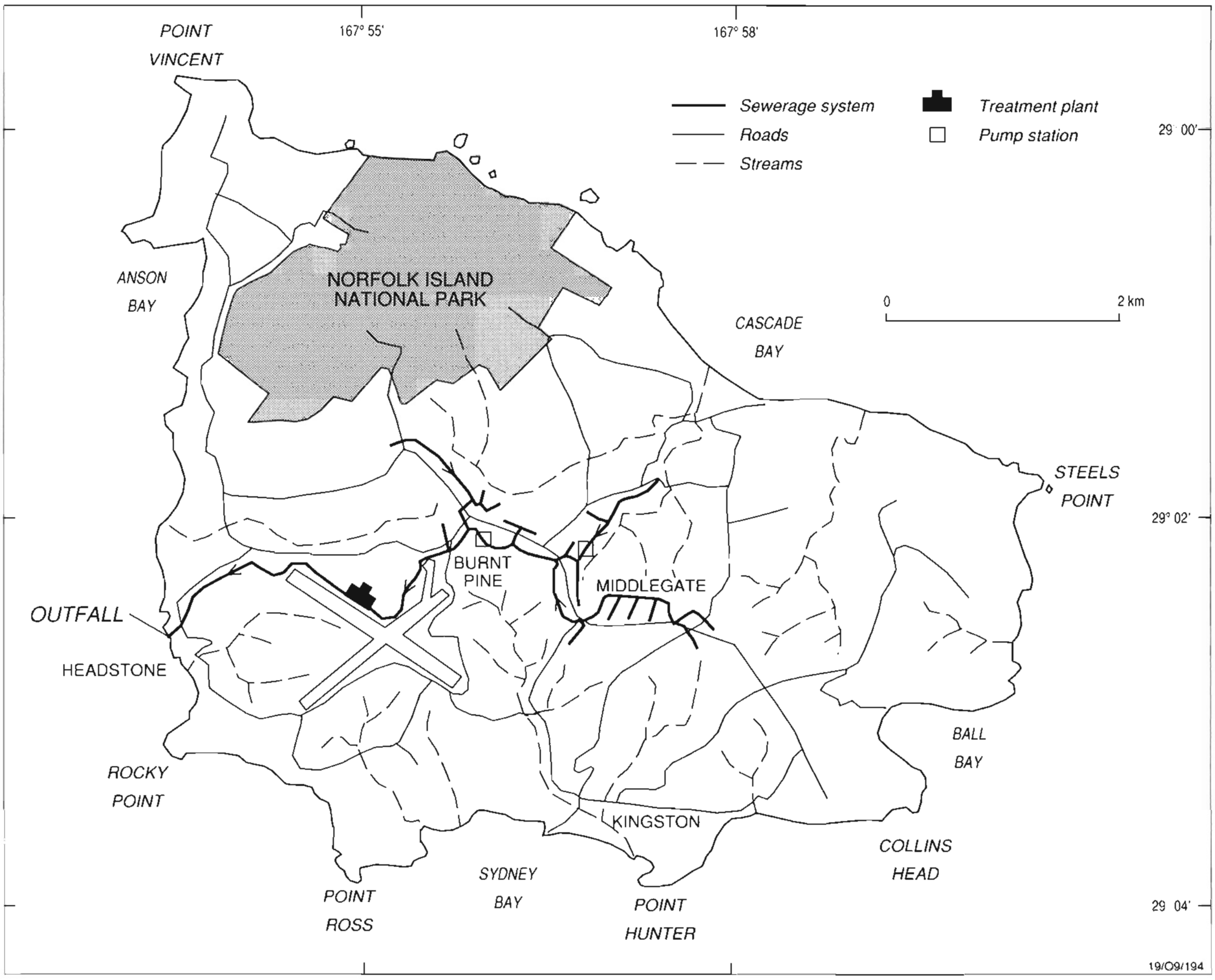

Figure 10. Plan of the water assurance scheme on Norfolk Island.