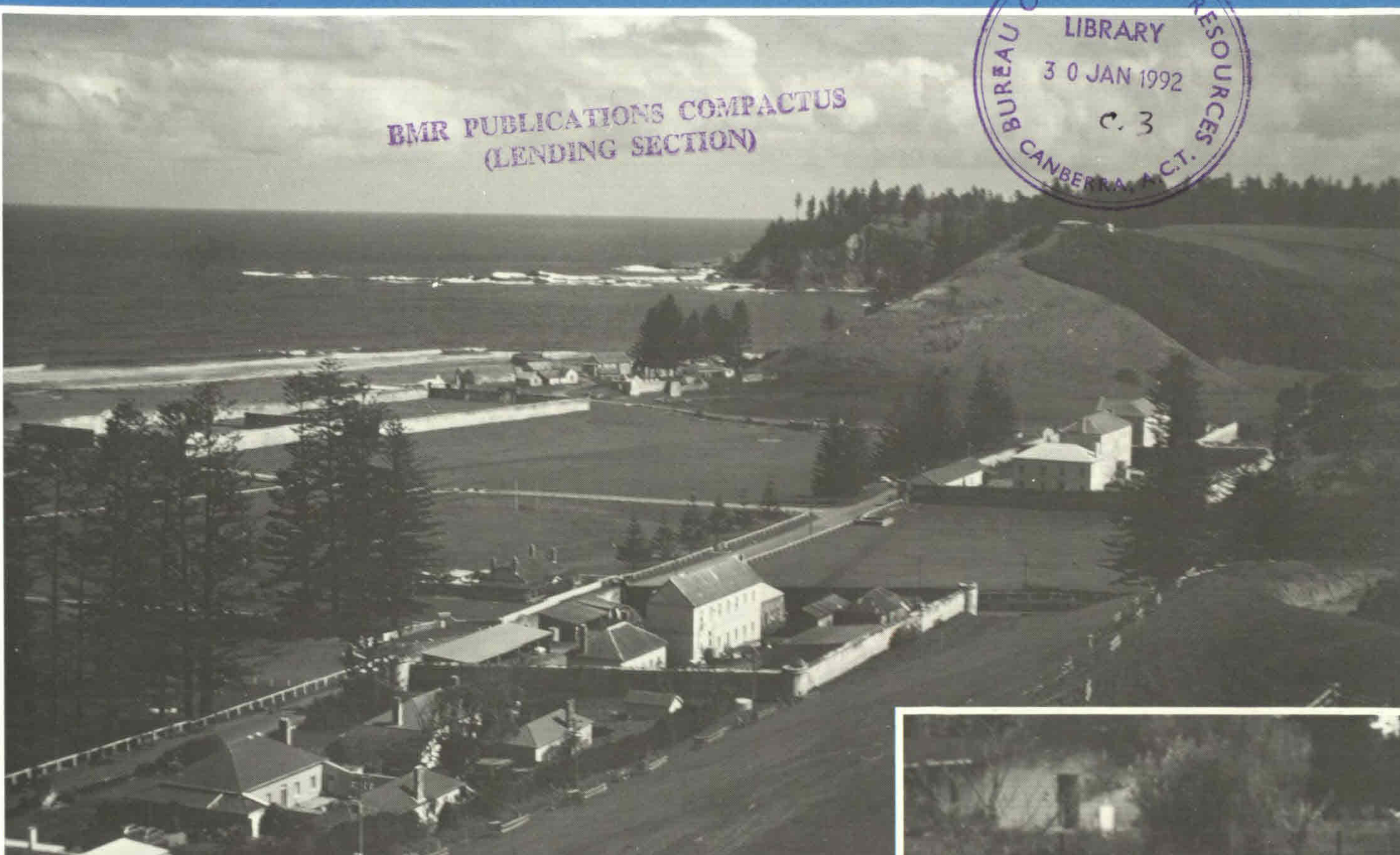
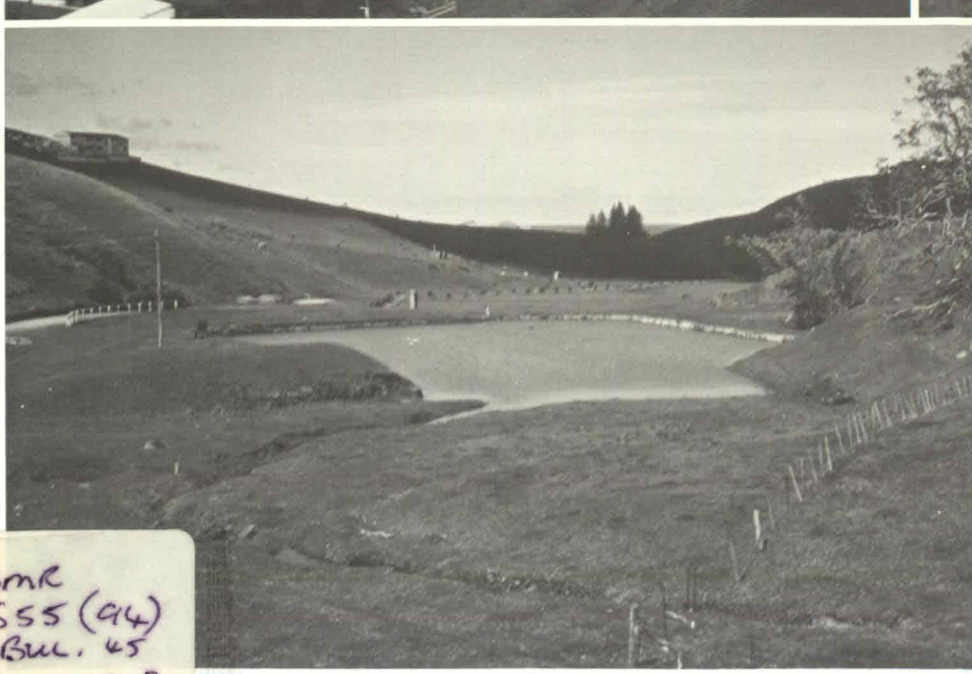
The hydrogeology of Norfolk Island, South Pacific Ocean

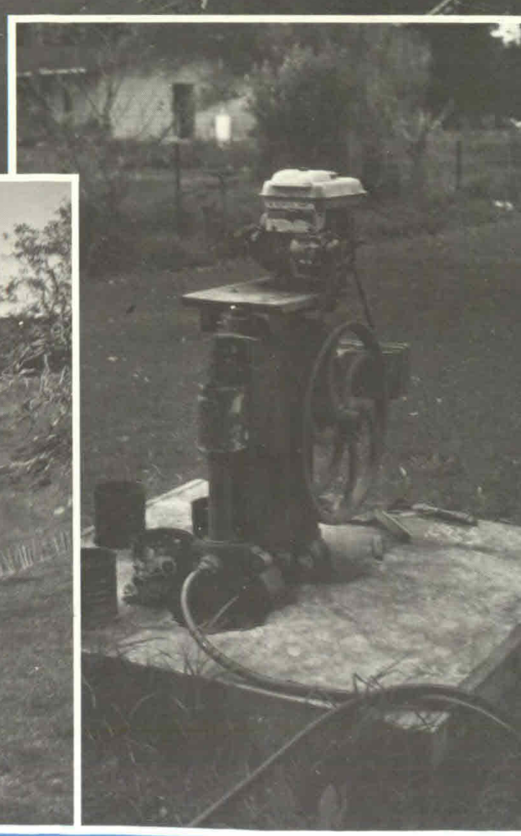
BMR Bulletin

234

R.S. Abell & A.C. Falkland







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ERRATA

p. 1, **Location and size** — first sentence should read '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 . . .'

p. 15, right col., para. 3 — second sentence should read 'The upper tributaries of all catchments are dry (Plate 6).'

p. 30, right col., para. 2 — the values for the quality limits listed should be preceded by a 'greater than' sign; e.g. pH > 7 (alkaline).

p. 38, **Water balance,** line 14 — 'spetic' should read 'septic'

p. 56, **References** — FALKLAND, A., 1983 should read FALKLAND, A., 1988

Insert the following reference — FALKLAND, A., 1983 — Christmas Island (Kiritimati) water resources study. Volume 1. General report. *The Australian Department of Housing and Construction.*

p. 57, The first reference to TAKASAKI, K.J., 1978, should be deleted.

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN 234

The hydrogeology of Norfolk Island South Pacific Ocean

by

R.S. ABELL[1] & A.C. FALKLAND[2]

[1]Bureau of Mineral Resources, Canberra, A.C.T.
[2]ACT Electricity and Water, Canberra, A.C.T.

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Edited by: K.H. Wolf

Line drawings by: Deborah O'Donoghue

Cover:
Top — Historic buildings along Quality Row at Kingston. View looking southwest across the coastal plain to volcanic cliffs in the background. *Left* — Surface water storage on Watermill Creek. This reservoir was originally constructed by convict labour to provide a water supply for early settlements on the coastal plain at Kingston. *Right* — A common design of lift pump used for groundwater extraction at an island home.

Frontispiece:
View looking south across the coastal plain to Nepean and Philip Islands. The rugged topography of the volcanic remnant of Philip Island (skyline) contrasts with the flat-topped (emergent wave-cut platform) nature of Nepean Island composed of calcareous aeolianite. The coastal plain (middle foreground) is also underlain by Quaternary sediments. Note Emily Bay (surrounded by Norfolk Island Pines) and a fringing reef to the centre right.

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Abstract

Norfolk Island in the southwest Pacific ocean has an area of 35 km^2 and rises to an altitude of just over 300 m. It is an erosional remnant of a volcanic complex consisting of subaerial basaltic lava flows and pyroclastics built on a submarine pile of hyaloclastite deposits and pillow lavas. A deep weathering profile has developed in the volcanic succession since eruptive activity ceased during the late Pliocene 2.3 Ma ago.

Throughout the island there is an upper water table aquifer in porous alluvium and weathered basaltic rock. At the base of the weathered profile groundwater moves towards sea level through a complex network of fractures and other interconnected openings in volcanic bedrock. Semi-confined aquifers occur in fractured basalt flows and interbedded basaltic pyroclastics (tuffs and agglomerates). However, the extent and quality of deep groundwater below sea level needs more evaluation.

The groundwater storage on Norfolk Island is tapped by more than 450 wells and bores. Groundwater is classified as the sodium chloride type, is generally of good quality and suitable for domestic use. Deuterium/oxygen-18 correlation indicates direct rain infiltration with recharging groundwater showing little evidence of evaporation or seawater mixing. Low tritium values indicate residence times for groundwater commonly exceeding 25 years.

Total water consumption is estimated to be 4.0 x $10^5 m^3$/year by the year 2000. Water balance calculations indicate that the volume of groundwater recharge is 14 x $10^6 m^3$/year or about 30% of average annual rainfall, which is sufficient to meet demands for groundwater in the foreseeable future. Shallow groundwater pollution from the disposal of sanitary and livestock waste is a current threat in parts of the island. Seawater contamination is not yet a widespread problem in deep bores sited near the island perimeter, but may become so in future.

Introduction

The first documented water-supply investigation on Norfolk Island is that by the Commonwealth Department of Works (NSW Branch) in 1949–51 (unpublished file report) for improving the water supply at the aerodrome, whereas the first water-resources study was prompted by a serious drought in 1965. Groundwater conditions were broadly outlined by Eden (1965), suggesting improvements of both ground and surface water supplies; commenting on water quality, particularly the dangers of potential groundwater pollution from septic-tank waste; and advocating legislative control.

Wood (1968) compiled a water-supply and sewerage-development report for the Commonwealth Department of Works (NSW Branch), and gave an overall assessment of the problems with much of the groundwater data quoted directly from Eden (1965). Other publications with groundwater information are those by Stephens & Hutton (1954) and Butland (1974), and unpublished file reports held by the Bureau of Mineral Resources (BMR) and the Norfolk Island Administration.

In October 1973, the Department of the Capital Territory requested BMR to study groundwater conditions on Norfolk Island, with the aim of establishing whether a freshwater lens overlies saltwater in the subsurface of the island.

Hydrological data collection and fieldwork were undertaken over a ten-week period between July and September 1974. The first six weeks were spent locating and examining all the wells and bores on the island. The remainder of the investigation — including one day on Philip Island — was devoted to fieldwork. The general geology of the island was studied mainly from outcrops along the accessible parts of the coast. A visual assessment of the water-bearing properties of the volcanic sequence was attempted, and coastal seepages were mapped. Field observations were also made with reference to the extent of surface water; consequently, the drainage network — particularly the distribution of inland seepages and the nature of the catchments — was mapped. Surface-water extraction points were located as part of an assessment of surface-water use. Further studies were recommended prior to developing a possible groundwater supply near sea level (Abell, 1976).

In June 1980, the Department of Housing and Construction (DHC) completed a report on a proposed water supply and sewerage project for Norfolk Island (Goldfinch & Cross, 1980). In response to recommendations therein, the Hydrology and Water Resources Section of the ACT region of DHC initiated a stream gauging program in early 1981. This program refined the measurement of the water- balance processes, which allowed for a more accurate estimate of groundwater recharge (Wheeler & Falkland, 1986).

In May and June 1981, hydrogeological and geophysical studies were carried out on Norfolk Island, with particular reference to the Broken Bridge–Mission Creek valleys; sites were selected for a deep drilling program to prove the existence of basal groundwater aquifers prior to planning a water resource and sewerage scheme (Abell & Taylor, 1981).

The present bulletin summarises these various studies of Norfolk Island hydrology, and also provides additional information as it was available up to mid 1988.

Two numbering systems are currently in use for groundwater extraction points on Norfolk Island; that used by BMR has a prefix NI and includes bores and wells. The system operated on the island by Mr G. C. Duvall (without the prefix NI) includes only bores. At various places in the report, a dual numbering system is used, for example 83/226 (the first number is Duvall's; the second is BMR's without the prefix NI). This allows easy cross-referencing between the two systems. Aerial photographs were used throughout the investigations to assist in bore and well location, outlining bedrock fracture traces, drainage mapping, and hydrogeological interpretation. At different times, photographs at nominal scales of 1:4000 (colour 1968), 1:16 000 (black and white 1968), and 1:50 000 (single-frame, black and white 1968) were used. A special topographic map at 1:10 000 with contours at 10 m intervals prepared by the Australian Survey Office, Canberra, was used as the metric base for compilation of the water table map.

Location and size

Norfolk Island is a territory of the Commonwealth of Australia, and with an area of 35 km^2 is the largest and only island of a remote group of three islands in the southwest Pacific Ocean at latitude 29°S and longitude 168°E (Fig. 1). Philip Island, 6 km south of Kingston (Norfolk Island's administrative centre) is uninhabited and precipitous with an area of about 2 km^2. Nepean Island is a flat-topped islet of 0.04 km^2 close to Norfolk Island's southern shoreline.

Access

Access to Norfolk Island is by either sea or air. Ships call regularly to deliver cargo to the island, but, as there are no harbour facilities, they moor off Kingston or Cascade (depending on the weather), and the cargo is brought ashore by lighters. An airstrip was built during World War II on the southwest portion of the island, so that aircraft can now provide the main means of passenger transport.

Internal access is served by an extensive network of roads; totalling about 80 km in length, of which about one-third is sealed. Forestry tracks have been developed in and around the Norfolk Island National Park (formerly Mount Pitt Reserve), but become temporarily impassable after heavy rain and are best negotiated by four-wheel-drive vehicles. Foot tracks are present at many places along the coastal perimeter.

Climate

The subtropical climate of Norfolk Island, with its mild temperature and well-distributed rainfall presents an equable environment for animals and plants. Climatological data from the Bureau of Meteorology, Melbourne, is based on records taken from the airport's meteorological station. Although the latter is not situated centrally on the island, the records adequately reflect the climate on the island.

The mean annual rainfall is 1326 mm; with a winter maximum between June and July, and summer minimum between November and January. The average number of raindays per month varies from 12 in November to January, to 23 in June (ANPWS, 1984). Cyclonic rainfall may occur in summer, but as Norfolk Island is sufficiently far south of the tropics, most cyclones weaken and are not normally a serious threat. Periods of very low rainfall displayed in Fig. 2 are associated with El Niño–Southern Oscillation (ENSO)

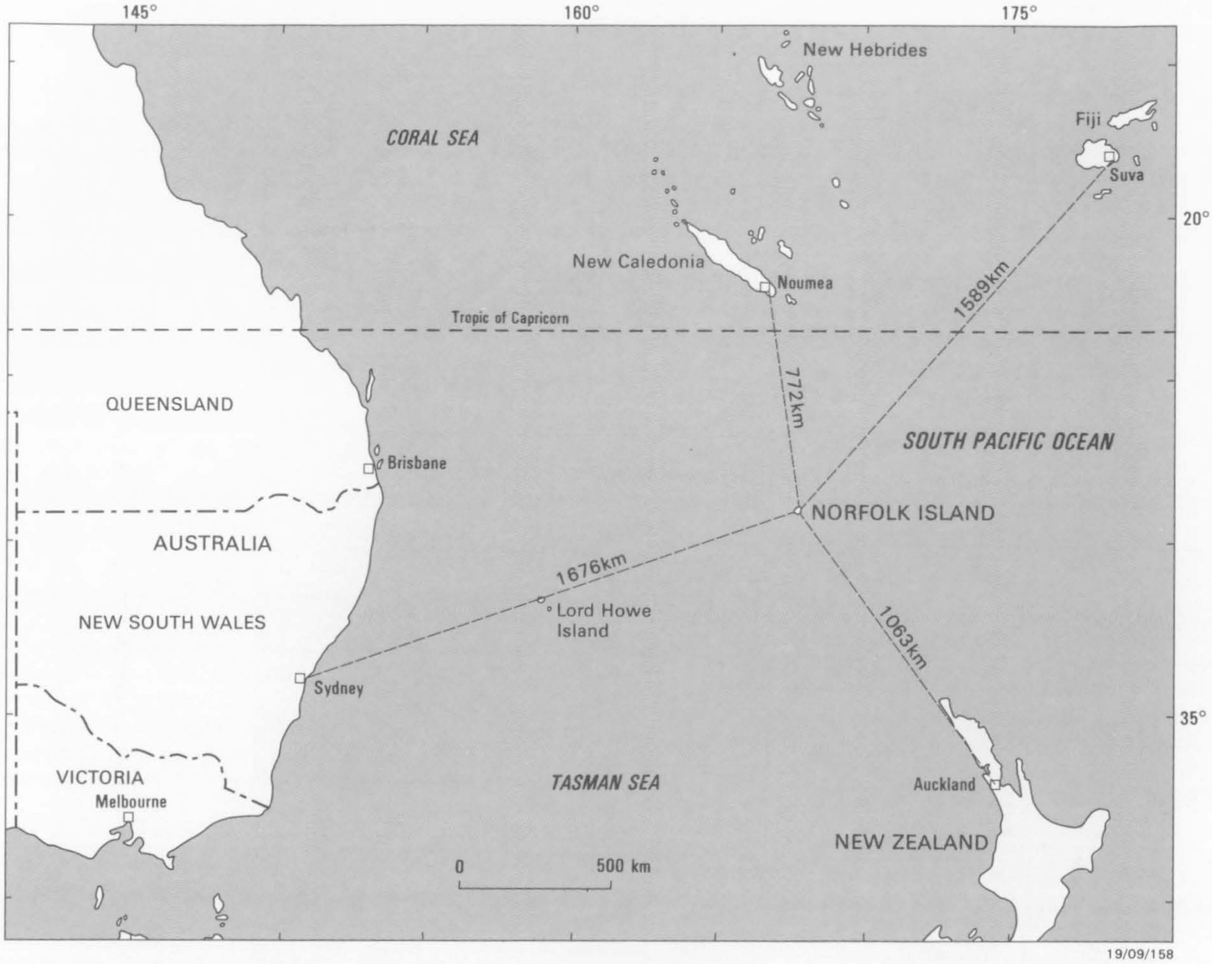

Fig. 1. Location of Norfolk Island.

events, discussed in more detail in the section dealing with the water balance (p. 39). The mean annual relative humidity is 79%, remaining fairly constant throughout the year, being slightly higher in summer than winter. The moderate humidity values are characteristic of an island that has persistent winds and small temperature variation. The island lies in the path of prevailing winds which blow predominantly from the east in summer months and from the west during winter. Average wind velocities oscillate around 11–20 km/hr (ANPWS, 1984).

Population

Fossil and archaeological evidence suggests that the Polynesians occupied Norfolk Island temporarily about 800–900 BP (Meredith & others, 1985) and about 1000–1400 AD (Specht, 1984). The island was uninhabited at the time of European discovery in 1774. The present-day residential population is spread widely over the island, with the exception of the Norfolk Island National Park. The greatest number of people are in the Burnt Pine–Middlegate residential–business complex and to a lesser extent, in Kingston.

The island is populated by 'Islanders', descendants of the mutineers of HMS *Bounty*, and by 'Mainlanders', later settlers, mostly from Australia, New Zealand, and the United Kingdom. In 1981, there were about 2175 permanent residents on the island; and, since 1974 attracted by the remoteness, beauty, and restful appeal more than 15 000 tourists have visited Norfolk Island annually (ANPWS, 1984).

Vegetation and land use

Norfolk Island had originally a dense subtropical forest of palms, ferns, creepers, flax, and pines, of which a remnant has been preserved around the slopes of Mount Pitt and Mount Bates. Since the original settlement in 1788, extensive areas have been cleared for cultivation and grazing. It is estimated that about a third of the island remains forested (Fig. 3), of which the densely covered areas are associated with Norfolk Island National Park and along some uninhabited valleys. Recent afforestation has been accomplished by planting eucalypts close to Anson Bay Road. As part of this program, Norfolk Island Pine (*Arucaria* sp.) has been planted to combat soil erosion in Watermill Creek. The open forest areas (produced by clearing of originally dense forest) has been taken over by a thick secondary growth, which includes olives, guava, wild tobacco, and lantana thicket. About 15% of the island around Kingston, Cascade, and Headstone is pastoral, supporting coarse kikuyu grass; the remainder is cultivated land and urban development with some open woodland and secondary growth.

Agriculture is practised mainly at subsistence level. There are few large agricultural schemes owing to the

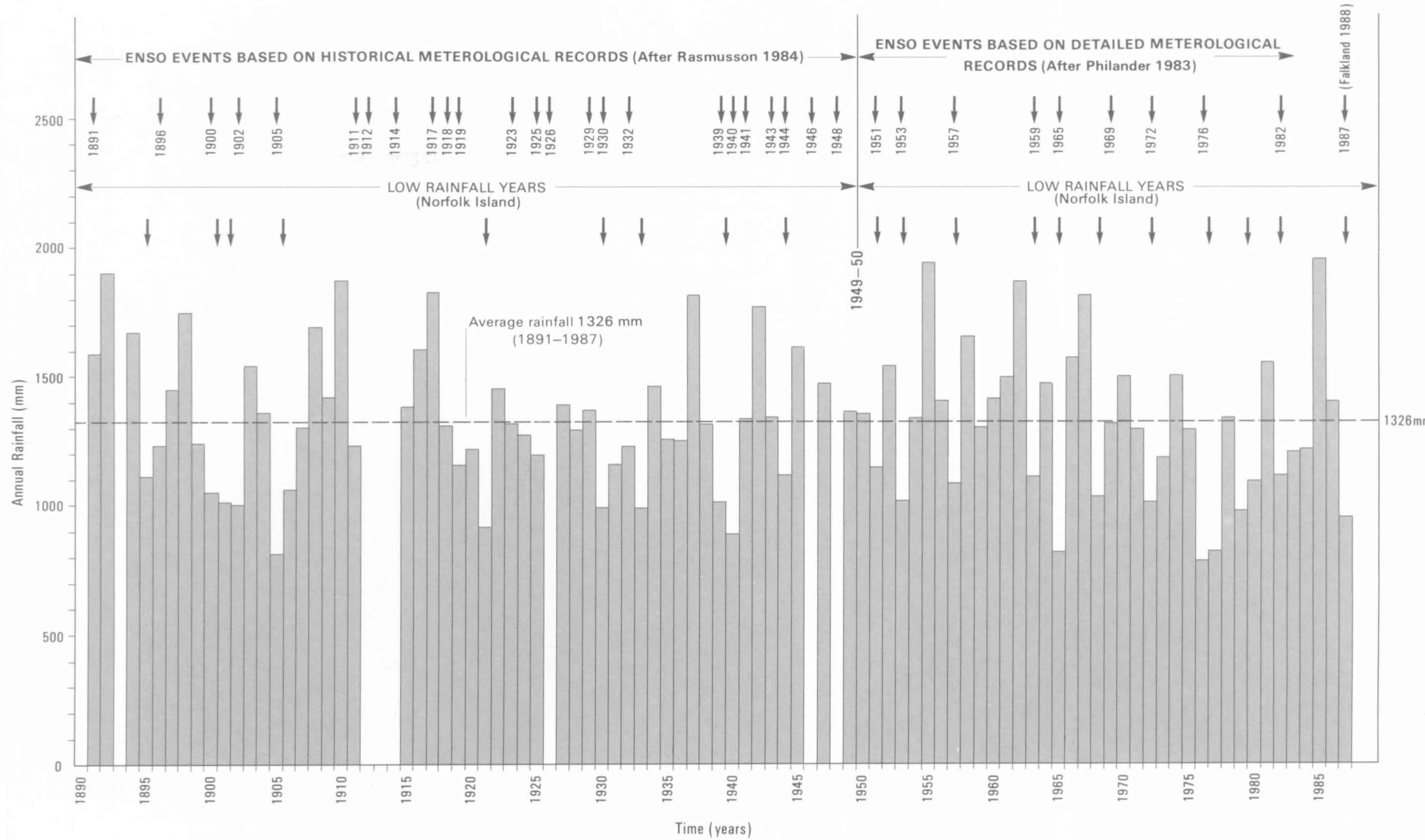

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Fig. 2. Annual rainfall record (1891–1987).

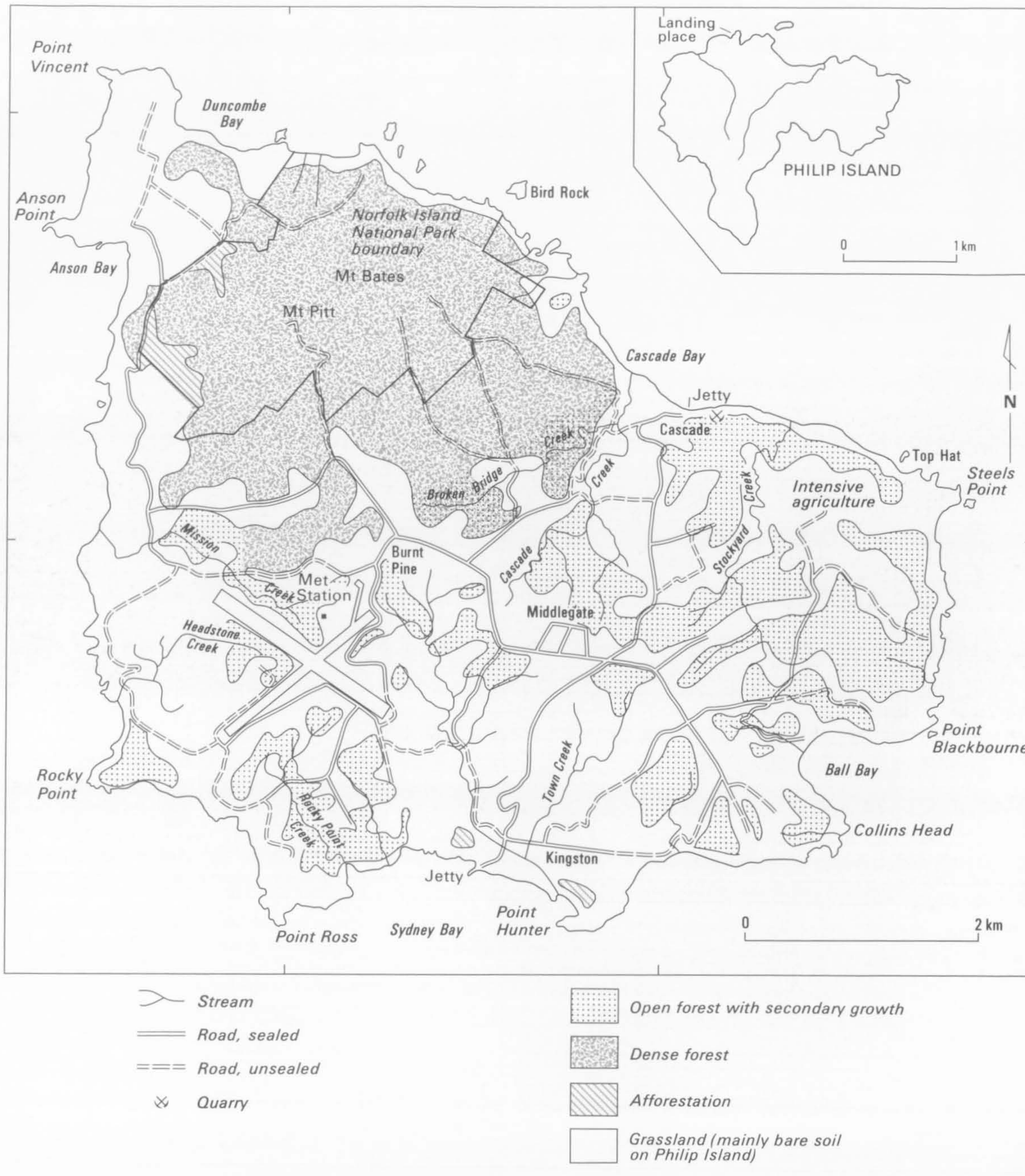

Fig. 3. Distribution of vegetation and land use.

fragmentary, and in places intensive, subdivision of land. Most people cultivate small tracts of land of only a few hectares and grow crops (mainly fruit, vegetables, and flowers) for their own and local needs. The most intensively used agricultural area is between Stockyard Creek and Steels Point, where fertile arable soils occupy flat and unbroken country. There appears to be potential for agriculture, but the greatest restrictions are transport and market limitations in neighbouring mainland areas.

A small industry revolves around forestry, particularly timber for power and telephone poles, fencing posts, and other building needs. A Quarry at Cascade and a crushing plant along Stockyard road provide aggregate for roads and other local needs. As the island lacks natural mineral resources, it is unlikely that any primary mining industry is likely to be established. Aeolianite–calcarenite makes a satisfactory building stone, and during the early settlements was quarried along the Kingston shoreline and Nepean Island.

Much of the cleared land is used for grazing. Pastures around Kingston, Cascade, Headstone, and Anson Bay carry livestock — mainly cattle and horses. Cattle are allowed to roam freely over the island, but their wanderings have led to overgrazing in some places, which has contributed to soil erosion. A pastoral industry based on dairying serves local needs.

Philip Island is a remarkable contrast to Norfolk Island, because it is more rugged and almost devoid of

Plate 1. Philip Island with its barren appearance, soil erosion, and lack of vegetation.

vegetation (Plate 1). During the early settlements, the island was stocked with domestic animals, including rabbits, which became responsible for the destruction of most of the vegetation cover. With the removal of the soil cover, erosion is now at an advanced stage, and the weathered volcanic rocks give the island an unusually barren but colourful appearance. The remaining vegetation consists of stunted trees and shrubs in the valleys and a few isolated Norfolk Island Pines; their roots are exposed by soil erosion. In 1980, experiments were started in an attempt to restore a natural grass cover on Philip Island (Coyne, 1982).

General geology

Norfolk Island lies towards the eastern edge of the Australian lithospheric plate and rises as a small landmass from the Norfolk Rise, a pronounced north-trending continental ridge between New Zealand and New Caledonia. A review of the plate tectonic background in the southwest Pacific over the last 100 Ma is given in Coleman (1980). Norfolk Island is an erosional remnant of probably a number of local volcanic centres that erupted several times in the Pliocene between 3.05 and 3.3 Ma ago. The stratigraphy, geochronology and eruptive history of the island has been studied by Jones & McDougall (1973).

Tertiary

The cliffs surrounding Norfolk Island (Plate 2) provide a nearly continuous section of the geology (Fig. 4). Inland, outcrop is obscured by deep weathering and in places by thick vegetation. The unweathered part of the volcanic sequence suggests a series of complex and spasmodic eruptive events in which lava and tuff units were deposited on a series of either weathered or eroded topographic surfaces. Intrusive basaltic dykes and sills have been described from Philip Island by Jones & McDougall (1973).

Basaltic lavas

Basaltic sheet lavas are the commonest rock on the island. They are generally flat-lying, although one at Anson Bay dips 30°S. Individual flows range up to 30 m thick, and commonly have well-developed columnar jointing. Some flows are lenticular, with complex and irregular joint patterns. Most lava flows are vesicular and have fragmental or slaggy tops which weather to clay. The petrology and geochemistry of the basalts have been studied by Green (1973), who demonstrated affinities with basalts in eastern Australia and North Island, New Zealand.

Pyroclastics

Reworked (indicated by cross-bedding), yellow palagonitized tuffs are interbedded with and rest unconformably on the basalts; they range in thickness from a few metres up to 15 m. The most continuous exposures of tuff are along the northwest coast, between Anson Bay and Cascade Bay. Tuff beds at Rocky Point, Steels Point, and Ball Bay suggest that, in addition to the main vent, other nearby volcanic foci may have been active during the island's history.

Each tuff and its overlying lava flow records a new cycle of volcanic activity after a period of quiescence during which erosion of the previous cycle has taken place. The tops of the tuff sequences are normally in conformable contact with the overlying penecontemporaneous lava flows.

The tuffs are composed of poorly sorted subangular basaltic fragments mostly less than 1 cm in size. The fragments consist of olivine and pyroxene crystals, and sideromelane (hydrated basaltic glass) with microlites of plagioclase feldspar aligned in flow texture. The formation of palagonite — an alteration product of sideromelane — has lithified the fragments. Palagonite imparts a deep yellow colour to the rocks in coastal exposures.

Bedding in the tuffs is generally horizontal, and is due to abrupt changes in grain size where weathering has etched out the less-well cemented coarse-grained layers. Sedimentary structures, such as current bedding,

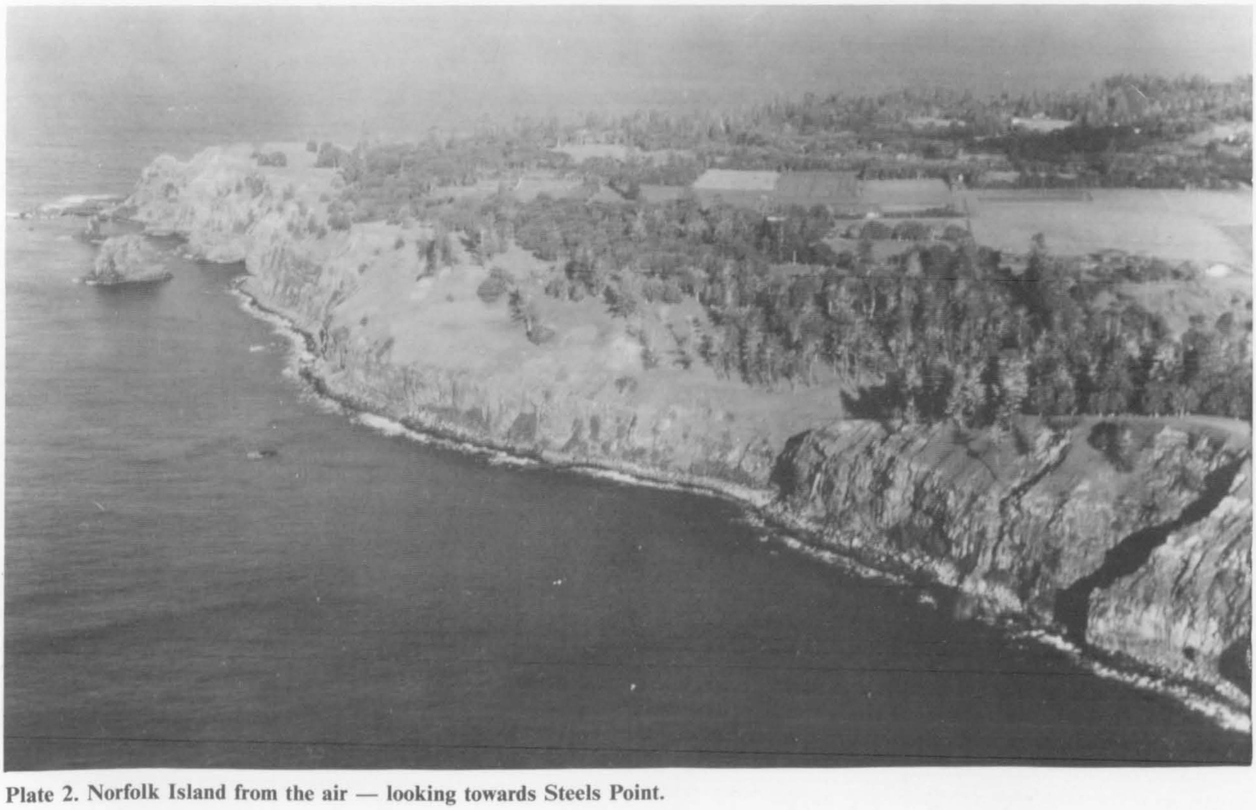

Plate 2. Norfolk Island from the air — looking towards Steels Point.

occasional scour-and-fill structures, and volcanic dropstone features have been recorded in these tuffs.

Other pyroclastics occur close to the summit area of Norfolk Island. One volcanic breccia exposed on Duncombe Road leading to Captain Cook Monument contains fossiliferous limestone clasts. The occurrence of fossils in similar breccias confirms the findings by Coleman & Veevers (1971), who examined inclusions of limestone in tuffs exposed at the landing place on Philip Island. They suggested a minimum lower Miocene age for a fauna that lived in a shallow sea covering Norfolk Ridge, which became reworked (and then incorporated in a pyroclastic deposit) during volcanic activity that formed Philip Island. Another volcanic breccia (deeply

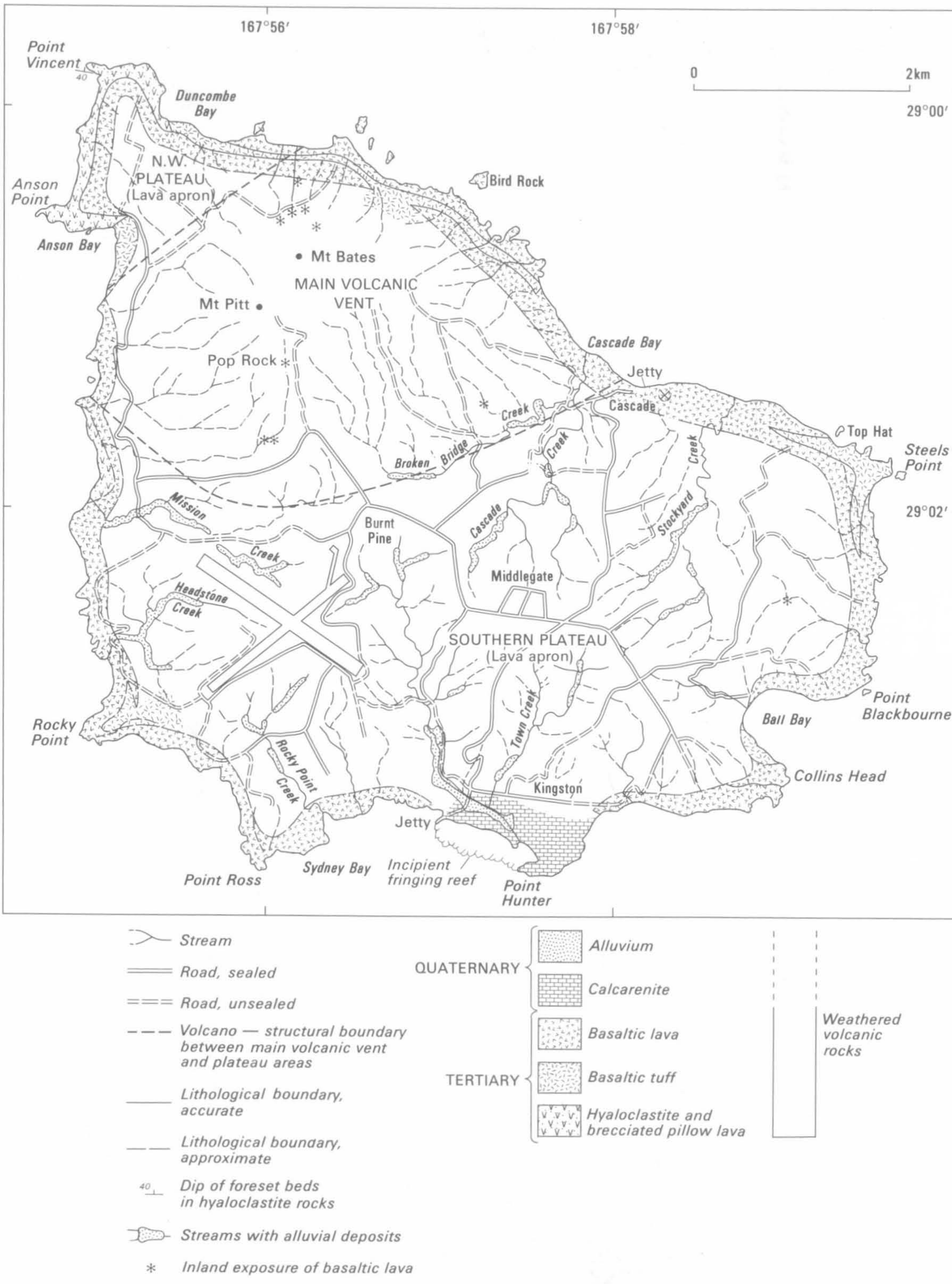

Fig. 4. Simplified geology (after Jones & McDougall, 1973). Refer also to Fig. 7.

weathered) with rounded basaltic boulders is exposed along a ridge on the north side of Mount Bates.

Hyaloclastic rocks

Along the northwest coast between Anson Bay and Duncombe Bay, exposures of hyaloclastite deposits occur at the base of cliffs a few metres above sea level. These deposits contain subrounded clasts of scoriaceous basalt (disrupted pillows) in a yellow, tuffaceous matrix which grades up into hackly (irregular) jointed lava. At Point Vincent, these breccias are crudely stratified at angles of up to 40°, and lava tongues within them dip northwards (Plate 3). The lower contact with pillow lavas is below present-day sea level. According to Jones & McDougall (1973), the autoclastic lithofacies was formed through fragmentation, the result of grinding or breakage and quenching as the lava flowed from the subaerial environment into the seawater. The gradational contact between lava and autoclastic breccia approximates to sea level at the time of eruption. This interpretation is confirmed by the presence of current-bedded tuffs and boulder deposits near the top of the quench zone, which represent a local reworking of the hyaloclastite breccias in a littoral or beach environment (Plate 4). A shallow-marine volcanic delta has been the interpretation given to similar rock studied by Furnes & Fridleifson (1974) in Iceland. The continuous distribution of the quench zone, a few metres above sea level around the northern half of the island, is taken to indicate slight post-volcanic tilting southwards (Jones & McDougall, 1973).

Weathered mantle

Except for the coastal lowland, Norfolk Island is deeply weathered, owing to prolonged chemical breakdown of the volcanic rocks in a humid subtropical climate, producing decomposed volcanic material with clay rich in iron and aluminium oxides. The main elements of the weathering profile are shown schematically in Fig. 5. The weathered mantle is well exposed in numerous road-cuttings and cliff sections around the island.

The soils have been described by Stephens & Hutton (1954) and Hutton & Stephens (1956) as mainly krasnozems. Within the profile, basalt shows various degrees of spheroidal weathering. In most places, unweathered cores of basalt are surrounded by concentric layers of decomposed basalt and clay. These spheroidal basalts are present at different topographic levels on the island, and are the progressive weathering of more than one flow. In some places, rounded corestones of basalt (up to 2 m in diameter) are well exposed either in eroding stream sections (Plate 5), or on interfluves where the ground has been cleared for pasture. Elsewhere the weathered mantle comprises volcanic-derived saprolite in which original textures and structures of the parent rock are preserved, e.g. vesicles and the outline of lava flows. This part of the sequence grades downward into unweathered basalt.

The weathering profile developed continuously up to depths in excess of 80 m since volcanism ceased in the late Pliocene. A drainage network carrying large quantities of surface runoff, typical of subtropical humid conditions, and a water-table that fluctuates in response to seasonal changes in rainfall, have all contributed towards a thickening of the profile. There is no evidence of erosion or a sudden compositional change in the weathering profile that might suggest submergence since its formation. As the profile is without laterite or other forms of hardpan, the island cannot have experienced extreme climatic conditions. A weathering rate of 16.1 m/Ma has been calculated from the average thickness of weathered volcanic rock (38.0 m) based on bore data (200 values). This weathering-rate estimate uses the age of the youngest stratigraphic unit, i.e. Steels Point

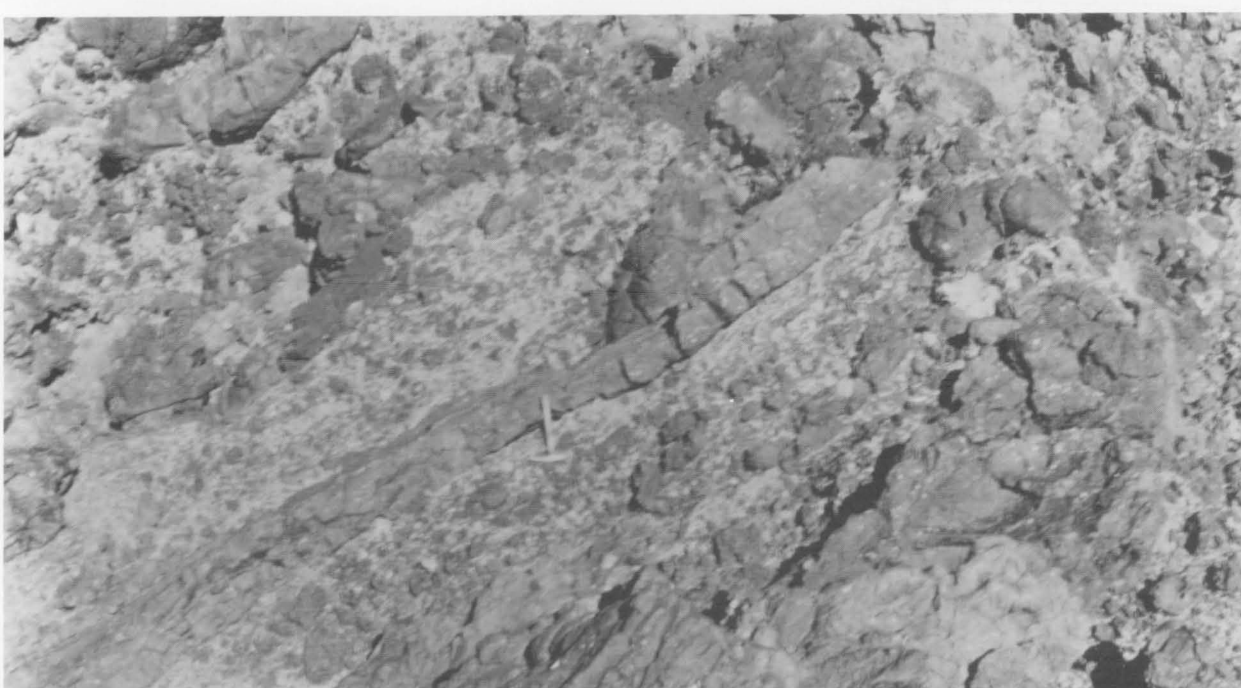

Plate 3. Dipping lava tongue in hyaloclastite deposit — Point Vincent.

Basalt, as being 2.36 ± 0.03 Ma. (The age was determined by palaeomagnetism; see Jones & McDougall, 1973.)

Quaternary

Along the shore of the Kingston lowland, and also forming Nepean Island, there is a sequence of cross-bedded and massive calcarenite with interbedded black carbonaceous clay (Veevers, 1976; and Rich & others, 1983). Figure 6 depicts the relationships between these rock units. Younger unconsolidated sediments include calcareous dune and beach sands in the Kingston area (Rich & others, 1983) and strips of alluvium along drainage lines.

Calcarenite

A thick fossil aeolianite or dune calcarenite ("Norfolk Island Aeolianite") is the best exposed unit and forms a wave-cut platform supporting an incipient fringing coral reef between Point Hunter and Kingston Jetty (Fig. 4). The dip of the cross-bedding indicates that these calcarenites were laid down by southerly winds, partly reworked by currents, during a low sea level stand in the Late Quaternary. A sequence of younger massive beach rock, derived in part from the underlying aeolianite by erosion and redeposition, also contain basalt pebbles and fragments of calcareous algae, foraminifera and coral (refer to Russell, 1959, 1962, for description of beachrock in the West Indies and elsewhere).

Carbonaceous clay

Black organic clay (saprophytic layer), mentioned above, is sporadically exposed in the vicinity of Cemetery and Slaughter bays. The clay contains logs of Norfolk Island pine, which have been dated as 4400 ± 90 yrs BP (Rich & others, 1983), based on work by P. Kaplin of the USSR Academy of Science (South Pacific expedition, 1976) and 4120 ± 70 yrs BP (M. Barbetti of the N.W.G. Macintosh Centre, for Quaternary Dating, University of Sydney, pers. comm., 1987). The pollen content reported on by Truswell (1981) indicates an assemblage similar to the modern vegetation pattern and hence a late Quaternary climate little different from the present. A coastal lagoon environment is suggested for the black clay on the basis of its sedimentology and stratigraphic setting (see Fig. 6).

Alluvium

In presently active creek catchments, surface water runoff has been sufficient to deposit narrow, localised strips of alluvial clay and silt (Fig. 4). Perched alluvium in the higher reaches of Watermill, Cascade, Stockyard, Rocky Point and Town Creeks probably represents local base levels of deposition. More continuous tracts of alluvium occur in Mission, Broken Bridge and Headstone creeks. Pollen recovered from a 2 m deep excavation in Mission Creek (Rich & others, 1983) reflect elements of the modern vegetation cover in the catchment.

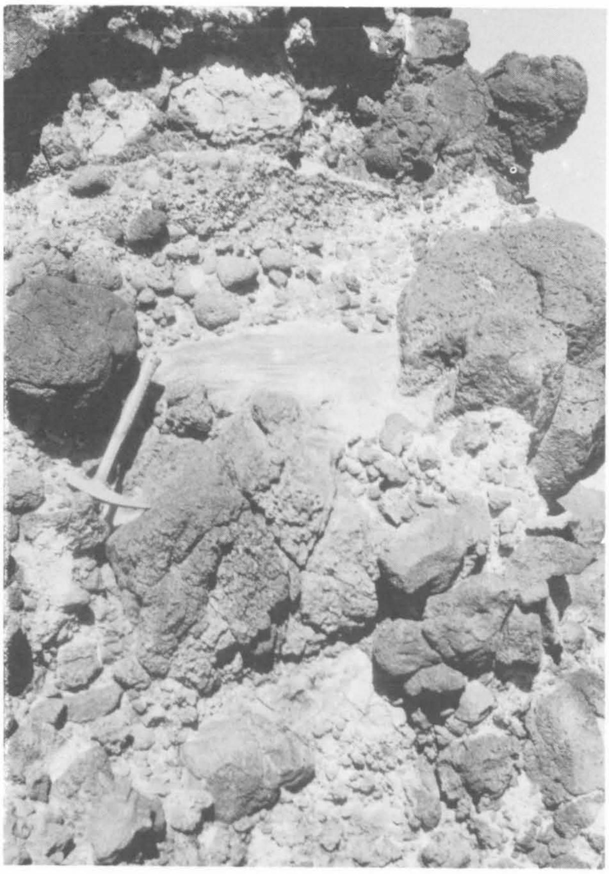

Plate 4. Reworked hyaloclastite deposit, Point Vincent. Note the infilling of tuff and graded boulder deposits.

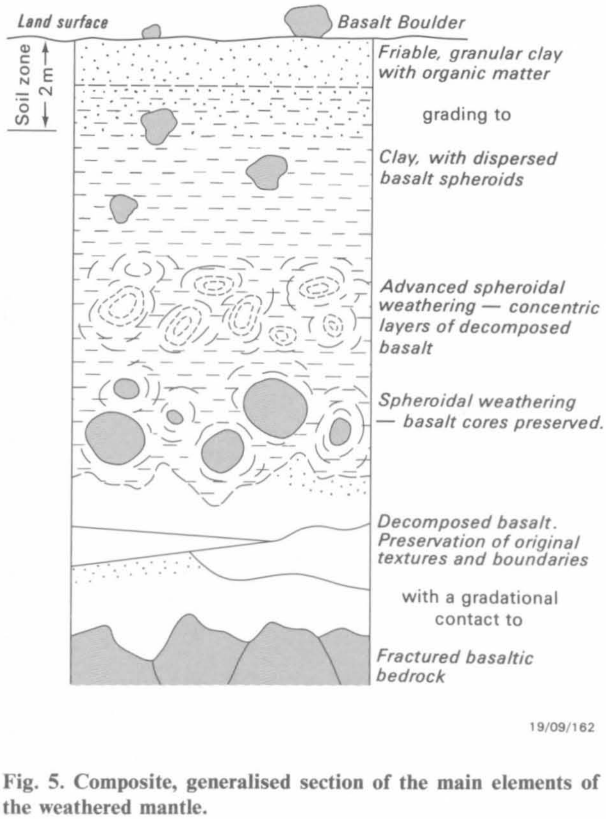

Fig. 5. Composite, generalised section of the main elements of the weathered mantle.

Structure

The interpretation of the structural framework of Norfolk Island is based on the evolution of a marine basaltic volcano, as proposed by Jones (1970). In this model, the pedestal (submarine foundation) of an island grows originally as a mound by successive effusions of pillow lava onto the sea floor. As the mound grows towards sea level, effusion gives way to explosive activity, and the volcano is established above sea level as a circular cone composed mainly of pyroclastics and breccia. This is followed by subaerial lava flows which spread out from the vent. As individual flows encountered water, they were quenched, which resulted in fragmentation and hackly jointing to form a flow-foot breccia. With continued activity, a basaltic lava apron develops overlying a pedestal of pyroclastic rocks.

Norfolk Island comprises two main volcano-structural elements: a major eruptive centre and a constructional lava apron (Fig. 7). This main eruptive centre corresponds to elevated terrain centered on Mt Pitt and Mt Bates, and is thought to be composed mainly of volcaniclastic rock, thin basalt lava flows, and intrusive dykes and sills. The constructional lava apron was modified to a deeply dissected plateau making up the southern half of the island and a small part of the northwest. This apron has built up around the main eruptive centre and comprises basalt lava flows and local basaltic tuff.

The complex boundary between the two volcano-structural elements is probably a stratigraphic change marked by the interdigitation of lava flows and volcaniclastic rocks. It is marked topographically by the deeply incised valley of Broken Bridge Creek, which trends northeast between Cascade and Burnt Pine. The upper valley development of Mission Creek maybe a continuation of this zone.

Aerial photographs show that the island is crossed by numerous lineaments or fracture traces which are an expression of either a single joint, zones of closely spaced joint systems, or faults. Polar graphs and a map showing the simplified pattern of fractures (Abell, 1976) show that their directions are predominantly NNW, but with a significant percentage trending ENE. It is probable that these fracture directions probably indicate a complex response to stress relief, resulting from a post-eruptive history of submergence and subsidence of the island since volcanism ceased in the late Pliocene.

Although the post-eruptive evolution of Norfolk Island is poorly known, an examination of the bathymetry show it as part of a submarine plateau (submerged pedestal), which approximates to about the

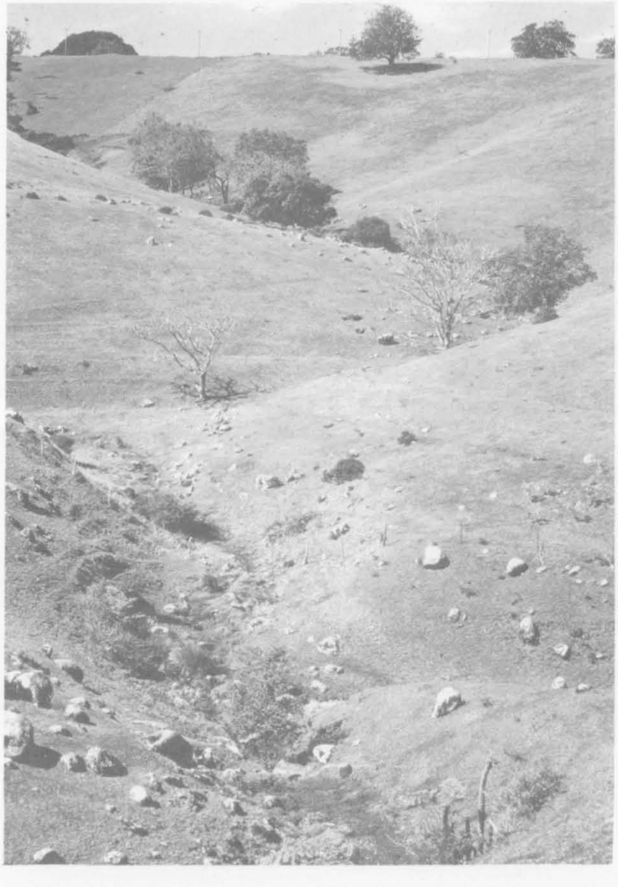

Plate 5. Basalt boulders as unweathered remnants from the weathered mantle, Town Creek.

100 m bathymetric contour (Main & McKnight, 1981). This submerged pedestal is taken to correspond with the greatest areal extent of the "Norfolk land mass" at the end of the Pliocene (Fig. 8). Small topographic highs on the pedestal may be remnants of other volcanic centres. Since the late Pliocene, there has been a progressive reduction in size of the "Norfolk land mass" by post-eruptive submergence (refer to sea level curves in Haq & others, 1987) to the extent that Norfolk and Philip islands now remain the only exposed portion of the submerged pedestal.

From 1969 to 1977, BMR operated a seismic station on Norfolk Island. No seismic activity from the island was recorded, suggesting that it occupies an area of low seismicity consistent with its position some distance from the margin of the Australian and Pacific plates.

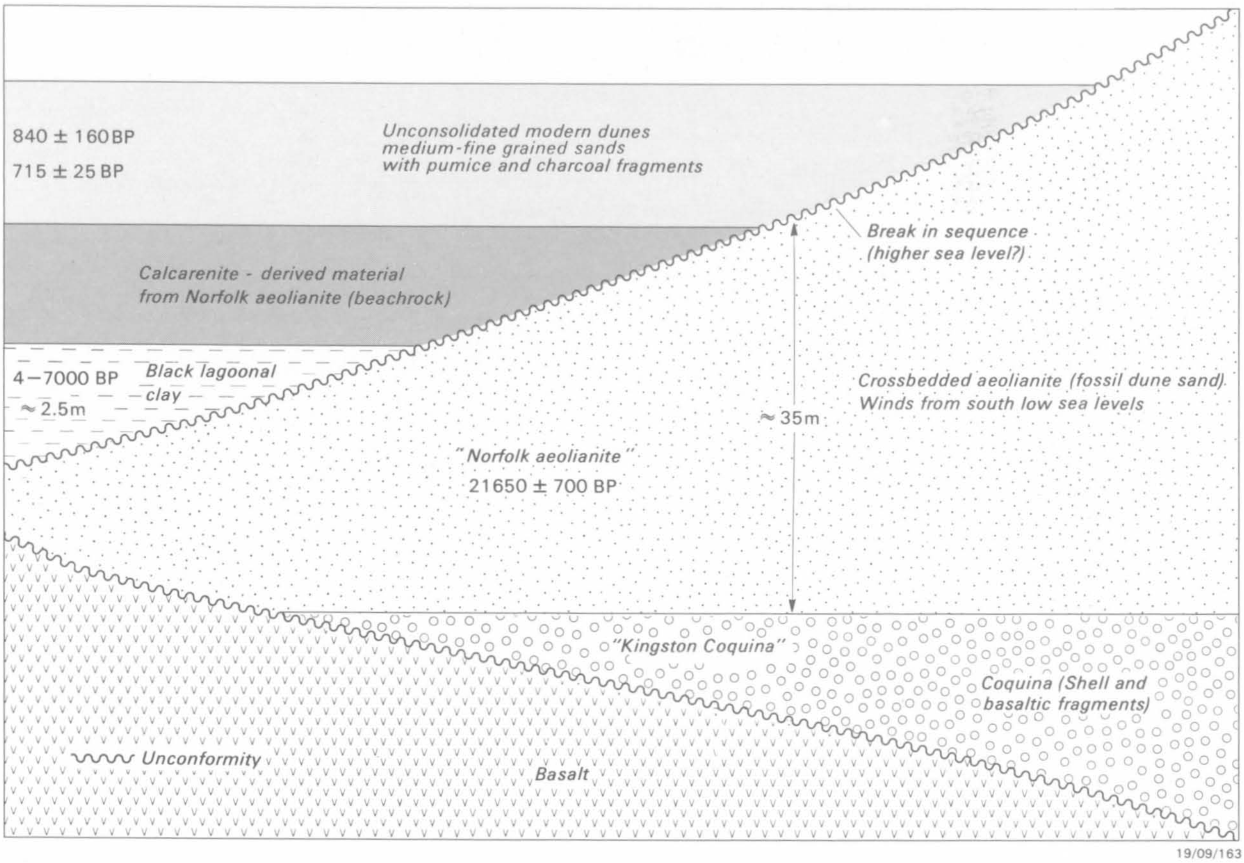

Fig. 6. Schematic Quaternary litho-stratigraphy (after Veevers, 1976; and Rich & others, 1983).

Geomorphology

Norfolk Island is rougly pear-shaped in plan, with its long axis trending northwest for about 8 km. Viewed from a distance, it gives a general appearance of subdued relief with a thick cover of vegetation contrasted to the spectacularly rugged coast line marked by poorly vegetated steep cliffs. In detail, the geomorphology is dominated by elevated terrain in the northwest, rising to a semicircular ridge on which Mount Bates (318 m) and Mount Pitt (316 m) are the highest points. The remainder of the island consists of a deeply incised southern plateau about 100 m high; a small remnant of the plateau occurs in the far northwest (Fig. 9). The higher terrain reflects the remains of the volcanic vent that was largely responsible for the formation of the island.

Norfolk Island has a 32 km long rugged coastline. Along the northwest side of the island, the cliffs are up to 100 m high, sloping down to the southeast, where they are up to 50 m. At Kingston, an ancient coastline modified by subaerial denudation marks the boundary between the southern plateau and coastal lowland. The latter, about 1.5 km long and 0.5 km wide, is less than 20 m above sea level.

Mass movement in the form of soil creep and landslips occurs along the coastline and in some catchments that have been cleared (Plate 6). Such movement is also encouraged by steep slopes, ground saturation after heavy rain, and the grazing habits of stock. Some control is being attempted by planting Norfolk Pine in the lower valley of Watermill Creek.

Marine erosion

The geomorphology of the coastline around Norfolk Island has evolved from the interaction of geological structure, lithology, marine and subaerial erosional processes, and sea level changes associated with climatic variations during and since the end of the Pliocene.

The cliff profiles are controlled by a combination of subaerial and marine erosional processes. During

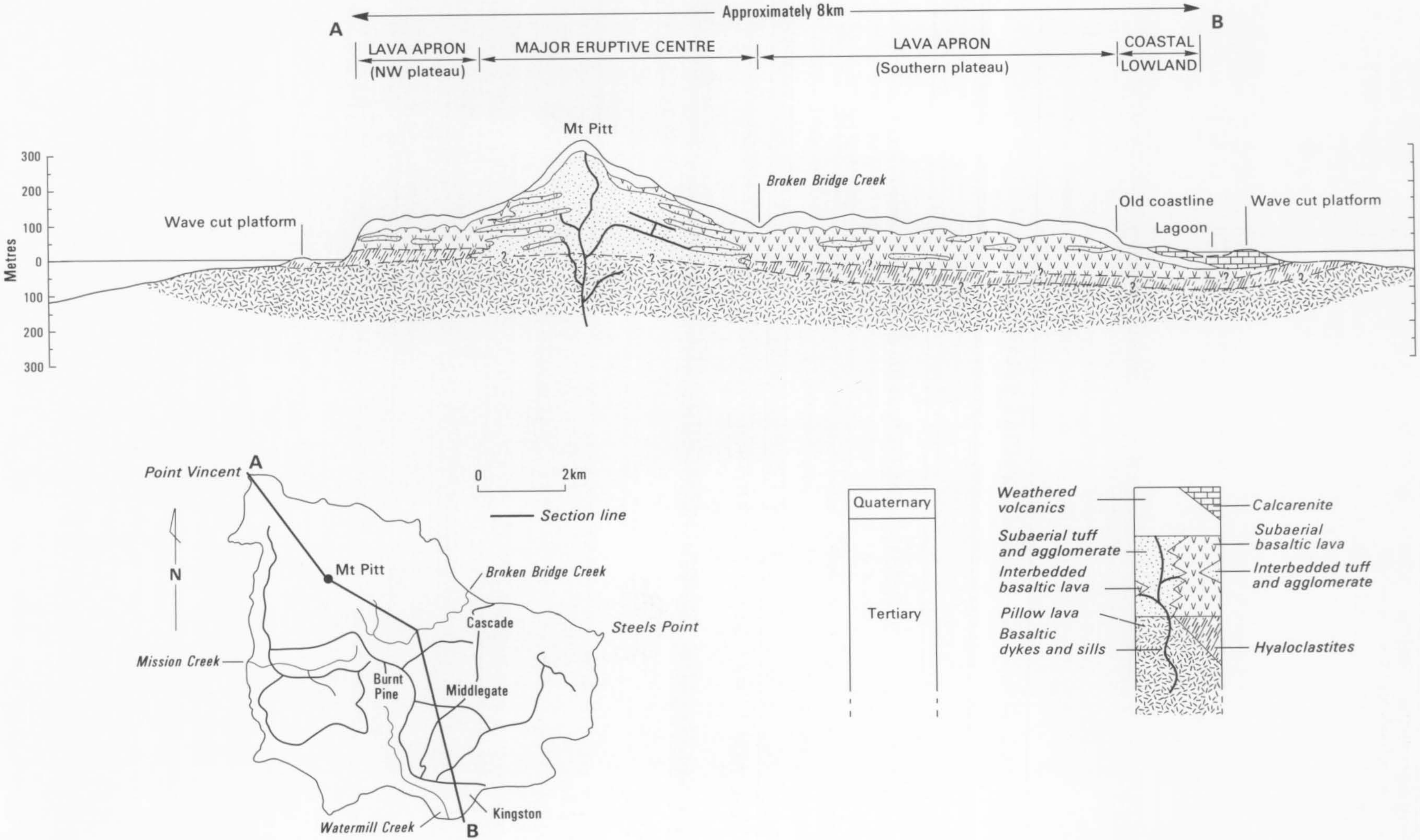

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Fig. 7. Simplified schematic geological section across Norfolk Island. Refer also to Fig. 4 of the geologic map.

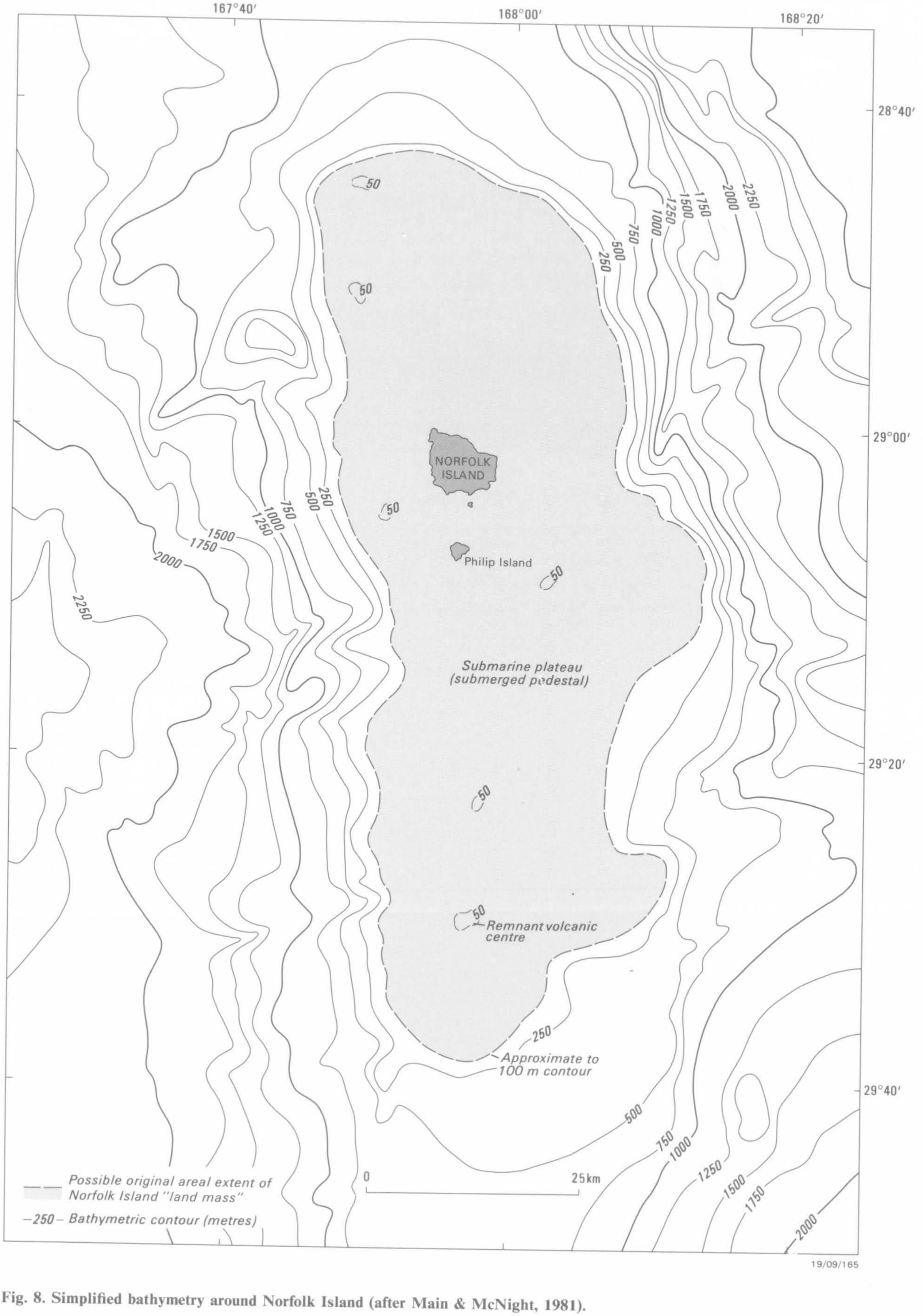

Fig. 8. Simplified bathymetry around Norfolk Island (after Main & McNight, 1981).

periods of lower sea level due to climatic change in the Pleistocene, cliff profiles were probably influenced by subaerial rather than marine erosion. The result is that cliff profiles tend towards the vertical in fresh rock, but are inclined at slopes of 45° or more in weathered rock (Plate 7).

Active marine processes are characterised by linear sections of coastline along which the remains of promontories now form sea stacks, e.g. Bird Rock. Valley-mouth embayments, truncated by cliff recession, have become hanging valleys that are dry or carry streams cascading over cliffs as rapids or small waterfalls. Clearly, the present cycle of marine erosion is causing cliffs to recede more quickly than streams can incise their courses. The rugged, and in some places, angular shape of the present coastline results from wave action along vertical joints in basalt lava. At Point Ross, wave action causes undercutting along weathered contacts between lava flows.

The smooth semicircular shape of Ball Bay is typical of Norfolk Island's coastline. The bay may have resulted from a phreatic volcanic eruption (between ascending magma and groundwater) creating a maar or crater that may have been breached by a Holocene sea level rise. Narrow wave-cut platforms at Steels Point and Rocky Point are related to cliff recession, and originated mainly from storm wave abrasion.

Calcareous sandstone along the coastal lowland at Kingston and on Nepean Island has a honeycomb appearance, which resulted from the solution and removal of calcium carbonate by spray and wind action.

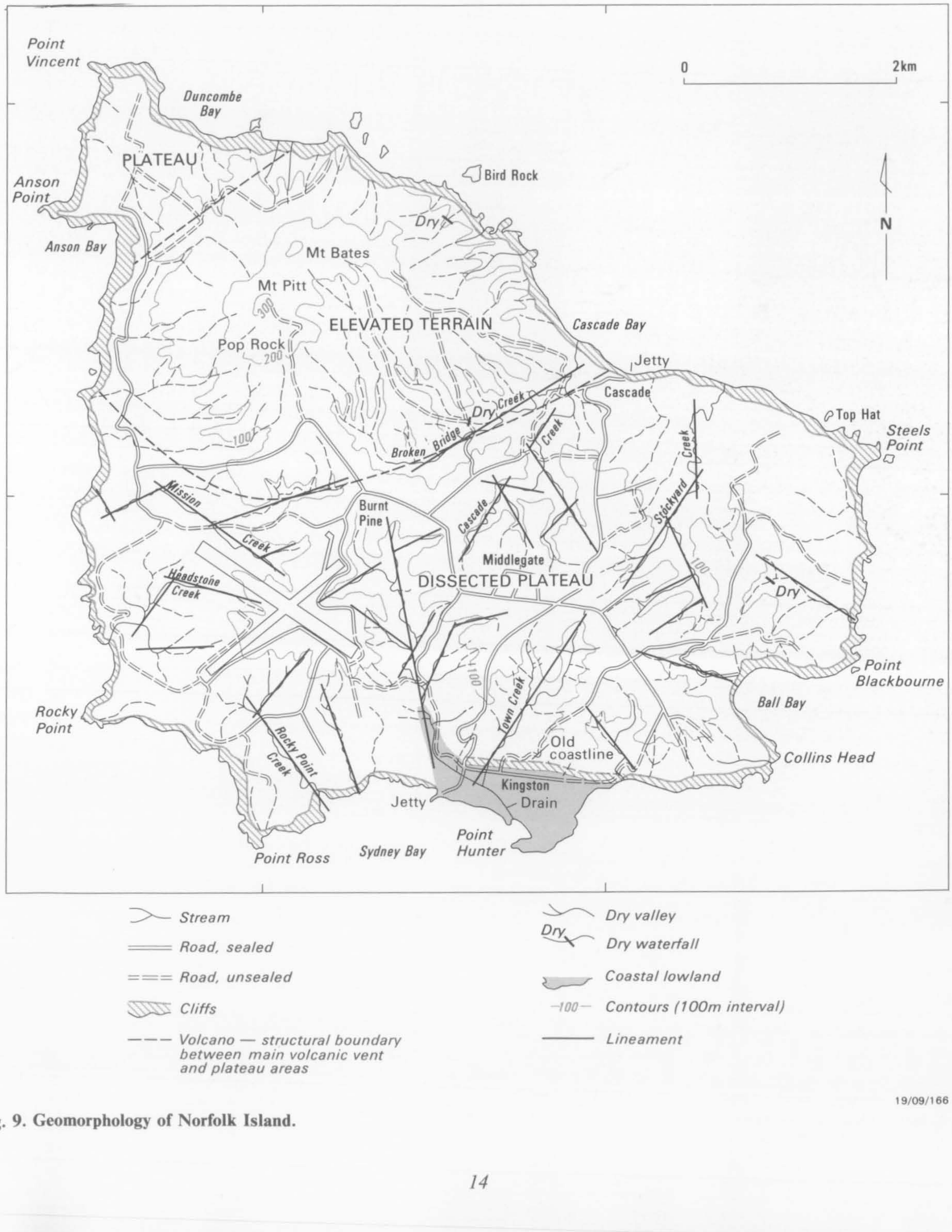

Fig. 9. Geomorphology of Norfolk Island.

Notch and vizor structures at the base of the cliffs suggest that undercutting is the main method of cliff recession.

Other typical marine erosional features — such as stacks, caves, and sea arches — commonly occur between Captain Cook Monument and Bird Rock, and also at Steels Point. These features indicate that the island had a greater extent in the past.

Drainage

Norfolk Island has developed a drainage system typical of volcanic terrain which has been deeply weathered in a subtropical climate. On the southern plateau, the drainage system consists of a network of dry valleys leading into perennial and intermittent streams. The elevated terrain around the Norfolk Island National Park supports an extensive network of dry gullies (Fig. 9).

The drainage pattern is radial to the main volcanic vent, except where the original crater was breached by lava flows that built the southern plateau. The present-day remainder of the original crater is a semicircular ridge at the head of a series of dry gullies forming the upper tributaries of Broken Bridge Creek. Some structural control of drainage by joints and fractures is suggested by local development of straight reaches and sharp turns of eroding streams. In some places, tributaries join the main stream at right angles. The effect of jointing has been to modify a dendritic drainage pattern that has developed in the head tributaries of each catchment (Fig. 9).

Streams draining the southern plateau are fed in their higher reaches by spring seepage and to a large degree are maintained by groundwater runoff (baseflow). The upper tributaries of all catchments are dry (Plate 7). The drainage on the southern plateau is dominated by Watermill Creek, which is centrally placed and flows southwards for 2.5 km across the southern plateau from Burnt Pine to Kingston. Most streams are active in the winter months, but in summer dry out or are reduced to disconnected pools and swamps. Only Watermill, Cascade, Stockyard, Headstone, Town, Rocky Point, Mission and Broken Bridge Creeks carry water in the dry periods.

Streams with interlocking spurs, and steep narrow-sided valleys commonly 60 m or more deep, are in a youthful stage of development. At present, most streams are 'underfit' — that is they flow in valleys which are too large for them; they have little erosive power; and they reach solid rock only at the perimeter of the island, where they discharge over cliffs as waterfalls (up to 30 m high) or as a series of rapids. The main exception is Watermill Creek, which shows signs of early maturity in its lower course where it is a gently graded stream below Watermill Dam. The creek reaches base level on the Kingston lowland, and enters the sea at Emily Bay through an artificial drain cut into alluvium (Plate 8).

It is evident that during the late Pliocene and at intervals in the Pleistocene many of the streams were probably perennial, with much greater erosive power than at present. Dry valleys were cut originally by active streams, which have since been reduced in size owing to change in climate, a lowering of the water-table, and the development of a porous weathered mantle. The Pop Rock, at an elevation of 180 m, is a basalt outcrop with waterworn grooves and potholes on its surface, suggesting that a greater volume of surface runoff occurred at higher elevations in the past.

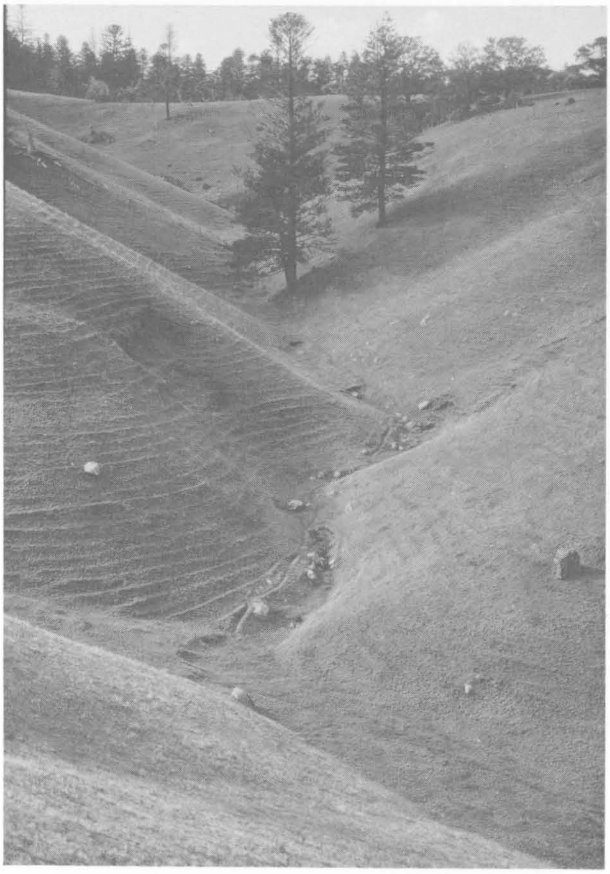

Plate 6. Interlocking spurs of a dry upper tributary of Watermill Creek. The soil creep on steep slopes is aided by grazing animals.

Groundwater occurrence

Groundwater on Norfolk Island functions as a dynamic system within the Island's hydrological cycle (Fig. 10). Rainfall reaching the ground surface either (a) returns to the atmosphere by evapotranspiration, or (b) runs off the surface into streams and thence to the sea, or (c) infiltrates and moves downwards under gravity past the root zone of plants to the saturated zone. The top of the saturated zone constitutes the water table in the weathered mantle. Groundwater moves both laterally in the direction of the water table-gradient discharging as coastal seepage springs, and within valley floors where the ground surface intersects the water table. If the water table drops below the base of the valleys during dry periods, streams are reduced in flow or dry up. At the base of the weathered mantle, it is likely that there is vertical leakage of groundwater through bedrock fractures. Some groundwater moving through these fractures is either discharged as coastal seepage springs close to sea level or recharges tuff beds and fragmented layers between lava flows to form local semi-confined aquifers; the remainder continues to deeper levels where it may be either discharged as submarine seepages at and beyond the margin of the island or ultimately mixed with seawater in volcanic rocks below sea level.

Plate 7. Typical coastal basaltic cliffs in Duncombe Bay looking west towards Point Howe.

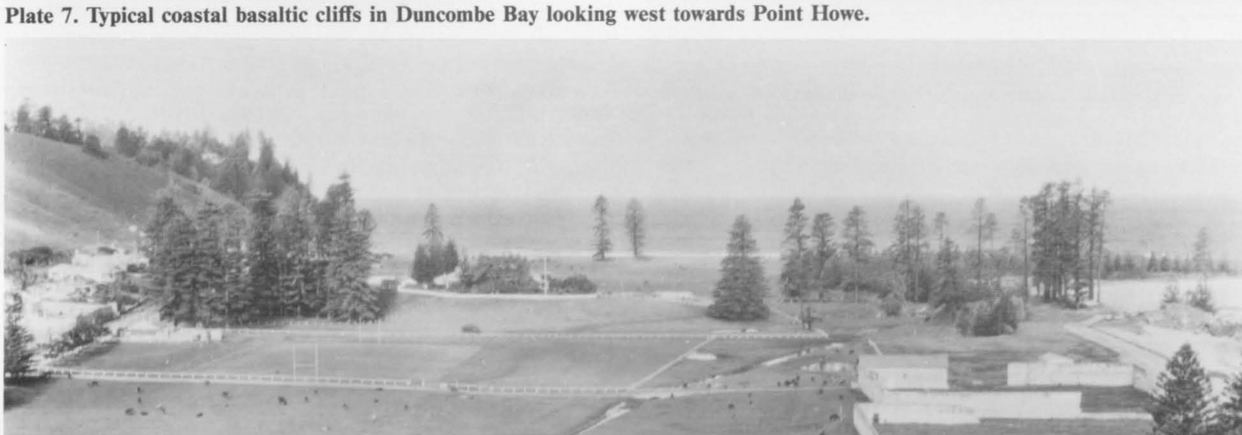

Plate 8. Kingston lowland — looking east along artificial drainage channel and old coastline on the left.

Weathered mantle

Early development of groundwater on the island was from wells and shallow bores tapping an unconfined aquifer in the weathered mantle high above sea level. On the southern plateau, the water table in this aquifer in places exceeds 100 m ASL (above sea level). The base of the aquifer has a gradational boundary with fresh volcanic rock; the aquifer's lateral extent is truncated by marine erosion at the margin of the island.

Weathering depths, as compiled from bore data, commonly range up to 60 m and in a few places exceed 80 m. This data also indicates that the weathered mantle is generally thicker along interfluves than along stream courses.

The porous nature of the weathered mantle suggests that it has considerable groundwater-storage capacity. However, the high percentage of clay, an elevated water table, and spring seepage- type loss suggest that the aquifer has only poor permeability.

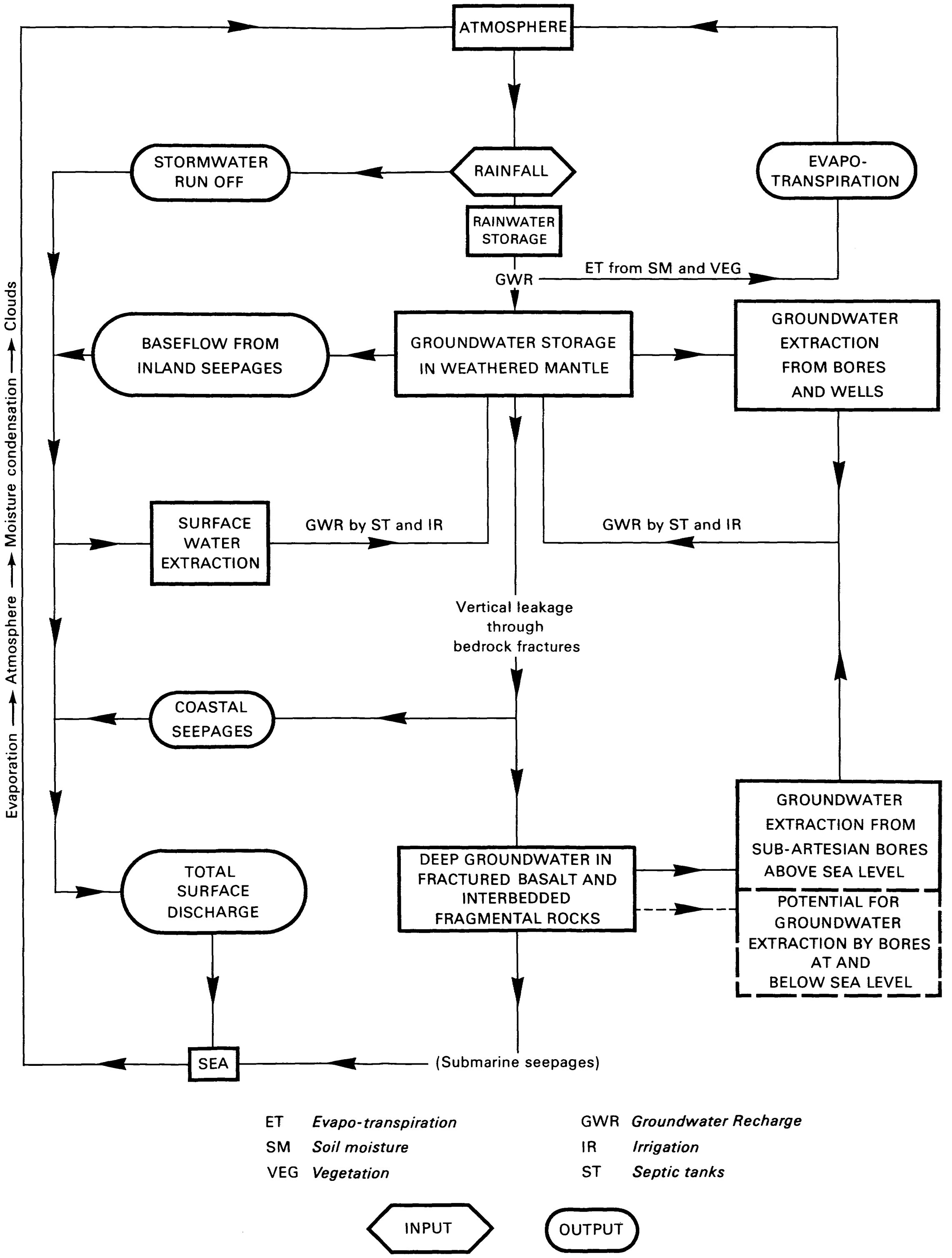

Fig. 10. Hydrological cycle applicable to Norfolk Island.

Basaltic lavas

Generally, basalt lava flows are heterogeneous water-bearing systems with the degree of permeability changing markedly over short distances. Visually, the basaltic lavas appear to have fracture permeability that is associated with both long vertical fractures and variably spaced columnar joints. Vertical tectonic fractures (in contrast to columnar jointing), act as important water conduits, probably extending to deep levels within the island. Evidence for these fractures comes from long joints cutting across polygonal (shrinkage) joints on wave-cut platforms and from linear geological and goemorphological features recognizable on aerial photographs, e.g. fracture control of drainage (see Fig. 9 herein and map 1 in Abell, 1976).

Although the vertical fracture component of permeability (K_v) normally exceeds that in the horizontal direction, increased horizontal permeability (K_h) occurs locally as irregular openings along subhorizontal joints and contacts between lava flows. Nevertheless, the fragmented or slaggy tops of the lava flows, weathered to clay, may impede the vertical movement of groundwater and cause it to flow laterally where it may emerge as coastal seepages.

Those basalt lava flows that are vesicular, and therefore of high porosity, but of very low permeability (due to lack of connection between vesicles), are readily observable in coastal sections. On the other hand, permeable zones may be associated with hackly jointed lavas near the top of the quench zone.

Basaltic lavas extruded above sea level are generally permeable since they display interconnected openings (joints, fractures, bedding, etc.); however, the central parts of thicker flows are more massive and less permeable. Pillow lavas extruded below sea level are quickly chilled and therefore more massive and comparatively impermeable.

Pyroclastics: basaltic tuff and agglomerate

These rocks are exposed along the northern coast at Anson Bay and from Duncombe Bay to Cascade, Steels Point, and between Rocky Point and Headstone. Although the lateral extent and thickness of these units in the interior is conjectural, it is likely that they increase in continuity and thicken towards the summit area of the island (the main volcanic source), but occur as thin lenticular beds underlying the southern plateau (Fig. 7).

Unlike the lava flows with which they are interbedded, tuffs have poorly developed fracture permeability. Primary intergranular porosity was originally high (50%) at the time of deposition, but has since been reduced by the formation of palagonite (a weathering product of basaltic glass). Porosity and permeability tests (Abell, 1976) showed good storage capacity (20–40% porosity) and good rate of flow (up to 7.3 m/day). In most samples, permeability in the horizontal direction exceeds that in the vertical owing to grain-size changes associated with bedding.

The lithological logs indicate that potential water-entry points in bores can be associated with permeable basaltic tuff and agglomerate between less-permeable basaltic lavas. Further evidence that these pyroclastics behave as aquifers is afforded by the presence of confined groundwater below the weathered mantle that rises under subartesian pressure (i.e. not reaching the surface) when tapped during drilling, and coastal spring seepages behind Cascade Jetty (Plate 9) and near Steels Point. These rocks are capable of storing and transmitting groundwater, provided there is access to recharge from fracture systems in surrounding basalt flows.

Hyaloclastic rocks

Between Anson Bay and Duncombe Bay, along the northwest coast, and also locally south of Puppy's Point, the primary porosity and permeability (based on degree of seepage) can be examined in exposures of hyaloclastite breccia at the base of cliffs a few metres above sea level.

Evidence that these rocks may have potential as aquifers is afforded by coastal spring seepage zones and laboratory-determined permeability. A seepage at the base of sheer cliffs on the northside of Anson Bay (access only at low tide levels) is the largest known on the island. At this locality groundwater discharges from hyaloclastite rocks and hackly jointed lava flows over an area of about twice that of the seepage at Cascade (~$60m^2$; see Plate 9). In addition, other smaller seepages are present just above a wave-cut platform east of Point Vincent. Porosity and permeability values determined by laboratory techniques (P.G. Duff; Appendix 2 in Abell & Taylor, 1981) show good water-storage capacity (20–40% porosity) and locally high rate of flow (~1 m/day).

Quaternary deposits (calcarenite, beach rock, and carbonaceous clay)

Calcarenite, with limited areal extent on the Kingston lowland, is locally exploited as an aquifer. Permeability is mainly intergranular, but some exposures show that fracture permeability exists along flaggy partings in cross-bedded sequences or along joints where the rock is massive. Primary porosity of the originally unconsolidated shell fragments has been reduced by calcite cementation as exemplified by the presence of beachrock (Fig.6). Although there is a considerable range of porosity and permeability values (Abell, 1976), it is likely that these rocks will function as an aquifer, but they may be liable to seawater intrusion as they are exposed close to sea level.

The lateral extent and variation in thickness of the interbedded black clay and beachrock is unknown. Where present they are assumed to act as thin semi-confining layers holding groundwater under pressure beneath the coastal plain.

Water table (in weathered mantle)

An elevated water table is indicated by the levels at which groundwater stands in wells and shallow bores tapping the weathered mantle. For example, the water table underlying the southern plateau is maintained at elevations of 100 m or more above sea level by the low to moderate permeability of the weathered mantle (Fig. 11).

The most readily obtainable water table data are from wells, as access to most bores is restricted by pumps. The water table was measured using a locally made single-electrode water-level recorder based on the principle of the earth-return circuit. The data was collected over a six-week period from mid-July to the end of August 1974, when water levels rose as a response to seasonal recharge from winter rainfall. These water table data (Fig. 11) are well distributed over the southern and northwestern parts of the plateau, but are scarce around the main volcanic vent, which is heavily forested and

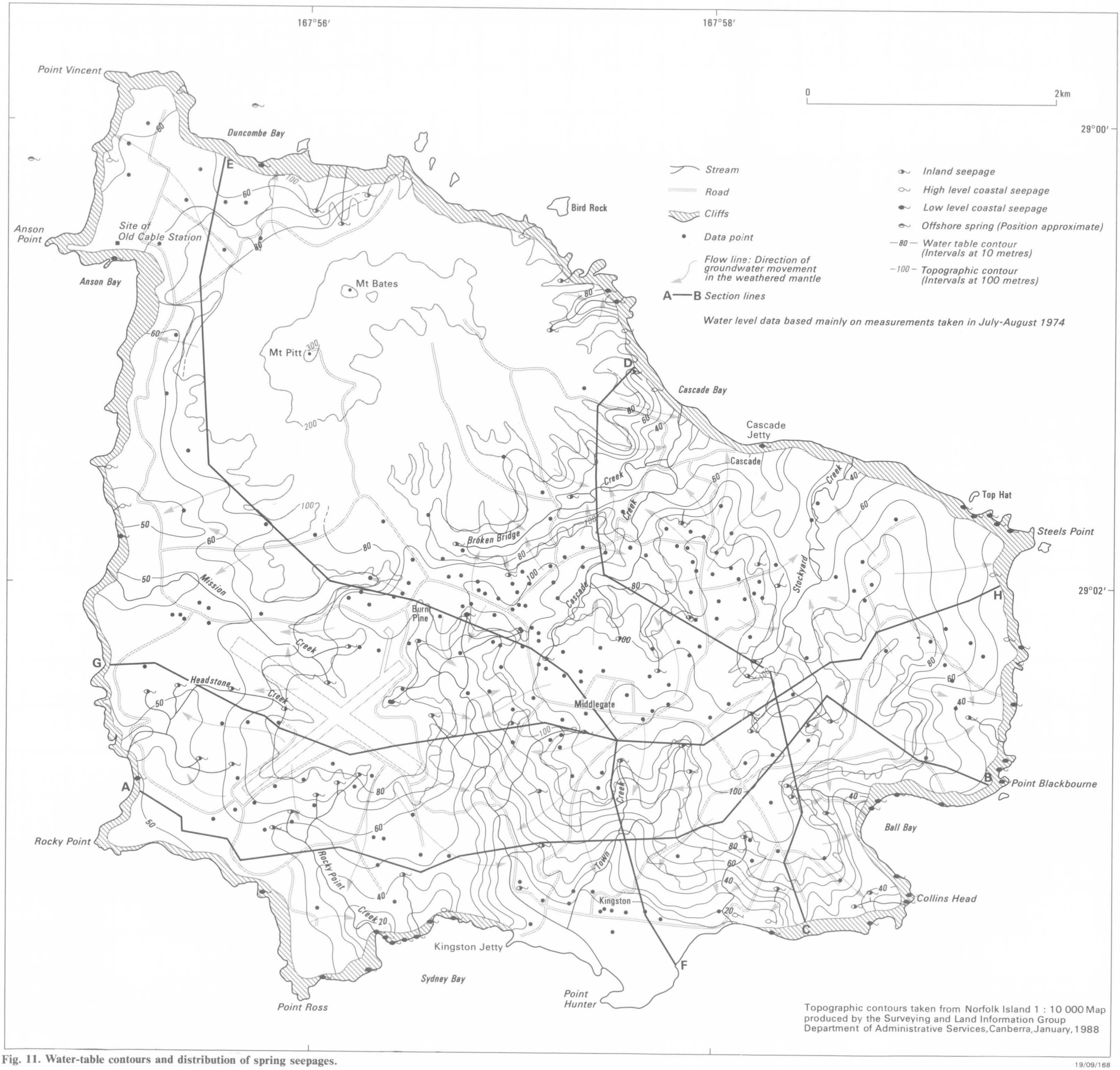

Fig. 11. Water-table contours and distribution of spring seepages.

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uninhabited. In contouring the data, it was assumed that since streams are fed and maintained largely by groundwater discharge, the water table accords with stream level.

Apart from valley and high-level coastal spring seepages, there is little field evidence for the water table, except a circular pond 45 m west of Cascade road which is regarded as a water-table window (Fig. 11; Plate 9). Governor Gidley King's early report of Norfolk Island mentioned this pond on an old map dated 1794?, showing its location as a small swamp; thus suggesting that in the days of first island settlement (1788–1814), the water level was higher. The pond is close to an early convict settlement, whose inhabitants might have formed its regular circular shape by clearing and deepening it for use as a water supply. Local people know of water-level fluctuations, some remember the water overflowing through a saddle on its northern side to a dry gully joining Cascade Creek below. Older residents know the pond to go dry; for example banana trees were planted in the bottom during a dry spell in the early 1920s. The pond's water level is similar to that of a nearby well (NI 185), as both are related to the same water table. Presently, the pond is used as a watering point for stock.

Configuration of water table

Like the topography, the water table is truncated at the margin of the island (Fig. 12); otherwise, the contours roughly parallel the ground surface but with more subdued relief. Hydraulic gradients are generally steep on valley sides, but flatten out on the interfluves.

Groundwater movement in the weathered mantle is indicated on the water-table map by flow lines (Fig. 11). These show that high-level groundwater moves laterally under the influence of gravity from areas of high hydraulic potential (recharge areas), mainly on the central portion of the southern plateau, to areas of lower hydraulic potential (discharge areas), at the perimeter of the island. This general picture is complicated by groundwater movement towards valleys where contours and flow lines show that groundwater seepage feeds and maintains streams as base flow. Owing to the size of the island and the dissected nature of the plateau, flow paths are short. The distance between recharge and discharge areas is generally less than 3 km.

Fluctuations

Only one long-term water table record exists on Norfolk Island: dating from 1974, from well NI 119 sited on a watershed separating Broken Bridge creek and Cascade creek. Water-table fluctuations spanning a time between July 1974 and September 1975 were also measured from a network of 14 observation wells and bores (fig. 13 in Abell, 1976).

The hydrographic records show that there is a clear response to seasonal patterns of rainfall. Generally, wells and bores in topographically high areas tend to exhibit larger fluctuations than those in valleys which are zones of groundwater discharge. In some cases, however, abrupt changes in water levels are due to pumping.

Groundwater movement in bedrock aquifers

Since 1976, water bore drilling on Norfolk Island has penetrated frequently below the weathered mantle to provide evidence of subartesian groundwater. Lithological logs (prepared from drill cuttings) and water-entry data indicate semi-confined groundwater associated with discrete permeable zones (fractures and tuff beds) within the volcanic sequence. The piezometric data from these water-bearing zones are represented on cross-sections (Fig. 11) by equipotential contours (Figs 12 A, B, C and D). These sections indicate that ground-

Plate 9. Water-table window at an elevation of about 100 m close to the western side of Old Cascade road.

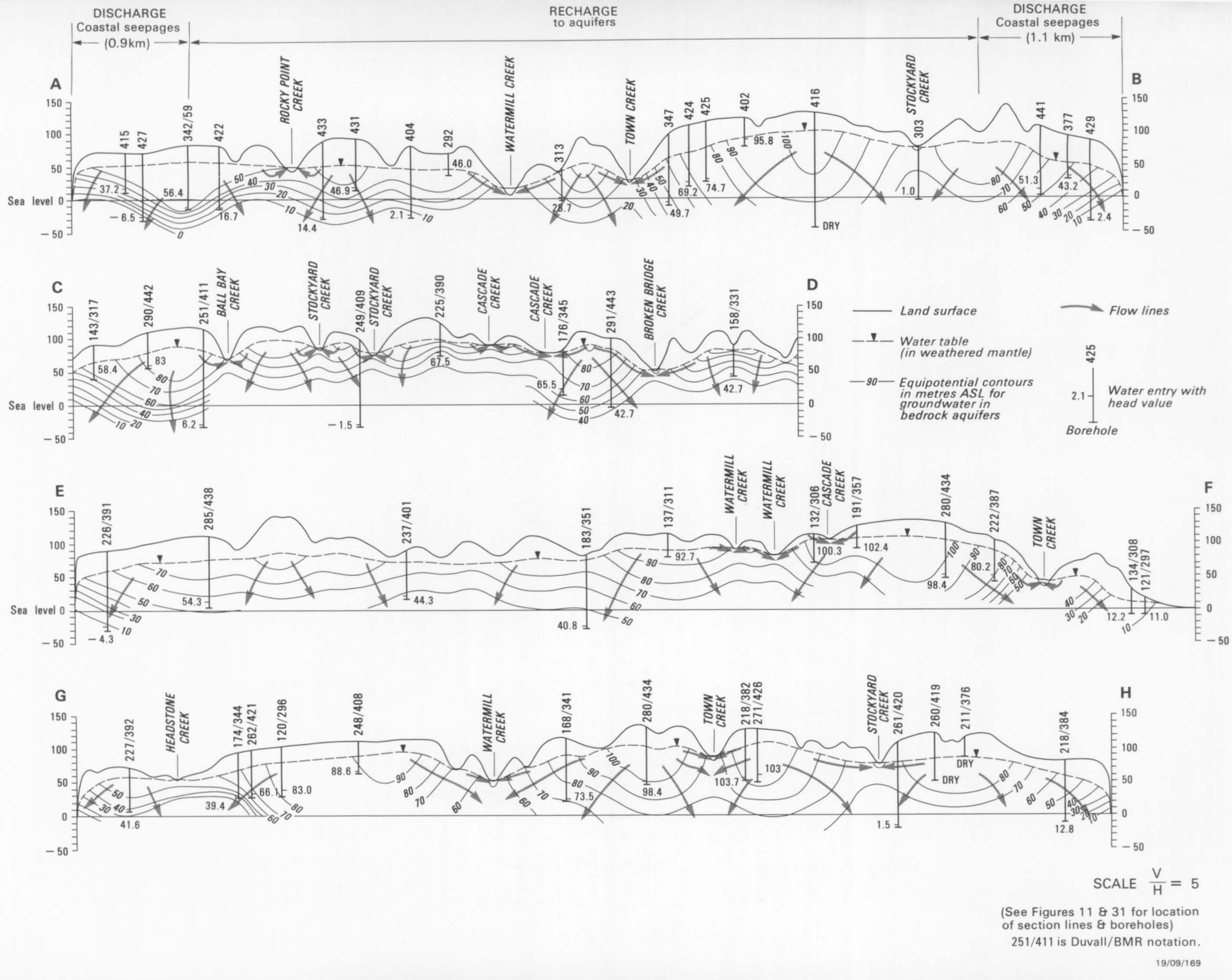

Fig. 12A to 12D. Regional groundwater flow system. (See Fig. 11 for location of section lines.)

water moves in a dominantly vertical direction from points of high potential (about 100 m ASL) to points of low potential (sea level and below). This hydrologic situation has been found within the island and in a zone up to a kilometre in width along the coastal margin (see Fig. 12 A). The sinusoidal pattern and high gradients of the equipotential contours reflect, respectively, the heterogeneous and moderate permeability of the bedrock aquifers. The distribution of equipotential lines also suggests that creeks, e.g. Watermill Creek in section A–B (Fig. 12), act as discharge conduits. It is assumed that the top of the groundwater flow system is the water table.

Following evidence of pollution (Goldfinch & Cross, 1980), an investigation into groundwater movement rates was conducted by the Department of Housing and Construction in 1982. Rhodamine WT (Red) dye inserted at a water bore (NI 138) at the South Pacific Hotel and later detected at Kingston, indicated a rate of 40 m/hour. This may be locally a high rate of movement, since the evidence from tritium shows that most groundwater is older than 25 years (Fig. 24 and Table 6), implying that movement rates are generally slow. Thus, the higher rates of groundwater movement appear to be dependant on particular large fractures, but is otherwise highly variable island-wide.

Groundwater discharge

Generally speaking, groundwater is lost by evaporation from plants and soil, and as spring seepages on and around the island (Fig. 11). There are no records to measure or estimate seepage discharge. The location, size, and distribution of seepages reflects the general hydrogeology of the island (Fig. 13), as explained below.

Inland spring seepages

Inland seepages are formed where the ground surface intersects the water table or local bodies of perched water. They normally occur in valleys and are the main contributors to base flow in all streams (Fig. 11). With the seasonal fall in the water-table, some seepages tend to become intermittent. Many seepages are associated with small 'knick-points' in the stream profile, usually marked by basalt boulders; the 'knick-points' suggest that the stream has some erosive power and is cutting back into the valley at the point of seepage discharge. The diffuse and sluggish groundwater discharge in drainage in higher topographic areas confirms that the weathered mantle has only moderate permeability.

Coastal spring seepages

Coastal seepages are poorly distributed around the margin of the island. They appear to be most numerous south of a line between Cascade and Headstone, whereas the western and northwestern coastline are barren of coastal seepages.

High-level coastal seepages (see Fig. 13) occur just above the base of the weathered mantle, where the water table is truncated at the margin of the island; some dry out in summer. Other high-level seepages are associated with vertical joints located just below the base of the weathered mantle.

Low-level coastal seepages (see Fig. 13) at Cascade (Plate 10) and Ball Bay may be related to northeasterly and northwesterly trending vertical fractures. Seepages at Steels Point associated with basaltic tuff suggest these rocks have some degree of permeability if accessible to recharge. A seepage zone on the north side of Anson Bay, related to a quench zone of hackly-jointed basaltic lava and massive hyaloclastite rocks, extends over a distance of about 30 m. This is probably the largest coastal seepage on the island and suggests that the quench zone may have locally high permeability near sea level. Some seepages, particularly those near Collins Head and Cresswell Bay, issue from permeable zones of fragmental and vesicular basalt.

Offshore springs

Two offshore springs have been reported by local residents within 1 km of the shore: one between Point Vincent and Anson Point; the other close off Duncombe

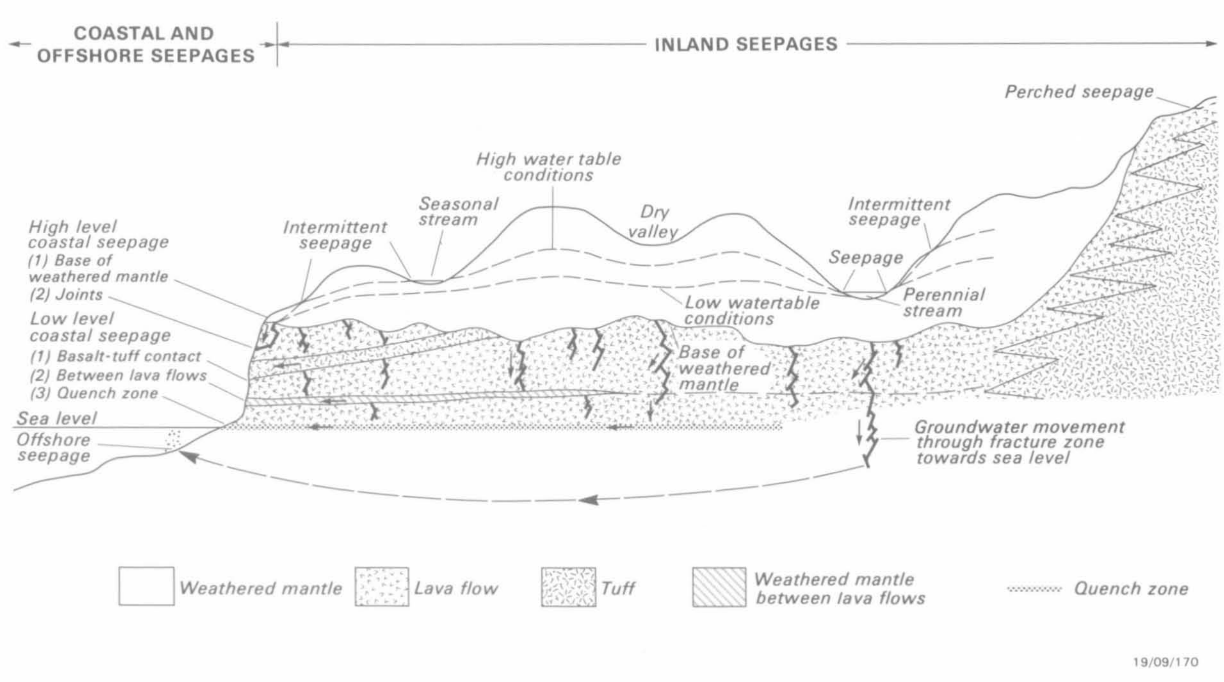

Fig. 13. Groundwater discharge. Note the three types of seepages (i.e. inland, coastal and offshore).

Bay (Fig. 11). Rising air bubbles or a muddy discolouration of the seawater after heavy rain have been observed at both places. Both springs are in line with northwest-trending fractures which extend from the island offshore. The sparsity of coastal seepages just above sea level suggests that more offshore springs may occur, but owing to a steeply shelving sea bed, strong winds, and heavy swells their location is difficult to determine.

Deep groundwater

In general, the basic requirements for a land-based groundwater lens (whose saline–freshwater contact is below sea level) are (a) suitable degree of permeability of the rocks that contain the water and control its movement, and (b) sufficient amount of rainfall recharge to maintain a water table above sea level. Fresh water floats on sea water–which has higher specific gravity–and thus displaces a volume of seawater equal to its own weight; this depresses the saltwater/freshwater interface below sea level. According to the Ghyben-Herzberg relation, the saltwater/freshwater interface beneath islands of coral-reef and sand-dune type extends in general to about 40 times as far below sea level as the water table is above sea level. The classical case, which is related to sand dunes, is theoretical and assumes no mixing between salt and freshwater through the rock sequence. In practice, however, the lens is a dynamic system as it is recharged from above and discharges downwards and outwards to the sea; permeability distribution is usually heterogeneous, and salt water and fresh water mix at the base of the lens to form a transition zone. Also, hydraulic head, density, temperature and tidal fluctuations effect the shape and distribution of the lens.

The hydrogeological investigations relating to groundwater lenses in basaltic volcanic islands is limited. Case studies include those of Guam (Ward & others, 1965); Cheju Do Island, Korea (Eckstein, 1969); Tenerife, Canary Islands (Ecker, 1976; Custodio, 1985, 1989); and the Hawaiian Islands (Takasaki, 1978; Fujimara & Chang, 1981). Brief summaries given at an international symposium on the hydrology of volcanic rocks at Lanzarote in the Canary Islands, under the auspices of the Government of Spain and UNESCO, have been provided by Davis & others (1974) and Fernandopulle & others (1975). For the Hawaiian Islands, Guam and Cheju Do Island, the accumulation of groundwater at or below sea level appear to follow the orthodox Ghyben-Herzberg model with some modification proposed for perched aquifers above sea level. In contrast to this, the occurrence of lithological heterogeneity in basaltic volcanic islands has led Ecker (1976) to depart from the classical Ghyben-Herzberg scheme. He has proposed a model of separate groundwater compartments, connected by either rocks of greater permeability and/or by secondary leakage conduits (i.e. fractures), in the rough shape of a lens to explain groundwater on Tenerife, the largest volcanic island in the Canary Group.

Groundwater model for Norfolk Island

A single-component groundwater storage system is likely to exist, although some degree of compartmentalisation following Ecker (1976) may have developed locally across Norfolk Island (Figs 14 and 15). The upper boundary of this system is defined by an elevated water table in the weathered mantle. Hydraulic continuity through fresh volcanic rocks to sea level and below is maintained primarily by a network of fractures and interconnected openings.

The ability of this hydrogeological system to support a substantial groundwater reservoir depends largely on the magnitude of permeability of the volcanic rocks below the weathered mantle. If $K_h > K_v$, it is unlikely that fresh groundwater will extend far below sea level. However, for Norfolk Island, where $K_v > K_h$, the prospects

Plate 10. Seepage from basaltic tuff and agglomerate exposed behind Cascade Jetty.

for deeper groundwater are enhanced. (K_h and K_v = respectively, horizontal and vertical permeability.) Field observations indicate that the predominantly vertical groundwater movement pattern and the large storage capacity of the volcanic sequence are supported by both poor surface runoff and small groundwater losses from coastal seepages.

The strictly geological models by Moore & Fiske (1969) and Jones (1970) for the substructure of oceanic volcanic islands support the present work in that the framework on Norfolk Island needs to incorporate pyroclastic deposits at or near sea level with the depth and distribution of the basaltic pillow lavas. The subsurface distribution of the pyroclastic units is poorly known, but it is assumed that they have water-bearing properties similar to tuffs and hence have the capability to function as aquifers. Conversely, pillow lavas which are assumed to form the bulk of the submerged pedestal probably act as an impermeable base for the hydrologic system.

Groundwater from the weathered mantle gravity-feeds and recharges bedrock aquifers through fractures. That

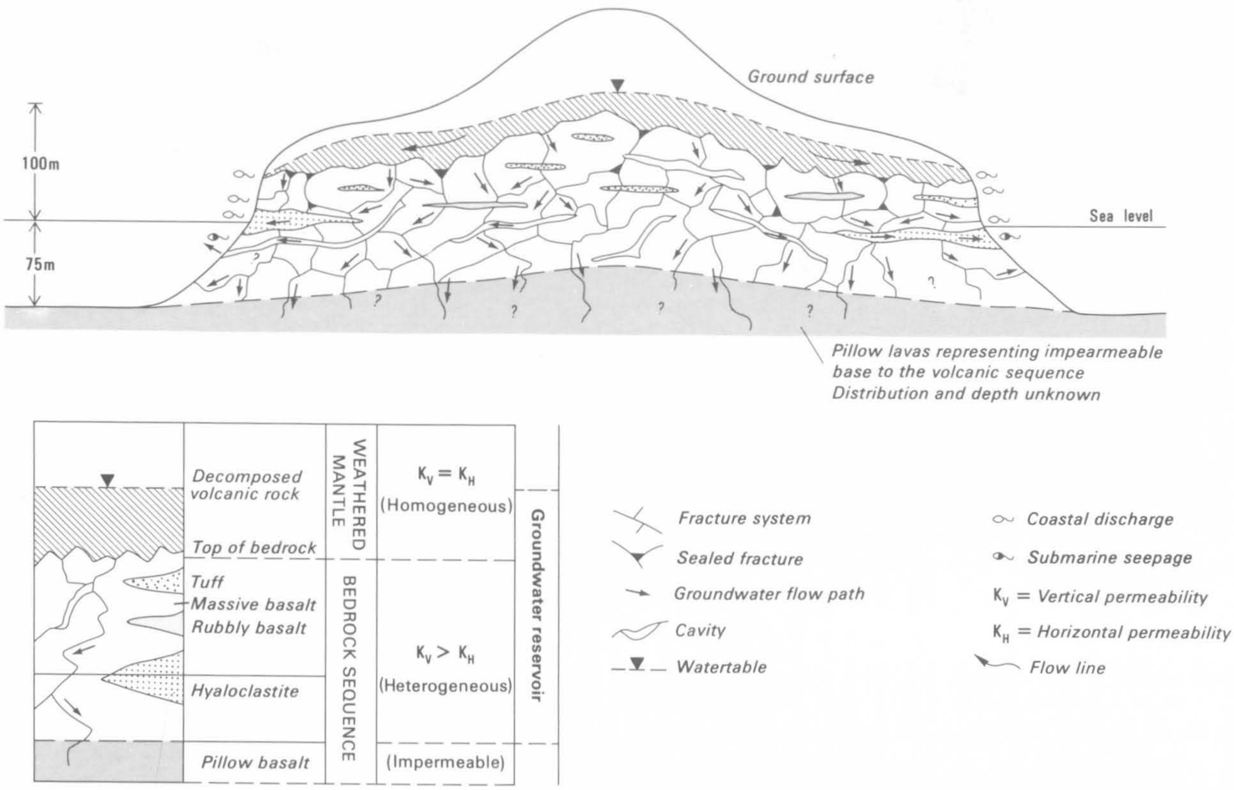

Fig. 14. Idealised hydrogeological model for Norfolk Island.

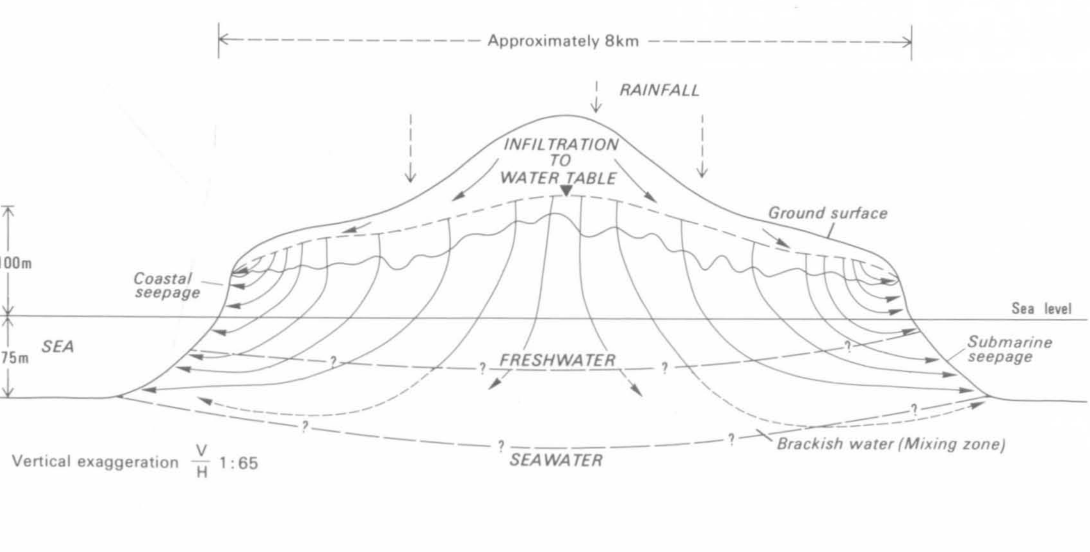

Fig. 15. Conceptualised groundwater flow system (simplifying heterogeneity of the volcanic sequence — contrast with Fig. 12).

such fracture controlled recharge may be widespread is indicated by a fracture-trace analysis (Abell, 1976), which suggests that vertical fractures trending NNW are the longest and most numerous; the reported existence of submarine springs close to Point Vincent confirms their importance as conduits for groundwater movement. Lost circulation reported in some drillholes indicates that permeability does increase at or near fractures. Over what length a fracture zone will behave as an active conduit for groundwater is uncertain, but permeability variation within a specific fracture relates to either the degree of fracture closure with depth, or locally to the amount of clay formed by the increased penetration of weathering into fracture zones.

However, where weathering has permeated to clay-seal fractures, recharge will be isolated locally for dry permeable zones to exist in bedrock. For example, it appears that the past disposal of sewage effluent down a bore at the South Pacific Hotel (NI 138) can be explained by dispersal into a dry, isolated cavity in the volcanic sequence not actively recharged by groundwater; a fact supported by a report of lost circulation when the hole was originally drilled. This clay-sealing process might also explain pockets of high-level saline groundwater at the base of the weathered mantle (see Fig. 16 — hydrochemistry).

The Ghyben–Herzberg model is not considered to apply *in toto* to Norfolk Island. The heterogeneity of the permeability evident in volcanic bedrock suggests that the classical geometric lensoid shape of a freshwater body is transitional and distorted into an interfingering shape. The zone of mixing between freshwater and seawater will be greater along fractures and other permeable zones. Furthermore, a theoretical value of about 4000 m for the maximum thickness of basal freshwater below sea level, derived from the Ghyben–Herzberg formula (and assuming a water table reading up to 100 m ASL), indicates the inapplicability of this formula to heterogeneous volcanic rocks, such as on Norfolk Island.

Water quality

Periodic sampling and analysis of water from wells, bores and creeks has been carried out since 1965; some ground and surface water analyses are listed in Table 1. Generally, water is suitable for domestic use, but it may locally exceed salinity limits in the northwest plateau, Kingston lowland and other coastal areas (Fig. 16). Groundwater pollution from inorganic and organic sources is a growing concern on Norfolk Island.

Chemical composition

The chemical analyses listed in Table 1 show that, generally, sodium accounts for more than 60% of cations and chloride 60% of anions. Ground and surface waters were classified by compiling a trilinear diagram using percentage of equivalents per million (% epm) of anions and cations (Fig. 17). All values plot in a sodium chloride field — these values are similar to diluted seawater.

Sodium chloride in groundwater is derived from two sources: (1) from salt spray which is more or less permanently in the atmosphere, and (2) from ocean salt that was deposited by spray blown inland from waves around the island periphery.

Groundwater quality is also determined by the composition of the volcanic succession. According to Green (1973), the most common minerals in Norfolk Island basalts are calcic plagioclase, olivine, pyroxene, accessory iron oxide, and apatite. Calcium and magnesium are released into the zone of weathering mainly from feldspars and ferromagnesian minerals, and in the early formation of the weathered profile, far more calcium and magnesium were available than at present. As the profile has developed, ion exchange has progressively operated between clay minerals rich in calcium and magnesium cations and sodium from atmospheric salt dissolved in groundwater.

Water quality guidelines

The total dissolved solids (TDS) gives a general indication of the salinity of a water sample, and is often used as an indicator of water quality. However, the concentration of individual constituents must be taken into account when determining the suitability of water for specific purposes.

The water quality guidelines given in Table 2 are based on recommendations provided by the National Health and Medical Research Council (NHMRC; AGPS, 1987). Accepted upper limits are somewhat subjective and may depend on individual human tolerances. In general, lower limits should apply to tourist accommodation on the island.

Rainwater

Rainfall is the primary source of freshwater on Norfolk Island. Samples were collected for analysis (Table 3) during 1978–80 to assess quality and atmospheric salt concentrations. The method for rainwater collection is outlined in Abell & Taylor (1981). Atmospheric concentrations of rainwater samples as determined by the SO_4:Cl ratio shows that rainwater salinity is due to atmospheric salt spray from the ocean dissolved during rainfall. This interpretation is confirmed by a graph of sulphate and chloride concentrations for rainwater on Norfolk Island, which plots close to the line representing the average SO_4:Cl ratio for seawater of 0.14 (Fig. 18).

Salinity levels of several samples ranging from 15–55 microsiemens/cm suggest that the location of the sampling point at an elevation of 128 m, and 2 km inland from the coast, is not a significant factor affecting the chemistry of rainwater. The low pH values (5.2–6.3) indicate that rainfall has a relatively high reactivity and therefore contributes to long-term weathering processes. Probably, variations in rainfall chemistry depend on the amount of rain, surf conditions and seasonal climatic change.

The low ionic concentrations in Norkolk Island rainwater have a range of low chloride and sulphate values comparable with other Pacific islands (Eriksson, 1957; Visher & Mink, 1964; and Kroopnick, 1977). The analyses for Norfolk Island provide a good example of

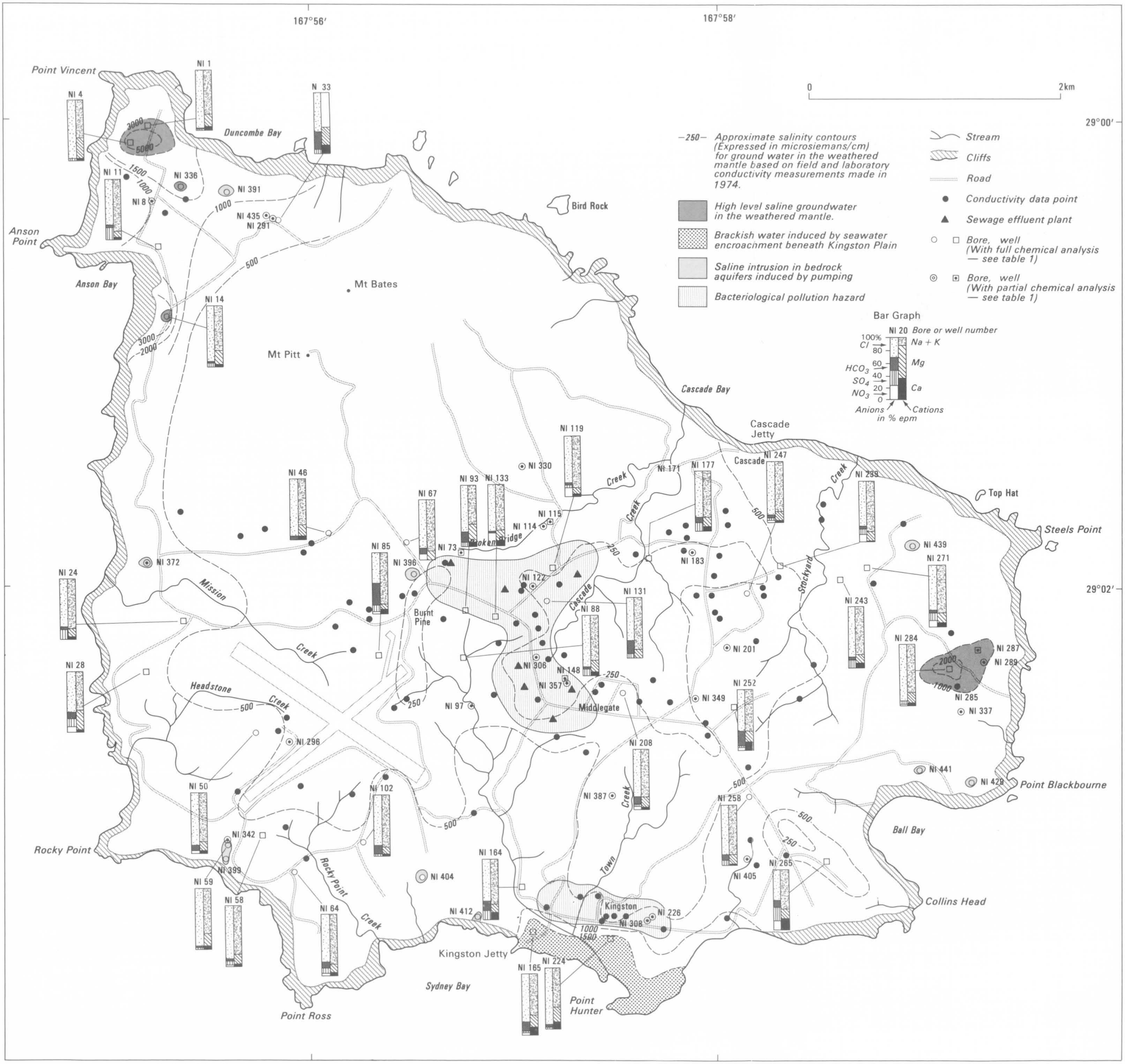

Fig. 16. Hydrochemistry of Norfolk Island.

TABLE 1. CHEMICAL ANALYSES OF GROUND AND SURFACE WATER FROM NORFOLK ISLAND (expressed in mg/l)

(a) GROUNDWATER

No.	Year	Type of Extraction	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	PO_4	Fe	Mn	pH	Total hardness (as $CaCO_3$)	TDS	Electrical conductivity (micro-siemens/cm)	Remarks
NI 265	1965	W	12	6	45	1.6	23	40	70	35	—	0.16	0.31	6.9	54	272	—	
NI 224	"	W	39	50	250	7.0	38	28	577	0.24	—	trace	—	6.3	312	1465	—	Brackish water
NI 28	"	W	4	20	72	2.5	39	35	130	34	—	—	—	6.9	92	408	—	
NI 11	"	W	8	16	245	9.0	20	115	320	0.58	—	0.21	0.06	5.9	86	1028	—	Brackish water
NI 4	"	W	70	—	1720	18.0	5	180	4125	—	—	0.43	4.40	4.2	1700	9096	—	Saline water
NI 271	"	W	6	9	71	3.1	11	35	159	45	—	0.11	0.45	5.6	80	399	—	
NI 183	1971	B	0.7	2.2	22.5	0.5	2.4	4	35.5	—	—	—	—	5.9	—	131	—	
NI 93	1973	W	5	12.5	54	1.3	—	12	97.5	0.20	0.05	0.33	—	5.8	40	—	—	
NI 243	1974	W	10	10	110	1.0	20	40	174	1	0.03	0.15	0.04	5.5	66	356	650	
NI 284	"	W	18	61	500	5.0	7	69	934	11	0.02	0.05	0.55	4.4	296	1601	2600	Brackish water
NI 253	"	B	3	13	139	1.0	47	27	235	<1	0.01	17.00	0.14	6.9	61	441	1000	
NI 252	"	W	12	9	65	<1	60	7	100	12	0.01	0.10	0.02	7.2	67	234	450	
NI 177	"	W	2	3	22	<1	3	12	36	<1	0.03	<0.05	0.20	5.0	17	77	160	
NI 239	"	W	3	9	68	1.0	13	18	128	38	0.01	<0.05	0.12	4.9	45	292	500	
NI 247	"	B	2	7	74	<1	13	8	126	7	0.02	4.25	0.28	5.8	34	230	525	
NI 208	"	B	2	7	63	<1	33	4	104	9	0.01	3.05	0.16	7.0	34	206	425	
NI 165	"	W	50	50	300	22.0	207	13	556	26	0.01	0.30	0.09	7.5	331	1119	1900	Brackish water
NI 164	"	W	18	11	112	4.0	67	50	154	1	0.03	<0.05	<0.02	6.8	90	393	675	
NI 119	"	W	2	4	53	<1	7	5	74	26	0.01	<0.05	0.08	4.9	21	167	300	
NI 131	"	B	1	2	28	<1	20	4	35	1	0.01	8.90	0.20	6.4	11	81	180	
NI 133	"	W	6	8	73	1.0	7	<2	116	56	0.01	0.35	0.12	5.1	48	263	450	
NI 67	"	B	1	5	54	<1	20	<2	80	18	0.01	0.05	0.05	6.3	23	168	325	
NI 85	"	W	4	4	59	<1	73	18	54	6	0.01	0.05	0.08	7.0	26	181	400	
NI 88	"	W	5	8	61	<1	7	19	106	3	0.02	0.05	0.14	5.4	45	205	360	
NI 102	"	B	2	6	84	<1	67	5	114	<1	0.01	3.50	0.34	7.0	30	244	525	
NI 64	"	B	9	28	285	3.0	93	77	438	8	0.02	0.05	0.14	7.1	138	894	1200	Brackish water
NI 58	"	W	5	14	136	2.0	7	30	231	7	0.02	0.01	0.22	5.1	73	430	750	
NI 50	"	B	6	14	153	1.0	40	<2	258	18	0.04	1.70	0.40	6.5	73	469	825	
NI 59	"	B	12	40	255	5.0	13	15	514	1	0.01	0.60	0.92	6.5	195	848	1600	Brackish water
NI 24	"	W	5	8	95	1.0	13	37	144	<1	0.01	26.50	0.52	5.6	45	297	675	
NI 14	"	B	38	146	925	11.0	20	161	1792	3	0.01	0.70	1.26	5.6	696	3086	5000	Saline water
NI 1	"	W	48	123	760	9.0	27	25	1590	1	0.02	2.20	1.12	5.9	626	2570	4250	Saline water
NI 33	"	B	22	28	103	2.0	140	23	178	<1	0.17	<0.05	<0.02	7.0	170	425	800	
NI 46	"	B	4.5	10.4	73	1.8	10.4	4	144.5	—	—	—	—	7.2	—	357	—	
NI 306	1978	B	1	—	52	0.6	—	15	74	0.42	0.01	—	—	4.8	16	—	325	
NI 289	"	B	14	—	225	3.3	—	48	331	3.42	0.01	—	—	5.0	98	—	1150	Brackish water
NI 114	"	B	25	—	155	2.9	—	26	174	1.09	—	—	—	6.2	89	—	—	
NI 8	"	B	41	—	330	5.0	—	67	419	0.85	—	—	—	5.8	155	—	1375	Brackish water
NI 73	"	W	13	—	38	0.7	—	12	31	0.18	0.02	—	—	7.1	29	—	160	
NI 122	"	B	6	—	39	1.0	—	8	36	2.04	0.01	—	—	5.7	23	—	180	
NI 226	"	B	40	—	120	4.0	—	51	278	1.22	0.25	—	—	6.4	123	—	—	
NI 171	"	B	10	—	53	1.6	—	26	68	1.24	0.10	—	—	6.6	34	—	—	Water trucking
NI 97	"	B	14	—	53	1.3	—	24	71	1.53	0.02	—	—	6.2	38	—	—	
NI 287	1979	W	38	—	380	4.3	—	28	418	0.89	0.01	—	—	6.1	128	—	1500	Brackish water
NI 337	"	B	32	—	140	4.5	—	53	242	0.83	0.04	—	—	6.2	104	—	920	
NI 291	"	B	10	—	150	2.8	—	20	274	0.78	0.01	—	—	4.8	65	—	920	
NI 201	"	B	—	—	58	1.0	—	22	68	1.82	0.02	—	—	5.9	30	—	400	
NI 296	"	B	26	—	82	2.9	—	20	135	2.70	0.15	—	—	6.1	69	—	590	
NI 330	1981	B	16	—	43	1.7	—	—	64	4.10	—	—	—	6.2	42	—	—	
NI 308	"	B	41	—	120	5.5	—	61	220	1.96	—	—	—	5.9	121	—	—	
NI 337	"	B	22	—	140	3.5	—	57	260	0.10	—	—	—	5.2	93	—	—	
NI 8	"	B	30	—	160	6.5	—	68	275	1.54	—	—	—	5.2	111	—	—	
NI 171	"	B	12	—	51	2.1	—	19	78.1	2.12	-	—	—	5.6	54	—	—	Water trucking
NI 336	"	B	83	—	290	5.0	—	68	587	2.55	—	—	—	6.1	251	—	—	Brackish water
NI 342	1982	B	21.8	35	200	6.0	72	42	376	1.40	—	0.24	0.17	6.4	197	749	1400	Brackish water
NI 372	1983	B	42	—	110	3.4	—	22	202	1.08	0.11	—	—	6.6	138	—	804	
NI 372	"	B	291	—	1060	29.0	—	452	2590	1.09	0.14	—	—	6.6	1275	—	8000	Saline intrusion
NI 115	"	W	5	—	46	0.8	—	21	77	0.65	0.01	—	—	5.8	36	—	320	
NI 387	"	B	7	—	47	1.8	—	28	81	0.87	0.07	—	—	5.2	35	—	350	
NI 171	"	B	10	—	57	1.7	—	26	75	1.70	0.19	—	—	6.0	44	—	380	Water trucking
NI 349	"	B	10	—	38	1.1	—	23	67	1.35	0.14	—	—	6.1	37	—	340	
NI 148	"	W	<1	—	31	0.6	—	19	46	4.48	<0.01	—	—	5.7	27	—	250	Hydrocarbon trace
NI 357	"	B	1	—	39	1.9	—	26	73	<0.01	<0.01	—	—	5.2	41	—	310	Hydrocarbon trace
NI 405	1986	B	3	20	172	—	—	14	350	—	—	—	—	5.1	—	—	1080	
NI 391	1987	B	78.3	148	582	13.2	—	—	712	—	—	<0.01	0.22	5.9	—	2451	4930	Saline intrusion
NI 435	"	B	44.8	47.4	83.5	4.5	—	—	95.7	—	—	<0.01	<0.01	7.0	—	682.5	975	

(b) SURFACE WATER

No.	Year	Type of Extraction	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	PO_4	Fe	Mn	pH	Total hardness (as $CaCO_3$)	TDS	Electrical conductivity (micro-siemens/cm)	Remarks
COCKPIT DAM (Cascade)	1965	S	2	21	70	2.8	48	15	147	—	—	0.04	0.02	7.2	97	403	—	
WATERMILL CREEK (near dam)	"	S	8	15	47	0.3	45	15	103	—	—	0.02	0.02	7.5	80	290	—	
OFFICERS BATH (Town Creek)	"	S	1	20	60	1.6	31	20	133	—	—	0.04	—	7.3	88	351	—	
HEADSTONE CREEK	"	S	8	25	136	5.1	35	20	284	—	—	0.31	0.02	7.1	128	466	—	

B = Bore; W = Well; S = Surface water.

uncontaminated rainwater typifying an oceanic environment far removed from continental influences, such as pollution.

Groundwater

Salinity

The salinity contours on the hydrochemical map (Fig. 16) show a pattern (based on field and laboratory electrical conductivity data) largely representing the chemical variation of shallow groundwater in the weathered mantle: across the southern plateau, groundwater salinity generally increases from the centre to the margin on the island. Low salinity values (electrical conductivity: < 500 microsiemens/cm) on the main watershed of the southern plateau are correlated with high hydraulic potential in recharge areas, as indicated by the water table contours. Waters on Norfolk Island have an HCO_3:Cl ratio which is less than 1.0 (Fig. 19). The various groups of waters also show a decrease in this ratio with increasing salinity indicating both a dissolution of rock and a trend approaching seawater mixing.

Table 4 lists bores and wells with saline groundwater. The quality limits, i.e. groundwater having values above one or more of these limits, is proposed to discriminate saline groundwater as a pollution hazard. These quality limits are:

pH	7 (alkaline)
Conductivity	1000 microsiemens/cm
Sodium	300 mg/l

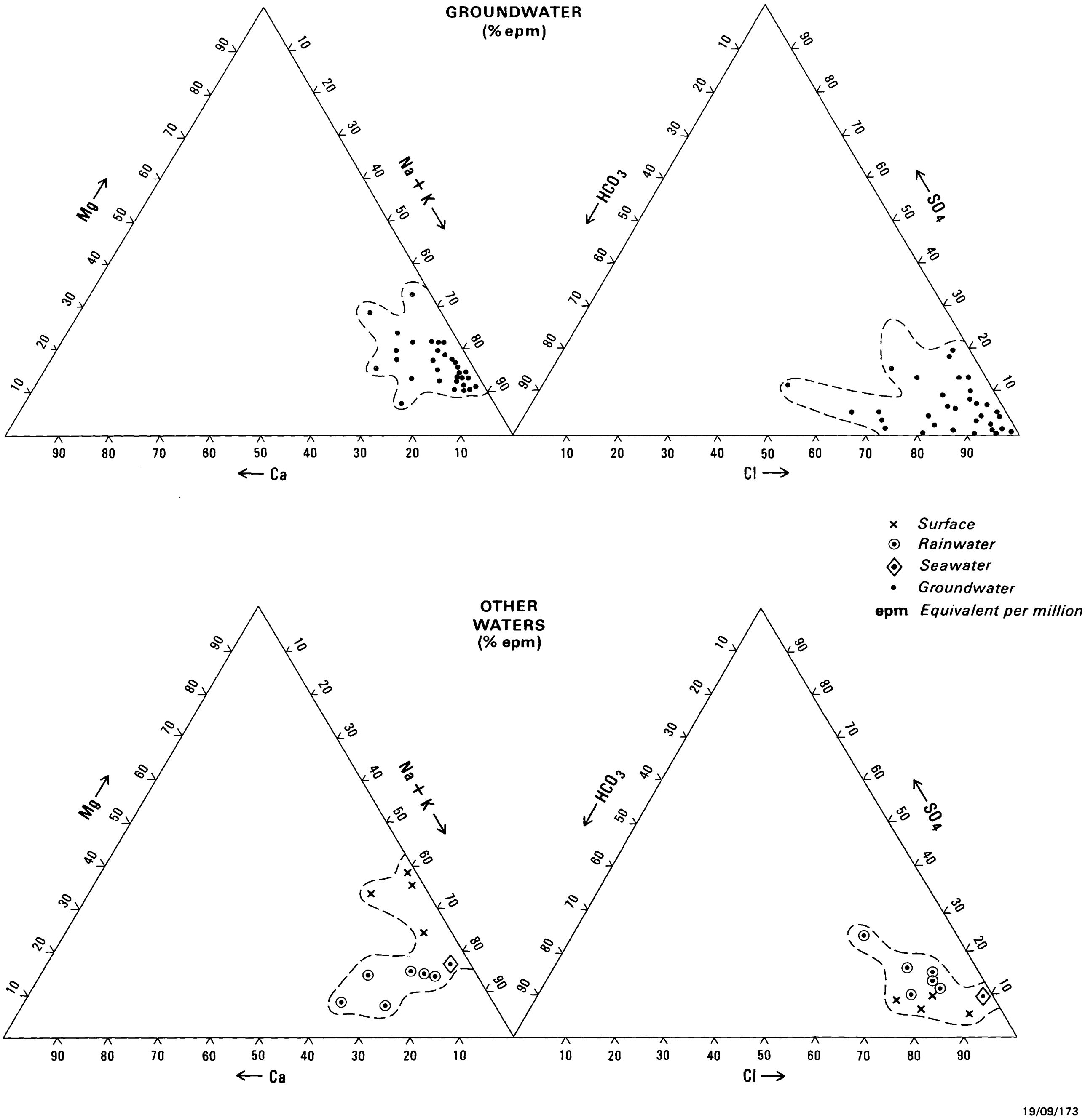

Fig. 17. Chemical classification of ground and other waters expressed in percentages of major ions (%epm).

Chloride	400 mg/l
Hardness	300 mg/l/$CaCO_3$

Patches of topographically elevated saline groundwater in the northwest peninsula and Two Chimneys area could be related to restricted flow systems at the base of the weathered mantle. In these areas, salinity levels may be aggravated by sewage effluent disposal and in summer by constant re-use of shallow groundwater (see Fig. 10).

Brackish water underlying the Kingston lowland indicates a saline wedge has formed in the shallow subsurface by natural mixing of seawater and freshwater. Around the island perimeter, there is some evidence that pumping can induce seawater intrusion to bores tapping bedrock aquifers at or below sea level (Fig. 16). In the Taylors Road area, saline groundwater detected in a pumped bore (NI 396) now offers the first indication of seawater contamination of deep groundwater in the central part of Norfolk Island.

Acidity

Most groundwaters have a pH value from 5 to 7. Water of such high pH rusts steel, corrodes copper and is aggressive to zinc in galvanised pipes and watertanks. This acidity is probably the result of a reaction of rainwater with carbon dioxide in the atmosphere and soil to form carbonic acid, and also oxidation and hydrolysis of dissolved ferrous iron according to the equation:

$$2Fe^{2+} + 1/2\ 0_2 + 5H_20 \rightarrow 2Fe\ (OH)_3 + 4H^+$$

If the hydrogeological profile has an excess of hydrogen ions (and therefore is highly acidic), there is a tendency for any bicarbonate that forms to dissociate and further increase the concentration of hydrogen ions. The chemically aggressive nature of the groundwater is also illustrated by its undersaturation with respect to calcite and dolomite (Figs 20 and 21).

Minor ions

A few wells and bores contain excessive amounts of minor ions, the most important being iron and manganese.

Iron is widely distributed in the weathered mantle, where it is released in the chemical breakdown of minerals in basalt, e.g. olivine, pyroxene, and iron oxides. Iron probably exists primarily in the ferrous state, but becomes oxidized to the ferric state in bores and wells shortly after pumping. When water is left to stand in rising mains or in storage tanks, ferrous hydroxide oxidised — resulting in precipitation of ferric iron oxide. In the swampy sections of streams with restricted flow, local oxidisation causes red-orange ferric iron oxide films on water surfaces. The iron content varies in Norfolk Island groundwater: the human tolerance of 0.3 mg/l iron being exceeded in 14 analyses (Table 1), with a highest value of 26.5 mg/l (NI 124). Some of the high values may result from sampling error, if the pump had not operated long enough to remove all standing water from the rising main. Nevertheless, the high iron content should be considered a constraint in groundwater used for domestic purposes, as it imparts a strong metallic taste and may cause red stains on laundered fabrics and plumbing fixtures.

TABLE 2: WATER QUALITY GUIDELINES FOR DOMESTIC USE

Constituent	*Guideline value (permissible upper limits in mg/l)*
Sodium	300
Sulphate	400
Chloride	400
Nitrate	10
Iron	0.3
Manganese	0.1
pH	6.5–8.5 mg/l
Hardness	500 (mg/l $CaCO_3$)
TDS	1000

Concentrations of manganese are lower than those of iron, which it resembles in its chemical behaviour. In most bores and wells, manganese exceeds the limit for domestic use, but only in one bore and one well (NI 1 and 14) does it exceed 1 mg/1. Manganese may cause dark brown or black stains on laundered fabrics, but concentrations are not high enough to be regarded as a health risk.

Hardness

Hardness in groundwater is due to magnesium and calcium salts. The level of hardness of domestic water supplies is 100 mg/1, but concentrations up to 500 mg/1 are acceptable where no other water is available. On Norfolk Island, most hardness values are < 500 mg/1. In general, the hardness pattern follows the salinity pattern, with an increase towards the margin of the island (see map 4 in Abell, 1976). Rainfall with sodium ions is a natural water softener and is partly responsible for the maintenance of low hardness values, but increased hardness concentrations noted in NI 1, 4, 14 and 372 relate to areas of saline groundwater (Fig. 16).

Irrigation

Factors which determine whether water can be used for irrigation are salinity and the concentration of sodium, boron, and bicarbonate ions. Other factors are climate (determining amount of rainfall), soil, position of the water-table and crop type.

The chemical classification of irrigation water adopted is based on the relations between electrical conductivity in microsiemens/cm and the sodium adsorption ratio (SAR). The sodium hazard is evaluted from the formula

$$SAR = Na^+/\sqrt{(Ca^{2+} + Mg^{2+})/2},$$

where ion concentrations are expressed in epm. The SAR value for water indicates the extent to which the clay minerals in a soil will adsorb sodium from groundwater, and the soil drainage characteristics (see below).

Figure 22 shows a classification based on SAR and salinity of the irrigation waters for Norfolk Island. The graph shows that most waters fall in the S_1 range, below a value of 10; these are low-sodium waters that can be used on most soils with little danger of harmful levels of exchangeable sodium, particularly in fine- textured soils. There is a wider dispersion of salinity, with most values falling within the C_2 range, corresponding to a medium salinity water that can be used on soils with a moderate amount of leaching. The graph demonstrates that four of the water samples (see area C_4) have an appreciable amount of exchangeable sodium ions and very high salinity. If such water was used, it would cause a reduction in permeability and a hardening of soils because of precipitation of mineral matter. The effect of high salinity would cause an increase in osmotic pressure of the soil solution, resulting in reduced availability of water for consumption by plants.

Groundwaters on Norfolk Island are suitable for small-scale irrigation as they have low SAR ratios, salinities, bicarbonate, and boron (the latter was analysed

TABLE 3. CHEMICAL ANALYSES OF RAINWATER (expressed in mg/l)

No.	Date collected	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	Total hardness (as $CaCO_3$)	TDS	Electrical conductivity (microsiemens/cm)	WIND Direction (degrees)	WIND Intensity (knots)	RAINFALL (mm) 24 hr period covering sample collection time	Remarks
1	7.2.78	0.05	0.03	3.20	0.06	1.00	<1.00	5.00	<0.10	6.3	1.00	9.00	26.0	050	15 and gusting to 25	28*(19.2)	
2	11.5.78	1.00	0.20	3.90	0.10	2.02	2.00	6.04	0.50	5.8	3.32	14.13	55.0	040	8	40*(40.6)	
3	9.11.78	0.62	0.10	1.30	0.40	1.40	1.40	2.20	0.19	5.2	1.96	6.79	19.0	035	13 (Ave. intensity)	Heavy rain for about 30 min. (25mm from 0.400 to 07.00 hrs)*	No rain for previous 14 days
4	8.5.79	0.10	0.10	1.07	0.04	—	0.30	1.50	<0.04	5.9	0.66	3.10	15.0	060	10	121.4*(96.8)	Heavy rain
5	11.8.79	1.20	0.50	4.20	0.30	2.50	1.40	7.60	<0.04	5.6	5.05	16.47	41.0	260	8	1.4	Short but heavy rainfall
6	18.11.78	0.31	0.26	2.67	0.10	1.10	1.40	5.30	0.30	5.6	1.84	10.87	25.0	140	2	2.6	Rainfall 1.11.78 to 18.11.78; only 13.9mm
7	13.2.80	0.88	0.65	5.89	0.16	2.50	2.40	10.90	<0.04	5.8	4.87	22.22	47.0	060	2	22.0	Light fine rain with occasional heavier falls for short periods
8	20.9.80	1.30	0.44	2.50	0.76	5.00	1.00	6.00	<1.00	6.2	5.00	15.00	55.0	—	—	—	Tarawa atoll, Kiribati (Jacobson & Taylor, 1981)
9	13 to 17.10.87	0.70	0.40	1.20	<0.50	5.70	0.40	2.30	<0.10	6.0	3.30	5.30	19.0	—	—	—	Nauru Island (Jacobson & Hill, 1988) — mean of 3 analyses
10	14.2.80	387	1337	11,280	393	141	2756	20057	<1.00	7.3	6468	36,280	45,933	—	—	—	Seawater sample from Kingston Jetty, Norfolk Island

*Rainfall as measured in rain gauge on Plot 43s; values in brackets are comparative rainfall measurements at the Meterological Station.

because of its potential toxicity). Although more data is required on the physical nature of the weathered zone, soils appear to be well drained and strongly leached in the upper portion of the profile, particularly along interfluves where swampy and water-logged conditions are unlikely to occur. At present, only a few bores can maintain sufficiently high yields of water over considerable time intervals. For irrigation schemes to be practicable, it is necessary to implement a proper management scheme.

Surface water

The ratio of different ions in the surface water (Table 1) show that the surface and groundwater systems are closely linked (streams are fed and maintained largely by groundwater discharge — see Fig. 11). Surface waters normally have close to neutral pH values, low salinities, and low nitrate values. These lower salinities reflect a short residence time for groundwater constituting baseflow in streams. As might be expected, salinity generally increases downstream. Lower salinity profiles are associated with the higher waterflows in perennial streams. The most saline surface water measured in the field was Ball Bay Creek, where a field conductivity value reached 1400 microsiemens/cm.

Generally, the quality of surface water is very good in the larger catchments and is thus suitable for all purposes. There is, however, a danger of pollution from freely wandering livestock.

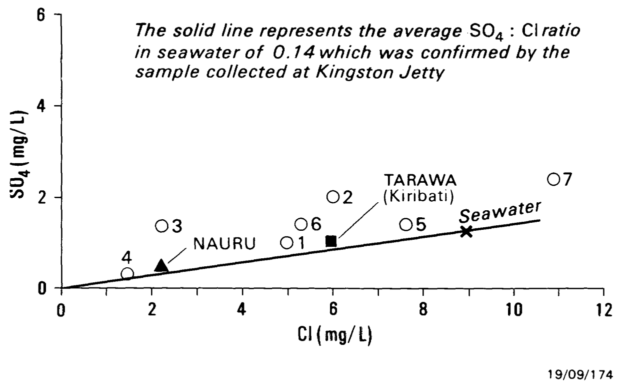

Fig. 18. Concentration of dissolved sulphate versus dissolved chloride in rainwater. (See Table 3.) Circle = Norfolk Island; triangle = Nauru; square = Tarawa.

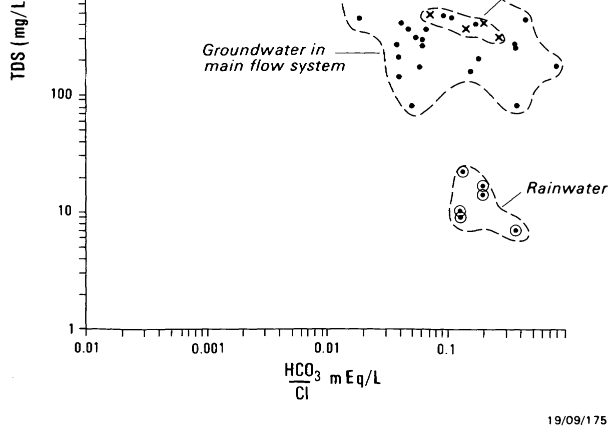

Fig. 19. Relationship of HCO_3/Cl ratio to salinity (TDS) for Norfolk Island water.

Pollution

For groundwater that is being pumped from a bore or well and intended for human consumption, proper precautions should be taken to protect the purity of water. For example, many of the older wells on the island are close to pit latrines or septic tanks, which pose a pollution threat to domestic water. New bores should be located at least 30 m and preferably at a greater distance from and, where possible, on the uphill side of waste disposal structures.

Whenever a well is abandoned, for whatever reason, it should be sealed either by filling in with earth or rubble or by constructing a removable concrete top if it is likely to be used again in the future. Even wells in use should be protected from surface contamination by being raised off the ground and having an appropriate cover or seal across the top. Open abandoned wells are common on Norfolk Island, and poor sealing means that they are potential accident hazards and can be easily polluted. Many old wells are only partially sealed or protected by pierced steel plating (PSP), which is often rusted and unsafe.

With a mean rainfall of 1326 mm/yr, the weathered mantle holds enough moisture to dissolve and transport metals, chemicals, and bacteria from any solid waste disposal in wells, pits, or natural gulleys. If such leachate dissolved from the latter is allowed to accumulate in large quantities, it poses a potential pollution source as many of the abandoned wells are in recharge areas with a dominantly vertical movement of groundwater.

All watering points should be adequately fenced or covered for protection from the weather, wandering livestock, rodents, and birds. Bores in use should be adequately sealed with a 1.5 m long concrete plug, and the pump should be mounted on a properly constructed concrete base which is raised sufficiently to stop contamination from surface sources down the outside of the casing or through the top of the bore.

Pathogenic bacteria

Bacteriological tests of groundwater indicate high levels of faecal contamination (Goldfinch & Cross, 1980; and DHC, 1987). A program of testing on 150 groundwater samples in 1982–83 showed that 134 exceeded the NHMRC guideline value for total coliforms (10 per 100 ml), with 68 exceeding the value for E. Coli (1 per 100 ml). This pollution, attributable to sewage and animal waste, is most evident in the Burnt Pine–Middlegate and Kingston areas (Fig. 16).

Nitrate

Nitrate levels (Table 1) are related to both high livestock densities in and around watering points and at dairy farms. An additional source of nitrate is domestic waste.

Microbiological transformation of this waste causes oxidation of organic nitrogen through amino acids to ammonia and then to nitrites and finally nitrates; a process favoured by aerobic conditions (in the presence of oxygen). Some plants take up nitrate to produce protein, but the remainder passes downwards towards the water-table.

The distribution of nitrate-rich waters on Norfolk

TABLE 4. SALINE GROUNDWATER[1]

No.	*Date*	*Extraction*	*Location*	*Depth to sea level*	*Na*	*K*	*Cl*	*pH*	*Electrical conductivity (micro-siemens/cm)*	*Hardness as $CaCO_3$*	*Remarks*
					(expressed in		*mg/l)*				
NI 1	1974	Well	North West	+45m	760	9	590	5.9	4250	626	High-level saline groundwater; restricted flow at the base
NI 4	1965/ 1974	Well	Peninsula	+54m	1720	18	4125	4.2	8500	1700	of the weathered mantle
NI 336	17.04.81	Bore		+57m	260	6.8	582	6.3	—	270	High-level saline groundwater
	09.07.81				290	6.1	587	6.1	—	251	
NI 391	17.04.84	Bore		−30m	2000	41	—	—	—	—	10 hrs pumping
	17.04.84				2850	72	—	—	—	—	
	25.05.84				2000	43	—	—	—	—	
	"				2780	76	—	—	—	—	
	"				3000	90	—	—	—	—	25 hrs pumping
	"				2950	84	—	—	—	—	
	26.04.84				2725	80	—	—	—	—	
	08.05.84				1660	39	—	—	—	—	Salinity decrease
	03.06.84				2575	75	—	—	—	—	
	21.10.84				2690	58	—	7	—	—	
	22.10.84				2850	66	—	7	—	—	Regular pumping
	23.10.84				2966	70	—	7	—	—	
	28.10.84				2989	78	—	7	—	—	
	08.12.84				3380	80	—	7	—	—	Regular pumping
	09.12.84				3560	90	—	7	—	—	
	31.03.86				1750	30	—	—	—	—	Salinity decrease
	08.04.86				2400	60	—	—	—	—	
	12.01.87				582	13.2	—	5.9	4930	—	Salinity decrease
											(NI 391, all dates:) COASTAL SALINE INTRUSION INDUCED BY PUMPING
NI 14	1974	Bore		+39m	925	11	1792	5.6	5000	—	High-level saline groundwater
NI 372	24.04.83	Bore	Mission Creek	−19m	480	7.8	—	6.6	—	—	
	28.11.83				110	3.4	—	6.6	804	—	
	28.11.83				1060	29	2590	6.6	8000	—	Coastal saline intrusion induced by pumping
NI 342	13.04.82	Bore	Rocky Point	−15m	200	6	376	6.4	1400	197	Early indication of coastal saline intrusion induced by pumping
NI 399	06.11.84	Bore		−20m	310	8	—	7	—	—	
	07.11.84				322	10	—	6	—	—	
	27.07.87				300	8	—	7	—	—	
	02.02.88				—	—	575	7.7	—	302	
NI 396	01.08.84	Bore	Taylors Road	−29m	70	4	—	7	—	—	
	06.02.85				1380	37	—	7	—	—	
	22.04.85				3750	110	—	7	—	—	Saline intrusion at depth induced by pumping
NI 165	1974	Well	Kingston	+1m	300	13	556	7.5	1900	331	Brackish water; shoreward encroachment of saline -
NI 224	1965/ 1974	Well		−8m	250	7	577	6.3	1625	321	freshwater interface
NI 412	20.03.85	Bore		−18m	600	12	—	7	—	—	
	15.07.85				1300	13	—	7	—	—	Costal saline intrusion induced by pumping
NI 404	28.09.85	Bore	Longridge Area	−27m	350	10	—	7	—	—	Early indication of saline intrusion at depth induced by
	29.09.85				450	8	—	7	—	—	pumping
NI 284	1974	Well	Two Chimneys	+59m	500	5	934	4.4	2600	296	High-level saline groundwater; restricted flow at the base of
NI 285	1974	Well	Area	+55m	—	—	—	—	1200	—	the weathered mantle
NI 287	11.06.79	Well		+53m	380	4.3	418	6.2	1500	128	
NI 289	08.02.78	Bore		+31m	225	3.3	331	5	1150	—	
NI 429	10.10.86	Bore		−33m	644	16	—	7	—	—	
	08.04.87				700	23	—	7	—	—	
	09.04.87				850	27	—	7	—	—	Coastal saline intrusion induced by pumping
NI 441	10.06.87	Bore		+3m	690	12	—	6	—	—	Early indication of coastal
	29.10.87				500	10	—	6	—	—	saline intrusion induced by pumping
NI 439	28.09.87	Bore		+55m	185	4	—	6	—	—	Early indication of saline
	06.01.88	(Depenning)		−76m	3200	120	—	6	—	—	intrusion at depth induced by
	07.01.88				3350	125	—	7	—	—	pumping

Chemical data supplied by Mr G. C. Duvall, Norfolk Island.

[1]Depth refers to corrected depth to sea level, i.e. + = a.s.l., — = b.s.l.

Island is uneven. All waters contain some nitrate, but values > 10 mg/l and up to the limit of 45 mg/l are mostly associated with wells rather than bores. As wells are open to the weathered mantle, they are more susceptible to nitrate contamination. However, bores are normally sealed off from the weathered mantle by plain PVC (polyvinyl chloride) casing.

High nitrate concentrations are usually associated with wells (uncased) which tap only the upper portion of the saturated zones, where groundwater moves seasonally under oxygen-rich conditions (see nitrate values in Table 1). In contrast, the bores (cased) usually reach through the saturated zone to bedrock, where reducing conditions are more common (except along hydrologically active fracture zones where oxygen is available).

Sanitary waste

Groundwater in the weathered mantle, after losses to base flow or to deeper levels, tends to circulate in a

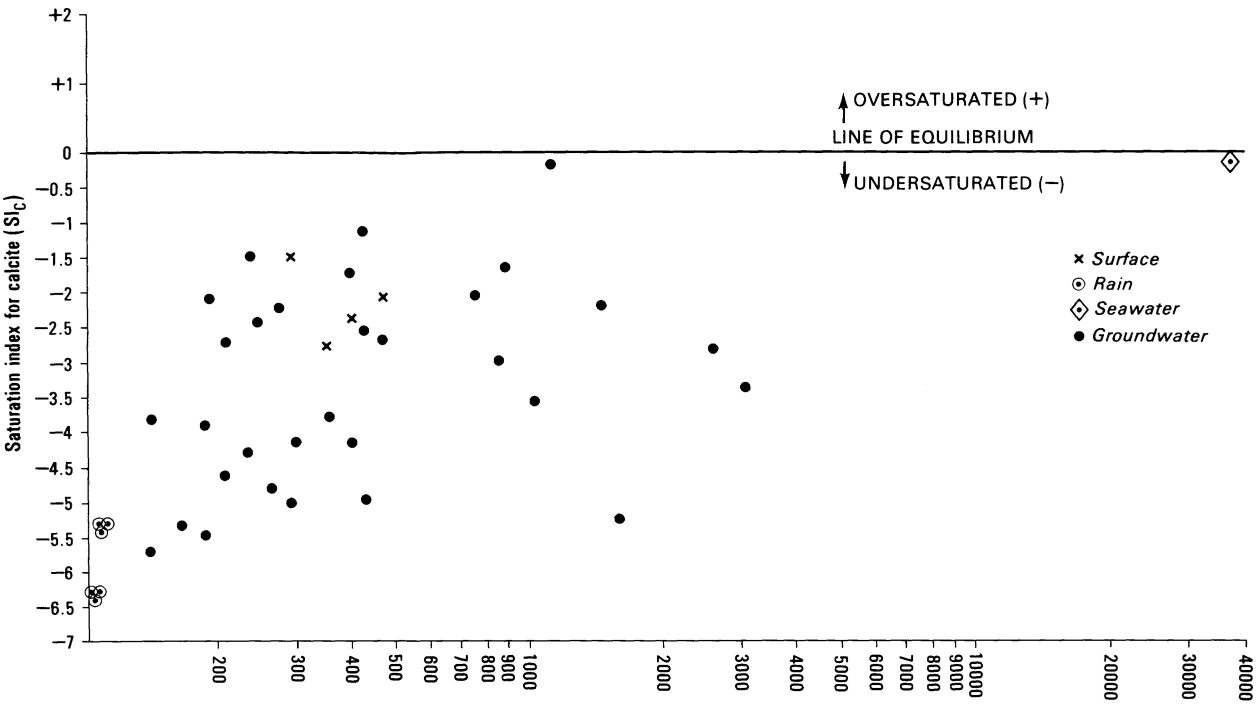

Fig. 20. Saturation index for calcite as a function of salinity.

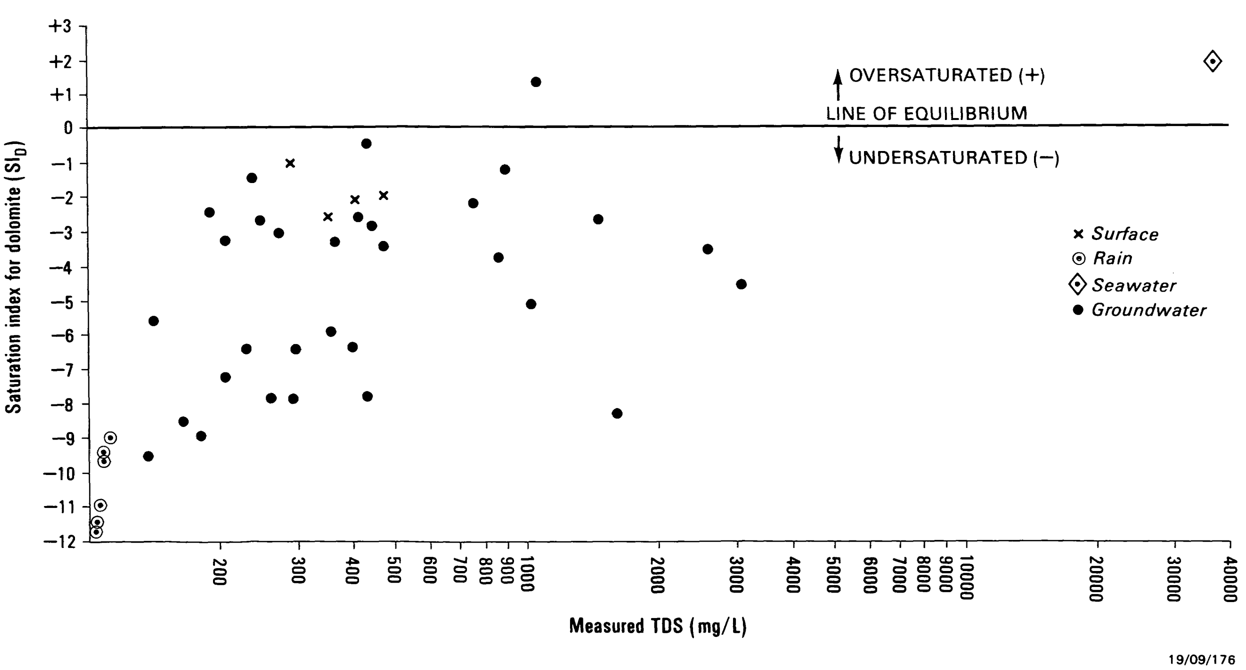

Fig. 21. Saturation index for dolomite as a function of salinity.

closed system (Fig. 10). During the summer, when groundwater demand is high, the constant re-use of shallow groundwater with a component of sanitary waste increases salinity levels and reduces water quality. Detectable levels of detergent occur in Norfolk Island groundwater (Abell, 1976; Goldfinch & Cross, 1980), although values remain within World Health Organisation limits, that is < 0.2 mg/l for Azure A. Traces of hydrocarbons from petroleum products have also been found in the Middlegate area (NI 148 and 357).

The entry and movement of sanitary waste in the ground is controlled by hydrogeological conditions. As the upper part of the weathered mantle is open and porous, infiltrating rainfall can carry surface and sanitary waste material into the subsurface. Subsequent to evaporation, sanitary waste moves by gravity through the unsaturated zones to the water-table. The rate and direction of this movement depends on the nature of the waste material, local hydraulic conditions in the weathered mantle, and any local pumping effects. As sanitary waste moves to the water-table, its polluting effects are reduced by filtration, chemical alteration, dilution, and dispersion.

The physical properties of the unsaturated weathered mantle can considerably effect natural purification of sanitary waste before it reaches the water-table. The porous clay filters and removes bacteria, undissolved solids, and some dissolved inorganic chemical contaminants; it will not, however, remove sodium chloride. The removal of bacteria and suspended solids is likely to clog the pores of clay immediately surrounding a septic tank or pit latrine, although fluids may still pass to deeper levels. Experiments show that clay-rich soils can remove bacteria from water by physical means: by mechanical straining and settling in fine clay-rich intergranular spaces. As bacteria move over grain surfaces, they can be killed by oxygen in contact with water in pore spaces. The rate of percolation in the unsaturated zone, and the life span of the bacteria, determine the distance the bacteria can travel. When introduced into a new environment, i.e. the unsaturated zone, bacteria may die because temperature, moisture, and pH factors are not favourable to their existence. To minimise the potential threat of pollution, septic tanks and sewage effluent plants should be properly constructed, maintained in good repair, and emptied at frequent intervals.

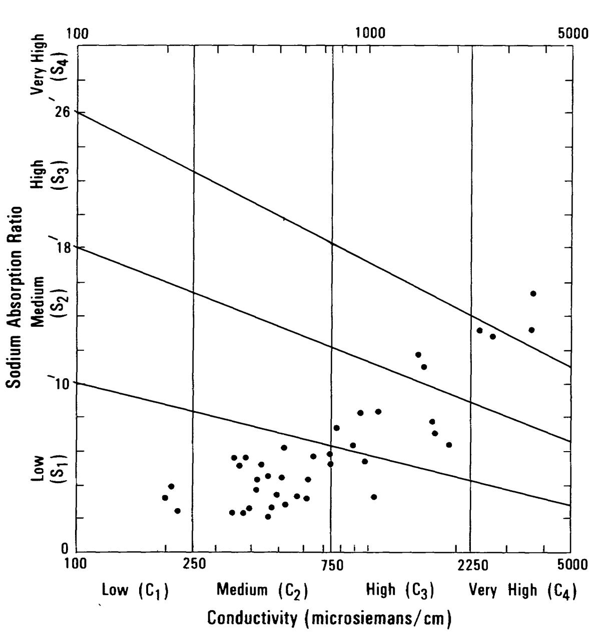

Fig. 22. Classification of irrigation waters (see for sodium adsorption ratio (SAR) on page 52). Simplified after Abell (1976).

In island environments, human waste disposal presents considerable problems. Measures to prevent pollution should be implemented before costly remedies have to be considered to purify groundwater resources. As a general rule, waste disposal should be directed to areas where it cannot pollute groundwater. A Water Assurance Scheme for the disposal of sewage effluent for the main commercial and tourist resort areas of Burnt Pine and Middlegate has been completed and was opened in December 1990. The system in time will also extend to Kingston, the administrative centre and surrounding historical areas.

Natural and environmental isotopes

Heavy stable isotopes of deuterium (D) and oxygen-18(^{18}O), and of radioactive tritium (^{3}H), were determined to obtain information on the recharge character and residence time of Norfolk Island groundwater (Fig. 23). Table 5 presents analyses of nine groundwater samples and one rainwater sample collected in August 1988.

Deuterium and oxygen-18

When clouds condense, fractionation occurs and rainwater becomes enriched in the stable isotopes of deuterium (D) and oxygen-18(^{18}O) (Lloyd & Heathcote, 1985). Consequently, dependant on climatic fluctuations (temperature, humidity and wind), groundwater has an isotopic signature primarily related to the composition of the recharging rainfall. Deuterium and oxygen-18 data (Fig. 24) are expressed as delta values (δ) per mil (‰), which is related to an arbitrary standard SMOW (standard mean ocean water).

On Norfolk Island, the D/$^{18}0$ ratio for groundwater is reasonably constant (mean value $\delta\ ^{18}0 = -4.6‰$ and $\delta\ D = -25.89‰$) and shows a close grouping falling on both the World meteoric water line (Craig, 1961) and Central Pacific meteoric water line (Jankowski, person. comm., 1989). This indicates direct rain infiltration with recharging groundwater showing little evidence of evaporation or seawater mixing. However, the single rainfall value obtained, which is isotopically enriched relative to groundwater, may only characterise a heavy downpour at the time of sampling. It is assumed, therefore, that replenishment of groundwater is normally from rain of lighter isotopic composition.

Tritium

Tritium is produced naturally by cosmic ray bombardment of oxygen and nitrogen in the upper atmosphere, and artificially by the atmospheric detonation of thermonuclear devices. The special value of tritium in hydrologic studies is due to its property of radioactive decay, which can be used to date recharge to a groundwater system. Once removed from contact with the atmosphere, tritium in groundwater cannot be replenished and decays exponentially with a half-life of 12.43 years. The presence of higher than background levels of tritium is unequivocal evidence of a component of modern recharge in groundwater. Tritium is measured in tritium units (TU), in which 1 TU corresponds

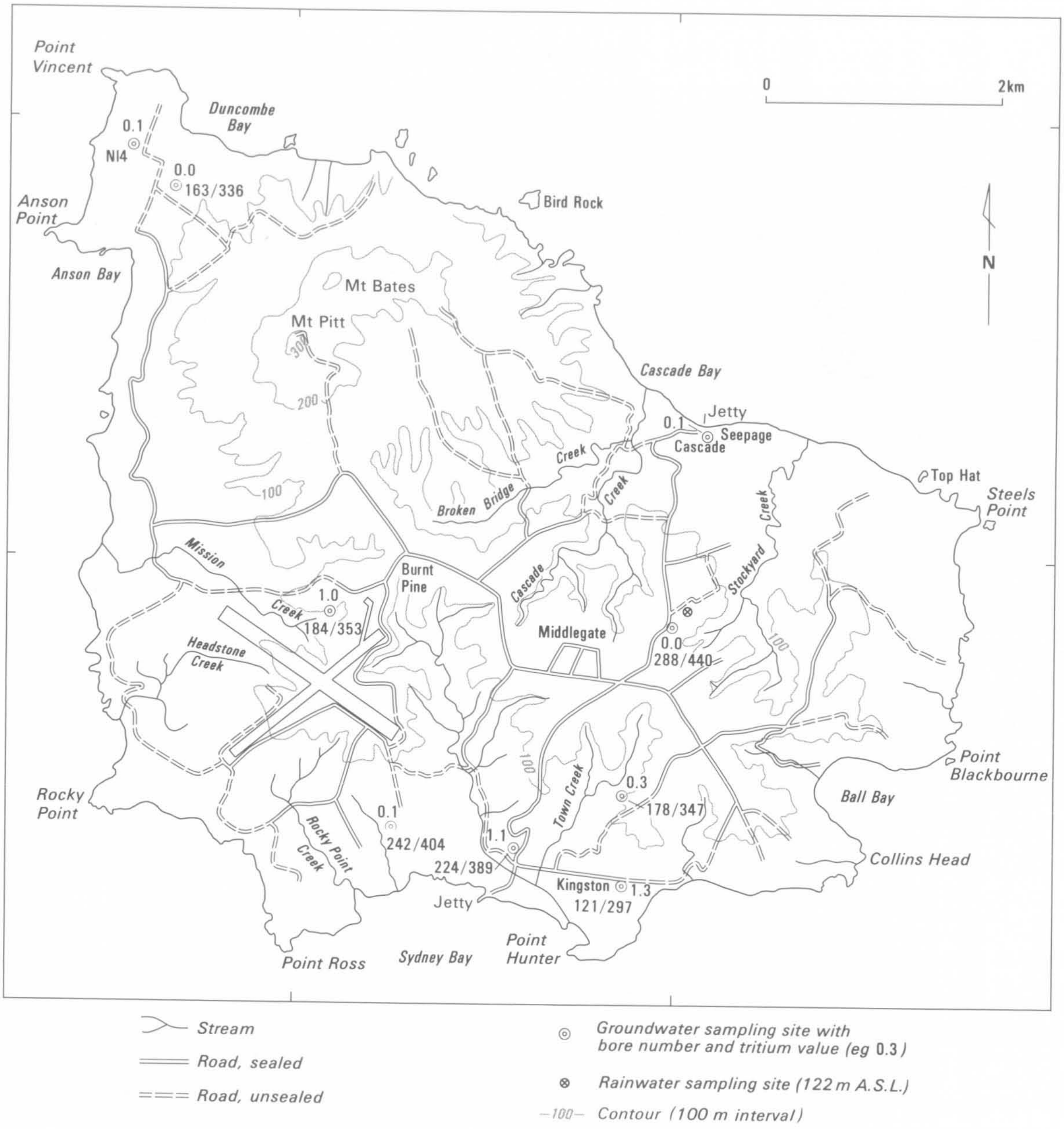

Fig. 23. Location of isotopic sampling sites.

TABLE 5. ISOTOPIC COMPOSITION OF GROUNDWATER AND RAINWATER ON NORFOLK ISLAND

Bore or Well Number	*Elevation (m)*	*Depth[1] (m)*	*Corrected depth to sealevel*	^3H *(TU)*	$\delta\ ^{18}O$	$\delta\ D$	*Electrical Conductivity (microsiemens/cm)*
163/336	97.0	39.6	+ 57.4	0.0 ± 0.3	- 4.42	- 26.85	1842
NI 4	88.0	34.0	+ 54.0	0.1 ± 0.3	- 4.99	- 27.79	11150
242/404	82.3	109.7	- 27.4	0.1 ± 0.3	- 4.71	- 26.77	4160
288/440	131.0	74.7	+ 56.3	0.0 ± 0.3	- 4.62	- 26.15	489
178/347	94.5	104.2	- 9.7	0.3 ± 0.3	- 4.39	- 26.68	791
121/297	14.0	24.0	- 10.0	1.3 ± 1.3	- 4.30	- 23.46	646
184/353	85.3	43.6	+ 41.7	1.0 ± 0.3	- 4.47	- 26.12	600
224/389	12.2	43.6	- 31.4	1.1 ± 0.3	- 4.82	- 24.69	704
Seepage from tuff bed	~SL[2]	—	—	0.1 ± 0.3	- 4.98	- 26.50	2950
Rainwater	—	—	—	2.3 ± 0.3	- 4.40	- 17.11	96

Sampling dates: 7–8 August 1988 (Rainwater)
13–14 August 1988 (Groundwater)

1 Depth of borehole from topographic surface
2 Sea level

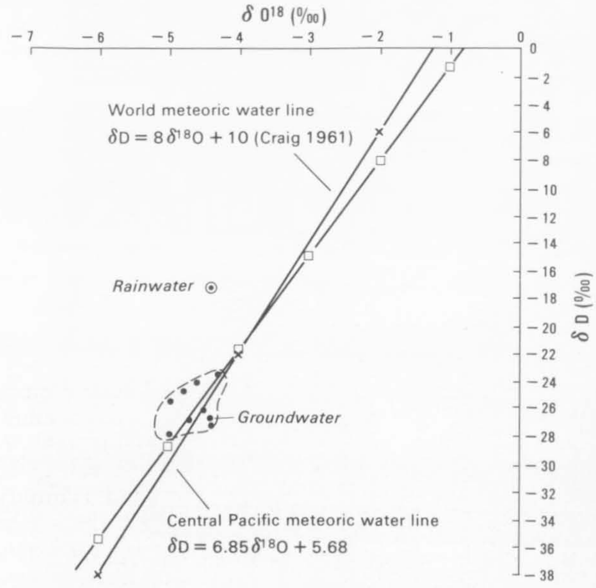

Fig. 24. $\delta^{18}O\delta$–D correlation for groundwater and rainfall on Norfolk Island. Values for Central Pacific meteoric water-line data, based on Nauru supplied by J. Jankowski (pers. comm., 1989).

to an atomic ratio of one atom of ^{3}H to 10^{18} atoms of hydrogen.

The areal distribution of tritium activity associated with groundwater is shown in Fig. 24. The tritium activity in the rainwater sample (2.3 ± 0.3 TU) corresponds to the expected value for this location and is approximately the same value as that determined for Brisbane (Australia) rainwater (G.E. Calf, pers. comm. of 1988). A reference for interpreting tritium in Norfolk Island groundwater is given in Table 6.

The tritium data demonstrate that no recent rainwater is being pumped from the bores. The absence of measurable tritium in the majority of the groundwater samples demonstrates that groundwater moves quite slowly towards sampling locations. However, samples from bores 121, 184 and 224 show some measurable tritium, implying that they are situated close to recharge sites and hence contain a mixture of recent recharge and old groundwater. The low tritium and high salinity values for groundwater sampled in NI 4, a well which is 54 m a.s.l, may relate to either lack of recharge or slow turnover of groundwater in the aquifer (see Fig. 16).

TABLE 6. INTERPRETATION OF TRITIUM ACTIVITY IN AUSTRALIAN GROUNDWATER (CALF, 1988)

Activity (TU)	*Interpretation*
Less than 0.2	Water is older than 50 years
Less than 2.0	Water is older than 25 years
Between 2 and 10	Interpretation is difficult; water is probably modern
Between 10 and 20	Water is 5 to 25 years old
More than 20	Probably related to water from peak fall-out period 1960–64

Water balance

A water balance analysis for Norfolk Island was performed to estimate the amount of recharge from rainfall to groundwater storage. The parameters involved in the water blance are dependent on spatial boundaries, and the time intervals of climatic and runoff data. The spatial boundary corresponds to the island's perimeter, i.e. the line on a map depicting where land meets either cliffs or the seashore. Water falling on land within this perimeter either evaporates, flows off as surface runoff, or passes through to groundwater storage (Fig. 10). A small proportion is also collected from roofs into tanks for various domestic, commercial and agricultural purposes, but this is later passed back into the ground mainly as spetic tank effluent. The total volume of tank storage is not considered significant to include in the water balance analysis. Within the perimeter of the island, spring seepages contribute to surface runoff and are included in the water balance equation. However, below the perimeter the groundwater, discharging as spring seepages from both cliffs above sea level and from undersea, has not been quantified as a loss in the water balance equation.

The natural hydrological cycle has progressively altered through vegetation clearance since Norfolk Island was settled in 1788. By 1810, a quarter of the land had been cleared or thinned to create pasture (Fig. 3). The result of this long-time land clearing is evident from the water balance (1976–84), which shows different evaporation and groundwater recharge rates under pasture and forest (Fig. 29).

The water balance equation can be expressed as:

$$P = E_a + R + G \qquad \text{Equation 1}$$

where
- P = Rainfall (mm)
- E_a = Evaporation (actual) from all vegetation and other sufaces (mm)
- R = Surface Runoff (mm)
- G = Groundwater Recharge (mm)

This equation ignores changes in water storage because monthly time increments are used in the water balance analysis. Such time increments are generally long enough to balance out any changes in storage. Rearranging the above equation in terms of the unknown groundwater recharge, G, gives:

$$G = P - (E_a + R) \qquad \text{Equation 2}$$

All terms on the right hand side of the equation can be quantified by measurement or estimation and thus G can be determined. The individual parameters are discussed below, i.e. rainfall, evaporation, surface runoff and groundwater recharge.

Rainfall

Rainfall has been recorded on Norfolk Island almost continually since 1890. Monthly totals are available for the whole period except for some short gaps. The present official meteorological station (No. 200288) is adjacent to the airport (Fig. 3), but records have not always been kept at this location. Prior to the late 1930's, measurements were taken at Government House in Kingston. The full record was compiled by the Bureau of Meteorology for both sites (Fig. 2). Rainfall records are also available from a number of privately read gauges.

The rainfall records have been analysed in detail by Falkland (1982) and Wheeler & Falkland (1986), and the following conclusions can be made:

- correlations of monthly rainfall data between official and private records are good — in all cases the correlation coefficient was equal to or above 0.90;
- monthly rainfall is relatively uniform over the island; and
- the small size and subdued relief of the island suggest that a water balance is satisfactory as based on the official rainfall records at the meteorological station.

El Niño Southern Oscillation (ENSO) events

The name El Niño (EN) was originally applied to a warm coastal current which moved south along the coasts of Ecuador and Peru each year at about Christmas time. In recent scientific usage, the term El Niño has been associated with the more extreme climatic events occurring every few years over most of the tropical Pacific Ocean. The Southern Oscillation (SO) involves the exchange of air and surface pressure reversals between the South East Pacific High Pressure Zone and the North Australian–Indonesian Low Pressure Zone. Over the tropical Pacific Ocean, the SO is associated with considerable fluctuations in rainfall, sea-surface temperature (SST), trade wind intensity, and ocean currents. This climatic oscillation has varying intensity, starting times and duration (Philander, 1983; Rasmusson, 1984; and Canby, 1984). Data describing El Niño Southern Oscillation (ENSO) events are most reliable since the late 1940's. Nine events have occurred since 1950 with some being more intense than others (Philander, 1983). The assumed occurrence of ENSO events prior to 1950, as listed in Rasmusson (1984) is largely based on wind and SST observations from ships travelling across the Pacific Ocean.

The existence of ENSO on Norfolk Island weather is pronounced: a typical ENSO correlates with an exceptionally low rainfall on the annual record sometimes being complemented the following year by high rainfall (Fig. 2). In contrast to Norfolk Island in the southwest Pacific, the reverse occurs on central and eastern Pacific islands in equatorial zones, such as Christmas Island (Falkland, 1983) and Nauru (Jacobson & Hill, 1988), which exhibit a higher than normal rainfall pattern. Norfolk Island, being about 1500 km from the Australian mainland, follows the ENSO-related drought pattern established when the North Australian–Indonesian Low Pressure Zone moves eastward. Post-1950 ENSO events on Norfolk Island are clearly evident in the annual rainfall record (Fig. 2) as low rainfall in 1951, 1953, 1957, 1963, 1965, 1968, 1972, 1976–77, 1979–80, 1982 and 1987. These years correlate extremely well with post-1950 ENSO's (Philander, 1983). Prior to 1950, there are periods of missing data, but ENSO-related rainfall is again evident in 1895, 1900–03, 1905–06, 1921, 1930, 1933, 1939–40 and 1944. These low rainfall years correlate reasonably well with pre-1950 ENSO events (Rasmusson, 1989).

The annual rainfall record on Norfolk island can assist with predicting low rainfall years and hence periods of minimum recharge to the groundwater reservoir. For instance, since 1950 there have been 11 ENSO-related rainfalls. The average period between events is 3.5 years, with the minimum being 2 and the maximum 5 years.

Evaporation

A U.S. Class 'A'-type evaporation plan has been operated at the Norfolk Island meteorological station since January 1976, and the resulting monthly and annual evaporation totals to July 1984 are presented in Table 7. A clear seasonal variation is evident in the data. The summer months of December, January and February have relatively high evaporation rates, while the winter months of June, July and August have considerably lower rates.

The actual evaporation that occurs from a catchment includes evaporation from soil, water and other open surfaces, and transpiration from the leaves of grasses, bushes and trees. The combined effect of evaporation and transpiration is often referred to as evapotranspiration.

The method adopted to convert the pan evaporation figures to actual evaporation is based on the method proposed by Doorenbos & Pruitt (1977). Falkland (1982) outlines the background and basis of the method.

The first stage of the conversion is to relate the pan evaporation figures to the reference crop evapotranspiration, ETo. Then, the ETo is related to ETcrop, which is a measure of the potential evaporation (Ep) from the actual crop or vegetation on the catchment in question. This is then converted to the actual evaporation (Ea) from the catchment using a water balance procedure (Appendix F in Wheeler & Falkland, 1986).

The following equations were used in the calcuations:

$$ETo = Kp \times Epan \qquad \text{Equation 3}$$

$$ETcrop\ (Ep) = Kc \times ETo \qquad \text{Equation 4}$$

$$Ea = Ep \times \frac{SMC - SMCmin}{SMCmax - SMCmin} \qquad \text{Equation 5}$$

TABLE 7. MONTHLY AND ANNUAL PAN EVAPORATION (1976–1984)

Year	*Month*												*Total*
	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*	*(mm)*
1976	159	166	135	146	112	91	101	102	133	134	124	195	1597
1977	189	171	161	136	108	75	95	103	123	155	151	183	1650
1978	150	157	163	130	106	80	88	112	106	167	160	188	1607
1979	209	135	139	131	116	78	91	120	127	148	158	189	1641
1980	163	141	156	119	106	93	103	96	122	122	160	182	1563
1981	178	142	151	140	105	97	102	116	115	152	141	130	1569
1982	159	142	147	102	99	93	74	102	108	146	165	177	1514
1983	167	156	133	90	102	93	93	102	105	133	156	177	1507
1984	173	180	136	123	96	78							
Mean	*172*	*154*	*147*	*124*	*106*	*86*	*93*	*107*	*117*	*144*	*153*	*178*	*1581*

where ETo = reference crop evapotranspiration (mm)
Epan = pan evaporation (mm)
Kp = pan coefficient (assumed to be 0.85 for all months of the year based on comparisons between pan evaporation estimates using the Penman equation (Wheeler & Falkland, 1986)
ETcrop = potential evapotranspiration for the actual vegetation in the catchments (mm)
Kc = crop factor (assumed to be 1.0 for all vegetation– grasses and forested areas–based on lists in Doorenbos & Pruitt, 1977)
Ea = actual evaporation (mm)
SMC = soil moisture content (mm)
SMCmax = maximum soil moisture content (mm) = SMZ x FC where FC = field capacity (assumed to be 0.25) and SMZ = soil moisture zone (mm) — assumed to be 500 mm for grassland, and 3000 mm for forest, and
SMCmin = minimum soil moisture content (mm) = SMZ x WP where WP = wilting point (assumed to be 0.15) and SMZ is as defined above.

Evaporation will only occur at the potential rate (equation 5) if sufficient water is available in the soil moisture zone of the roots. If the soil moisture is depleted, then evaporation will occur at a slower rate until the wilting point is reached. Below the wilting point, no further evaporation occurs and the vegetation wilts. If the soil is saturated (field capacity), evaporation will occur at the maximum rate and any additional water (from rainfall) in the soil moisture zone will lead to groundwater recharge.

Surface runoff

Gauging stations were constructed along eight creeks (Fig. 25) in March and April 1981 (Fitzgerald & Falkland, 1981). In all cases, the gauging sites were as close as practicable to the island perimeter. All major creeks of the island have been gauged, which represent 54% of the total catchment area. The remaining 46% of the island consists of small areas of the gauged catchments downstream of a gauging station, and other areas mainly in the northwest and eastern portions of the island with dry or only minor creeks. For a reasonable water-balance calculation, the discharges from the eight major creeks can be considered to represent nearly all of the surface runoff component. One station at Cascade Creek (Station 1) was serviced by a continuous recorder, while the others were daily or twice-weekly read-staff gauges. Flow measurements to establish rating curves were made at each station using a combination of simple volumetric methods (pipe discharging into a bucket) for low flows, and Cipoletti weirs for high flows.

The gauged catchments have concurrent streamflow records covering the period May 1981 to June 1984. An electronic data logger has provided an additional record for Cascade Creek since mid-1987 until 1989 when the station was damaged during a flood. Runoff character as typified by the hydrograph for Cascade Creek (Fig. 26) shows a significant correlation with rainfall events.

There is no simple relationship between catchment area and runoff (refer Table 8), which indicates that other factors, such as porosity and permeability of rock and soils and vegetative cover, may be important runoff characteristics. It is also apparent that the gauged catchments in the south of the island (Fig. 25), namely Town, Rocky Point and Watermill Creeks, have higher than average percentage runoff (expressed as the ratio of runoff to rainfall; see Falkland, 1986) and would appear to be the least-effective catchments for groundwater recharge.

The higher values of percentage runoff in these catchments most likely result from a combination of lower evaporation (owing to grass cover rather than forest) and the consequence of positioning the gauging stations close to sea level, thus measuring a higher degree of groundwater seepage than at stations situated on elevated parts of the island. The lowest values of percentage runoff are for Broken Bridge, Stockyard, Cascade and Mission Creeks and suggest they are potentially the best for groundwater recharge, as has been independently assessed from geological and geophysical studies (Abell, 1976; Abell & Taylor, 1981). The lower runoff values are also due to higher evapotranspiration from the forested areas in these catchments.

Groundwater recharge

Norfolk Island is divided into two water-balance areas as indicated in Figure 25. The northern area, representing 12.25 km^2 or 35% of the island, includes the northwest plateau and elevated terrain around Mount Pitt and Mount Bates (the Norfolk Island National Park); it is characterised by forest and poor runoff. The southern area, of 22.75 km^2 or 65% of the island, comprises the southern plateau and Kingston lowland; it is mainly grassed with patches of open forest and supports surface runoff. Losses owing to groundwater extraction were ignored in the water balance equation, because most of it passes back into the ground as sanitary waste. The assumptions, methodology and results of the water balance model are outlined in detail in Wheeler & Falkland (1986).

To calculate the long-term average percentage recharge, values of annual rainfall were plotted against annual recharge for the eight years from 1976 to 1983 for a typical grassed catchment (Fig. 27 — Cascade Creek subcatchment) and a typical forested catchment (Fig. 28 — Broken Bridge Creek). Linear regression lines were fitted to the data and the average percentage recharge values were determined as 34% for the grassed catchment and 19% for the forested catchment.

The components of the long-term water balance and their interaction with one another are represented graphically in Fig. 29. During summer, there is soil moisture depletion as evaporation exceeds rainfall for both grassed and forested catchments. When the soil moisture store is at 125 mm (grassland) and 750 mm (forested), soils are at field capacity and recharge occurs. Groundwater recharge tends to take place in winter months, although the duration depends on the amount of rainfall and vegetation cover. Storms may cause water surpluses in summer. Figure 29 shows that recharge can be expected during about 5 1/2 months/year in grassed areas and 2 1/2 months/year in forested areas. In dry years, such as 1976–77, recharge spans only a few weeks in grassland, and does not occur in forested areas at all.

Using the average percentage recharge values for Cascade (34%) and Broken Bridge (19%) creeks for the period 1976–84 and values of 65% and 35%, respectively for grassed (southern) and forested (northern) areas, a reasonable estimate for average annual recharge for the island is 0.65 x 0.34 + 0.35 x 0.19 = 29%, or for simplicity 30%. About 1/4 of annual recharge is apportioned to the northern or forested area with the remainder distributed over the southern or grassed area.

The volume of water passing through to the weathered mantle and deeper bedrock aquifers under the island is estimated as follows:

Average rainfall (up to 1983)	= 1320 mm/year
	= 1.32 m/year
Area of Norfolk Island	= 35km^2
	= 3.5 x 10^7 m^2

Hence, the average rainfall volume = 3.5 x 10^7 x 1.32 = 4.62 x 10^7 m^3/year.

Since groundwater recharge is 30% of rainfall, the volume of water available for storage is 0.3 x 4.62 x 10^7 or approximately 14 x 10^6 m^3/year. However, not all of this water is available for groundwater extraction as some must be used for 'flushing' along the freshwater–seawater transition zone at the margin and base of the island.

Using an approximate rule-of-thumb estimate of sustainable yield as 20% of average annual recharge (Hamlin & Anthony, 1987), it appears in the long term that groundwater withdrawal on Norfolk Island should not exceed 2.8 x 10^6 m^3/year sustainable yield.

The estimate of groundwater recharge is subject to a number of constraints:

- The evaporation component in the water balance equation is the most difficult variable to quantify; the water balance does not take account of interception

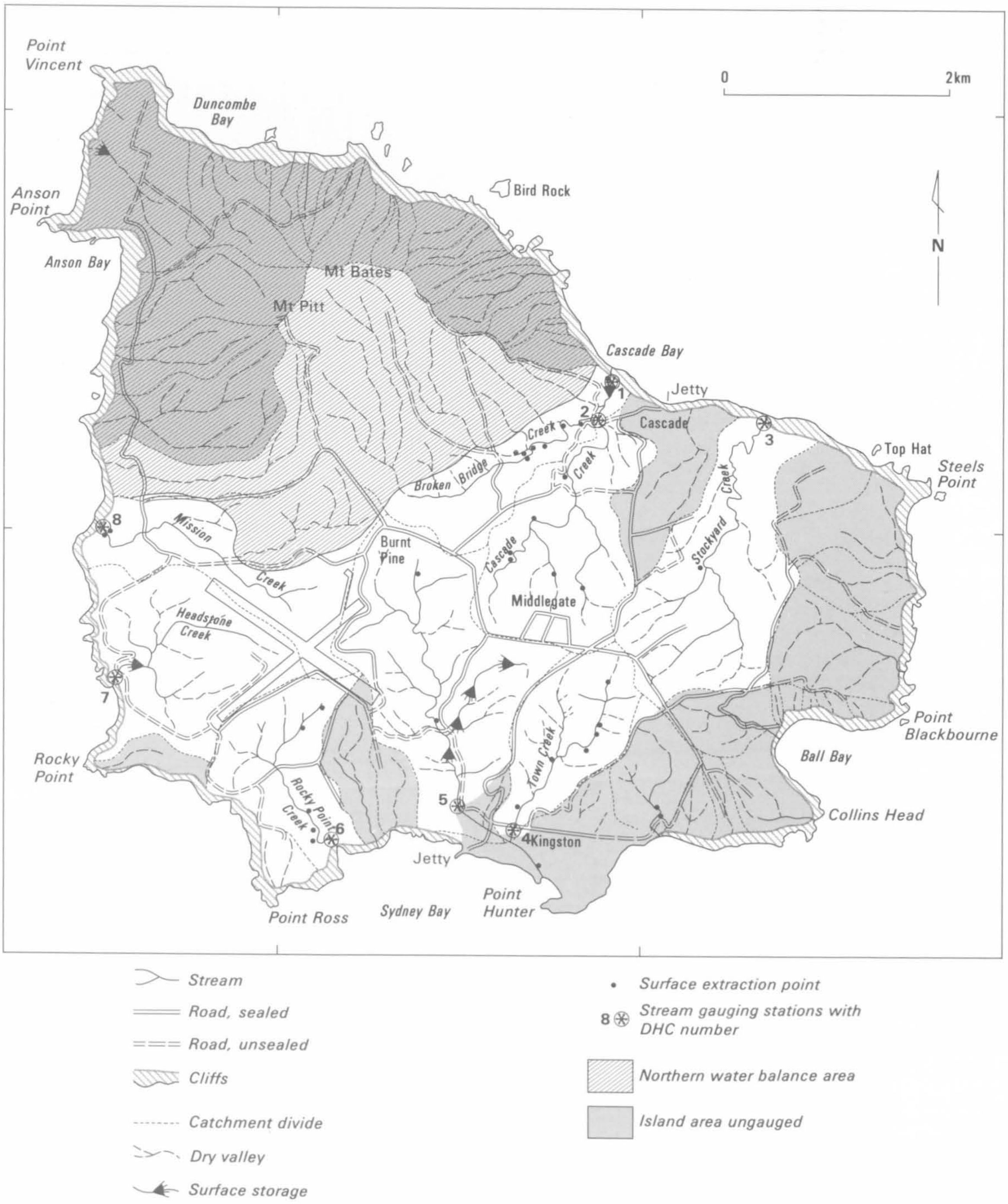

Fig. 25. Surface water on Norfolk Island.

losses; a more informed distribution of vegetation types would allow better estimates of crop coefficients; and parameters relevant to evaporation — such as soil moisture zone thickness, field capacity, and wilting point — need to be measured rather than estimated.

- Interception is the temporary detention of rainfall by vegetation. The water, which remains on the plant surfaces, is returned to the atmosphere by evaporation. The quantitative significance of interception depends on the density of the vegetative cover (measured by the leaf area index, which is the ratio of total leaf area to ground area) and the rainfall regime. In extreme conditions, such as a closed canopy forest in a region dominated by low intensity rainfall, the interception loss may exceed 50% of the rainfall. Lysimeter data from east Australian eucalypt communities show that between 10–20% of annual precipitation can be lost from interception (Bell, 1987), while for pine trees (*Pinus radiata*) with a greater leaf area, interception may typically increase by a further 10% (Dunin & Mackay, 1982). In the Norfolk Island environment, with much more open vegetation and frequent high-intensity rainfall, the interception loss will be relatively low. However, at some stage tests with plausible parameters should be made to determine whether this loss can reasonably be ignored.

- Groundwater is lost through cliff seepages around the island. Seepage loss has not been quantified and hence groundwater recharge has been computed only

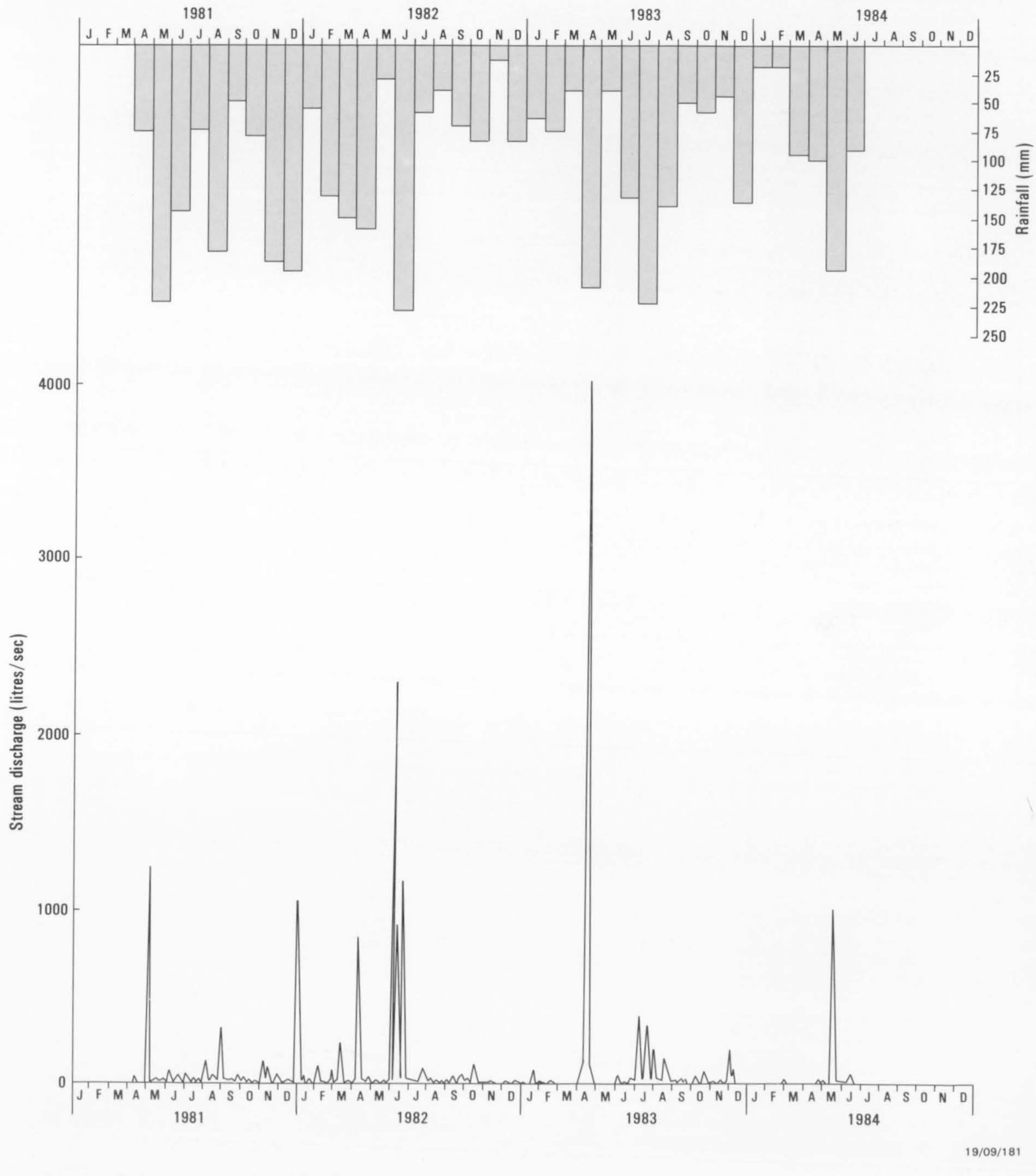

Fig. 26. Runoff hydrograph for Cascade Creek.

in terms of the spatial boundary already defined (p. 38). However, some estimate of groundwater loss from high and low-level coastal seepages needs to be attempted to assess the impact of recharge at various

TABLE 8. SUMMARY OF STREAMFLOW DATA (5/5/81–6/6/84)

Creek	*Station No.*	*Catchment Area (ha)*	*Daily Flow (l/sec) Max*	*Min*	*Mean*	*Percentage Runoff*
Cascade	1	628	600	1.4	15.0	6.3
Broken Bridge (sub-catchment of Cascade)	2	393	280	0.5	5.8	4.7
Stockyard	3	249	315	0.0	5.8	5.5
Town	4	133	212	4.5	10.0	22.7
Watermill	5	305	605	0.2	11.4	11.9
Rocky Point	6	124	265	0.4	4.7	14.0
Headstone	7	197	1110	0.0	5.1	6.6
Mission	8	237	523	0.0	5.6	5.4

levels within the island. There is some groundwater loss as baseflow, most notably from small creeks on the ungauged eastern portion of the inland, e.g. Ball Bay Creek and Music Valley.

- The use of a monthly, rather than a daily, water balance data tends to underestimate recharge by about 5–10% (Hunt & Peterson, 1980; Falkland, 1988).

Allowing for the above constraints imposed on the water balance model, which could amount to a further 10–20% of annual rainfall, groundwater recharge and sustainable yield will still exceed total water use on the island, estimated at 4.0×10^5 m^3/year by the year 2000 (DHC 1987). The estimate of groundwater recharge for Norfolk Island compares favourably with an average of 30% of annual rainfall for highly porous volcanic soils on the Hawaiian Islands (Takasaki, 1978).

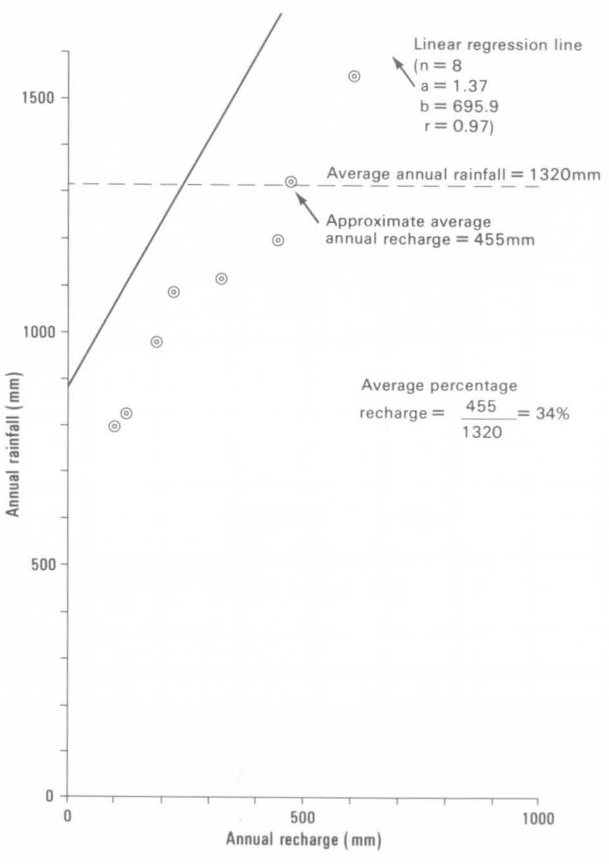

Fig. 27. Cascade Creek subcatchment: annual recharge vs. annual rainfall; 1976 to 1984.

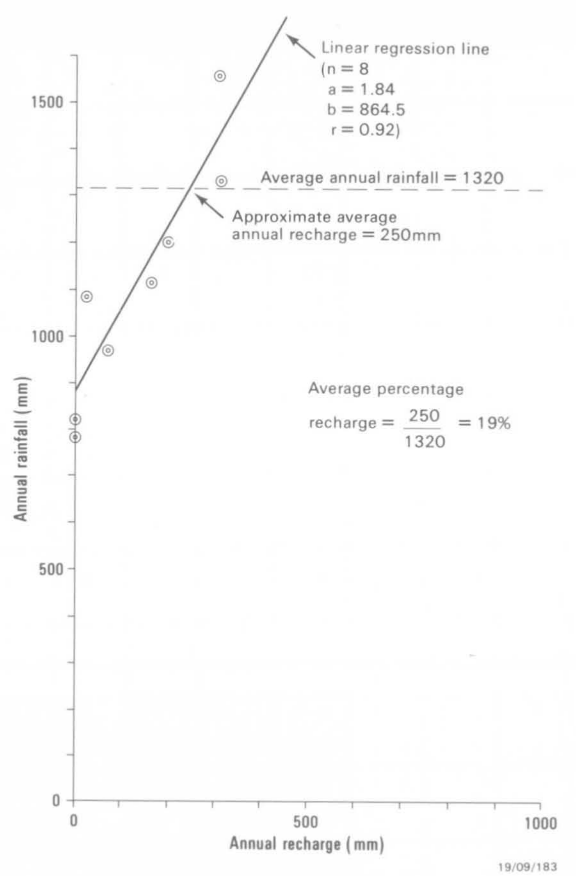

Fig. 28. Broken Bridge Creek catchment annual recharge vs. annual rainfall; 1976 to 1984.

Water-supply development

Historical records indicate that early settlers found the island well watered. Those living in the lowland at Kingston depended initially on surface water from Watermill Creek. Around 1793, an open channel (Watermill drain) was constructed to drain swampy lowland in the lower reaches of Watermill Creek, so that a more permanent settlement was possible at Kingston. Although the course of the channel has been altered several times, it can still be seen crossing the Kingston lowland, to enter the sea at Emily Bay (Plate 8). When the main administration buildings at Kingston were erected during the second settlement (1825–1847), a culvert was built to divert Town Creek into Watermill drain. Probably the first surface water storage constructed was Watermill Dam, which was used principally to drive a watermill — but also to provide a local water supply. From the middle of the 19th century, the dam gradually fell into disuse; however, in 1969 it was emptied of soil and debris and recommissioned as a water storage.

Groundwater development from wells tapping a shallow water-table in the Watermill floodplain dates from early convict times. In 1856, the settlement of Norfolk Island by the Pitcairners gave increased stimulus to the clearing and division of land on the plateau above Kingston. It was soon found that groundwater could be extracted from wells, because the weathered volcanic rocks were not only soft and unusually thick, but groundwater was mostly within 30 m of the surface. The ease with which groundwater could be obtained meant that early island homes were able to have their wells sited conveniently close to the house rather than in the valleys below. The advent of rotary drilling on Norfolk Island in the early 1970's offered easy penetration of the weathered mantle and the opportunity to progressively develop deeper sources of groundwater from aquifers in hard volcanic bedrock.

Rainwater from roofs has probably been collected and stored since the island was first settled. In the latter half of the 19th and early 20th centuries, corrugated galvanized iron sheets were imported to replace the leaking bark roofs of homes and probably improved the collection and storage of rainwater. At present, rainwater supply is the most important source of water on the island, and most householders use, or have access to, this source. Surface water has always been exploited on a small scale, but is likely to retain only subsidiary importance. The present water supply on Norfolk Island is based on the combined use of groundwater and rainwater.

Rainwater storage

The commonest and most important type of water supply on Norfolk Island is direct use of rainwater.

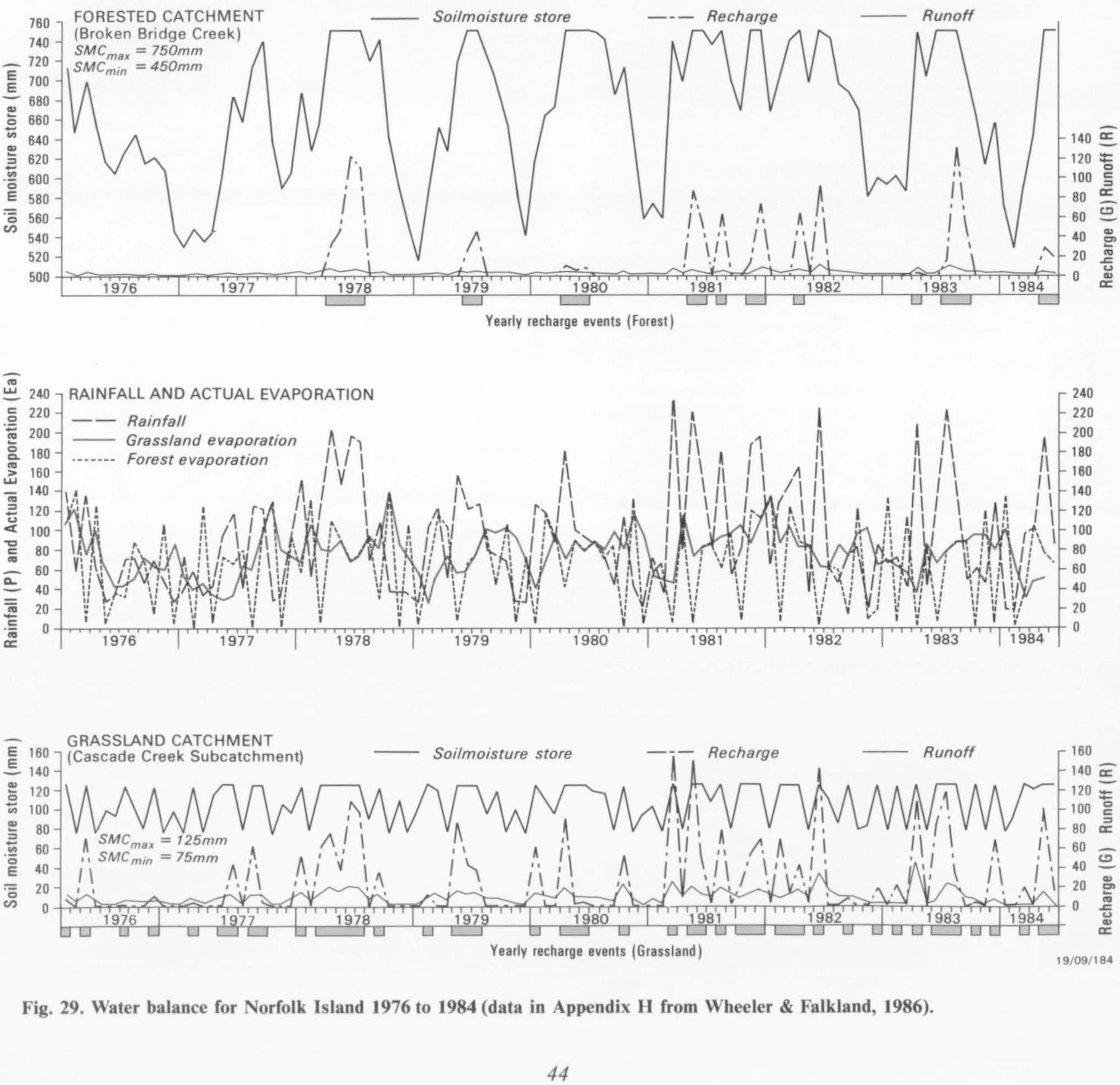

Fig. 29. Water balance for Norfolk Island 1976 to 1984 (data in Appendix H from Wheeler & Falkland, 1986).

Rainwater runoff from roofs has a number of advantages, among which are simplicity, ease of collection, and negligible operating costs. Capital costs may mitigate against this method for large-scale water collection.

Water obtained from a roof is fed by a system of drains or pipes to corrugated, galvanized iron tanks mounted on a concrete base or perched on stands at the side of the house. In some of the older houses, these installations are not well maintained. In newer houses, rainwater may be stored in large concrete tanks sunk into the ground which have advantages over the, less corosion- resistant, corrugated iron tanks.

Stored rainwater offers an effective supply on Norfolk Island, since the distribution of rainfall is not markedly seasonal. According to DHC (1987), the roof-collected rainwater with reasonable storage (say 150 m^2) would cater for most one-family household needs, but much larger storage would be required for medium to large accommodation units. Rainwater stored in tanks is subject to bacteriological pollution (*Entamoeba Coli*) from animals (rats), birds and other disease-producing carriers, such as mosquitoes and flies.

Surface water

Surface water is used by either pumping directly from streams or from small surface storages. The distribution of streams, catchment boundaries, and extraction points are shown in Fig. 25. The largest surface-water storage on the island is behind Watermill dam. Other smaller storages include an earth dam on Headstone Creek, a concrete weir on Cascade Creek (now disused), which was originally constructed to serve the old whaling station and subsequently the fish factory, and a small concrete dam on an upper tributary of Watermill Creek that provides an emergency supply for the Norfolk Hotel. Several other small storages exist on properties with access to Watermill, Stockyard, and Mission Creeks.

A number of factors militate against the large-scale development of surface water on Norfolk Island. The more important are limited space, the strongly dissected topography, potential instability of valley sides in cleared areas, the potential leakage from storage given the permeable nature of the weathered mantle and underlying fractured bedrock, and livestock pollution. Schemes for the collection of water from either a storage on Cascade Creek, or from existing paved areas at the airport shedding into a dam on the upper part of Mission Creek, are discussed in detail by DHC (1987). These schemes have high capital, operational and maintenance costs, compared with other water supply alternatives.

Water demand and consumption

The demand for water has increased considerably over the last 20 years: a rise in personal hygiene standards have followed the introduction of such appliances as washing-machines and fixed baths and showers in private homes, and garden watering is now more common since the introduction of sprayers. Studies on the Australian mainland suggest that seasonal variations in climate, in particular the number of raindays/month, determine garden watering use. The increased number of cars on the island has generated a substantial water demand for car washing. In contrast to all that, the agricultural and industrial demand for water on the island is comparatively small.

The climate exerts a considerable influence on water demand. During periods of drought or below average rainfall, wells dry out and rainwater storages are depleted, causing severe personal hardship. Owners having a bore or well with a substantial yield often make water available to more than one user. A small number of water carriers operate on the island and deliver up to eight truck loads/day in summer months. Suggestions have been made for communal watering points, carefully sited, that would alleviate water shortages during dry periods. Such watering points could be either bores supplying groundwater, or large concrete tanks set in the ground to store surface water pumped or gravity-fed from creeks.

In the absence of a water reticulation system on the island, data on water consumption is sparse. The increased demand for water brought on by an expansion of the tourist industry (Fig. 30) has meant the erection of more hotels, boarding houses and growth of the business sector (shops, restaurants, clubs, etc.) in the Burnt Pine–Middlegate area. Based on a population of 2000 (including tourists) and a daily water demand of 450 litres/capita/day, Goldfinch & Cross (1980) estimated that water requirements were $3.3 \times 10^5 m^3$/year. DHC (1987) have foreshadowed that by the year 2000, water consumption will increase to $4.0 \times 10^5 m^3$/year. Abell (1976) gives an estimate of livestock water consumption as 4.9×10^4 m^3/year.

Few households rely entirely on groundwater and some people use it only to supplement rainfall storage in summer months. Most groundwater is used for garden and domestic purposes and some for stock and irrigation; little is for drinking. Groundwater accounts for about 40% of total water consumption on Norfolk Island (Abell, 1976).

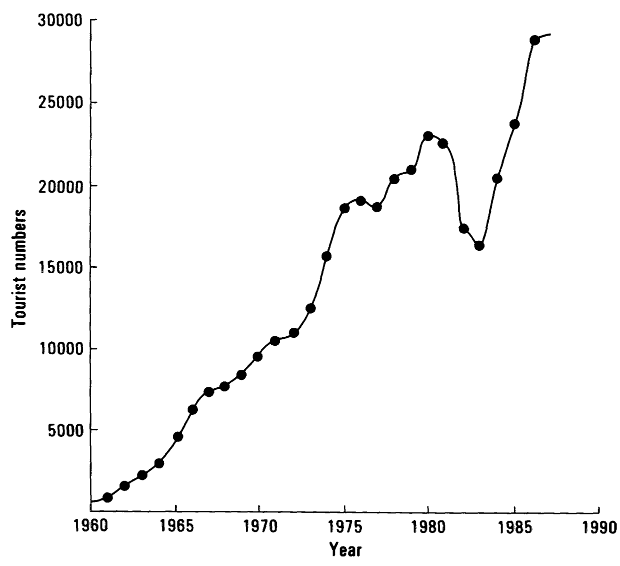

Fig. 30. Annual tourist population (1960 to 1987).

Groundwater development

Early groundwater development on Norfolk Island began with wells as they are an appropriate method for small-scale groundwater extraction from the weathered mantle because — with a large surface area of aquifer exposed — there is maximum entry and storage of groundwater. Even until modern times, wells were dug by a minimum of two men using a pickaxe, shovel, and a bucket and hoist pulled by a horse to remove the spoil. Wells were excavated either to solid rock or more usually to a few metres below the water-table; hard layers were blasted. The wells were lined from the top with up to 2 m of loosely cemented stone slabs quarried from calcareous sandstone along the Kingston shoreline or from Nepean Island. The more recent wells are lined with concrete or sheets of galvanized iron, and many of them remain in good condition, because the weathered volcanic rocks have a high clay content which rapidly hardens on exposure to air and allows the well sides to resist collapse. The mean depth of wells varies according to topographic position: on the ridges they average 26 m; in valleys, 7 m. The deepest one measured was 60 m (NI 105). Most wells range from 1.2 to 1.5 m in diameter.

According to local information, some bores may have been drilled in the early 1950s, but no records are available. The first documented and properly constructed water-bore was drilled in 1966 at the site of the old Kingfisher Hotel with a percussion rig brought from the Australian mainland. The bore gives a consistent water supply of 0.60 l/sec from a hole reported as being 50 m deep. Groundwater development from bores was not significant until 1970, when a rotary drilling rig mounted on a truck arrived on the island from New Zealand. The rig was able to drill effectively through the weathered mantle, but had initial difficulties completing boreholes in hard rock. At present, water bores are drilled by a reconditioned rig imported from Australia by C. McCullough. Over the last five years or so, drilling procedures have improved to an extent that water bores can now be satisfactorily drilled to 150 m.

A total off 456 bores and wells have now been completed on Norfolk Island (data to 1988). There is a fairly even distribution across the Southern plateau with local concentrations on the northwest plateau and at Kingston (Fig. 31); however, there is no groundwater development in the Norfolk Island National Park. An inventory of groundwater extraction points shows that 175 are wells and 281 are bores. Information on 297 bores and wells as recorded by BMR up to 1975 are summarised in Abell (1976). Since that time, Mr. G. Duvall has maintained a record of bores drilled on the island and has forwarded copies to the BMR.

Aquifer characteristics

Lack of hydraulic data hinders proper appraisal of aquifer capability. Bore yields rarely exceed 1.0 l/sec. Some bores show nil or small drawdown with pumping, which suggests a potential for yields > 1.0 l/sec. In some places, yields > 3.0 l/sec have been recorded in shallow bores located along major drainage lines. Yield values are, in many cases, based on pump capacity or owner's estimate. This yield data depends as much on the condition, type, setting and placing of pumps as on local groundwater conditions. Yield is also affected by the standard of bore completion. Since 1975, about 30 boreholes have been dry or abandoned on completion giving a failure rate of one in every five drilled.

The hydraulic properties of the basaltic aquifer on Norfolk Island are poorly known. The only known pump test carried out so far was by AGC (1986) on a bore (NI 401) at the edge of the Norfolk Island National Park, about 2.4 km northwest of Burnt Pine. This bore was tested at a rate of 1.0 l/sec for a period of 48 hours, whilst drawdown and recovery was measured in an observation well 30 m to the east. Some estimate of borehole productivity and aquifer character can be obtained from specific capacity data (Table 9). The variable nature of bedrock permeability is illustrated on a histogram (Fig. 32). In the volcanic bedrock, specific capacities of bores range from 0–2600 m^3/day/m, while lower permeability in the weathered mantle is evident from the specific capacity range of 0–300m^3/day/m.

An approximation of transmissivity was obtained using LOGANS METHOD (Kruseman & de Ridder, 1983), according to the relationship $T = 1.22Q/S$, where T = transmissivity in m^2/day, Q = discharge in m^3/day and s = drawdown in metres in the pumped well. It was assumed that bedrock aquifers are semiconfined and that steady-state conditions were reached after a minimum test time of four hours. Similar assumptions were applied to bores in the unconfined weathered mantle, with an additional correction being made for partial penetration according to the relationship $S' = S-S^2/2d$ where S' = corrected drawndown and d = depth of bore penetration in metres. The transmissivity data (Table 9) closely follow those for specific capacity, with lower values pertaining to the weathered mantle and a high degree of variability in volcanic bedrock.

Influence of fractures on yields

Generally, where bores intersect fractures, they should provide high groundwater yields. Although the importance of fractures in groundwater occurrence is well known, there have been few detailed fracture-trace studies for groundwater development in volcanic rocks.

On Norfolk Island, most bores appear to have been sited between fracture zones (Abell, 1976). The few that are sited within these zones either give reasonably high yields of groundwater or are dry. Some bores sited on or close to fracture traces are able to maintain a moderate yield over long periods, because they tap a locally increased thickness of weathering in a fracture zone. However, lost circulation reported at drilling suggests that, in some areas, permeability increases at the base of the weathered mantle; this may be associated with either interconnected fracture systems or with long fractures crossing the island.

Available data that correlated bore yield with fracture orientation is sparse and tends to be contradictory. The permeability variation either may be related only to the degree of fracture closure with depth or the amount of clay formed by the locally increased depth of penetration of weathering in a fracture zone. Offshore seepages seen by local residents off Point Vincent and close to Duncombe Bay are aligned with north-northwesterly

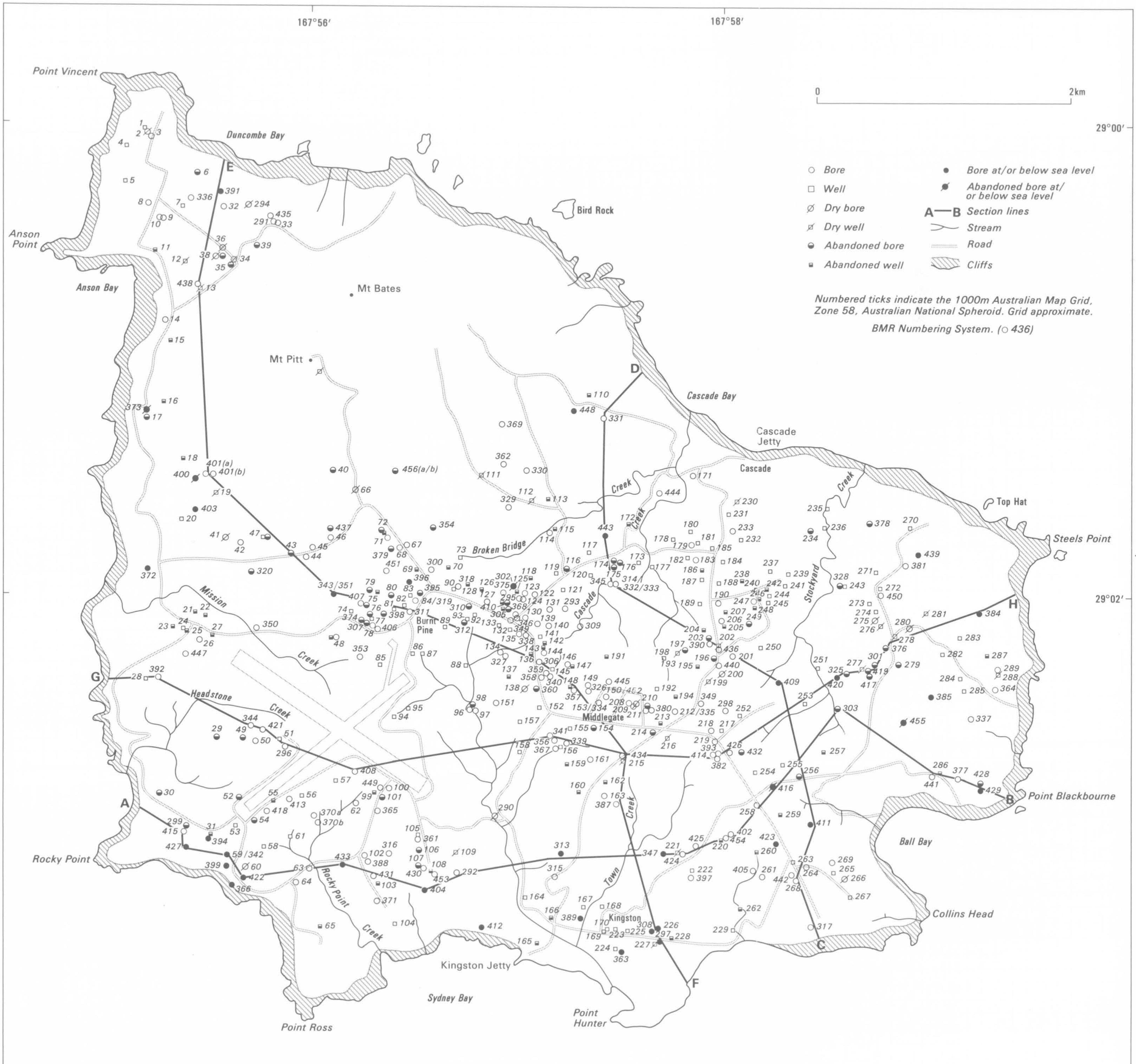

Fig. 31. Location of bores and wells on Norfolk Island.

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fracture orientations; these directions may be significant for water-supply purposes.

Favourable drilling sites might occur where fractures can be related to visible zones of weakness, such as joints and faults in coastal exposures. As the surface drainage network is partly fracture-controlled, fractures along valleys may be more concentrated and open beneath a superficial cover of alluvium.

Shallow groundwater

Shallow groundwater resources are currently exploited by both wells and bores tapping a high-level unconfined aquifer in the weathered mantle and alluvium. For water-supply development in the weathered mantle some knowledge of the depth to the water-table, and its range of seasonal fluctuation, is necessary for estimating a minimum drilling depth. Water table data seems to suggest that over a period of below-average rainfall groundwater-levels fall substantially, but then quickly recover in years of average or above-average rainfall. Many of the older wells on the island have little water in summer or dry up completely in droughts, which suggests that at the time they were dug they did not allow for appropriate seasonal fluctuations in groundwater level.

Most wells derive their groundwater from *temporary storage* (Fig. 33), which is the amount of water that can be made available to a well between minimum and maximum seasonal groundwater levels. These are called "replenishment resources" as they depend only on changes in water level due to rainfall recharge. Wells or bores sited in valleys are probably tapping groundwater in *permanent storage* (Fig. 33). In general, wells have limited capacity which will be increasingly depleted during long dry spells. If not adequately protected on the surface, they can become contaminated with sewage effluent and/or animal excreta.

Significant yields in excess of 3.0 l/sec are already known from bores drilled into alluvium in upper tribu taries of the Watermill and Rocky Point creeks. Annual streamflow in these catchments is maintained largely by baseflow which, if properly developed, has the capacity to provide useful reserves of shallow groundwater. Similarly, exploitation of shallow groundwater as a second-class water supply from alluvium along Mission creek is recommended by Abell & Taylor (1981).

Spring seepages are not generally used as sources of water. However, occasionally, wells have been sited in creek beds close to a seepage source. The only well known to be in current use is 250 m north of the meteorological station in the headwaters of Mission Creek. Only one attempt has been made to use groundwater from a coastal seepage. At Anson Bay, a collecting tank was lowered over the cliff below the Old Cable Station to collect seepage flow, which was then pumped to the top of the cliff. This supply is now disused, but the remains of the old tank and standpipe are still present.

The development of spring seepage, either inland or along the coast, is unlikely to be more than local significance for individual property owners. If a water supply

TABLE 9. AQUIFER TEST DATA

Bore No.	*Rock Type*	*Depth (m)*	*Water[1] level (m) (Depth from surface)*	*Discharge (Q in m^3/d)*	*Drawdown (s in m)*	*Specific Capacity (Q/s in $m^3/d/m$)*	*Transmissivity (T in m^2/d)*	*Remarks*
NI 17	WM	64.0	15.0	17.3	15.0	1.2	1.4	
NI 268	WM	76.2	33.5	19.0	2.4	7.9	9.9	
NI 269	WM	41.4	14.0	31.9	6.1	5.2	7.2	
NI 292	WM	22.0	15.0	26.8	2.0	13.4	19.0	
NI 293	WM	38.0	29.0	18.1	2.0	9.1	12.4	
NI 295	WM	12.0	8.0	31.9	1.0	31.9	44.2	
NI 296	BR	74.0	21.0	43.2	2.4	18.0	21.9	
NI 297	BR	24.0	3.0	43.2	Nil(.05)	864.0	1054.1	Bore depth -10m(b.s.l.)
NI 298	WM	50.0	32.0	43.2	0.3	144.0	177.1	
NI 300	WM	84.0	38.0	26.8	0.3	89.3	109.2	
NI 308	WM	29.2	7.6	29.4	7.6	3.9	5.7	
NI 309	WM	13.7	0.9	64.8	0.3	216.0	267.1	
NI 311	BR	36.0	21.0	12.9	3.0	4.3	5.3	
NI 313	BR	45.0	14.0	26.8	Nil(.50)	536.0	653.9	Bore depth -2.3m (b.s.l.)
NI 316	WM	33.0	4.0	25.9	15.0	1.7	2.8	
NI 318	BR	49.0	17.0	43.2	Nil(.05)	864.0	1054.1	
NI 326	WM	49.0	17.0	21.6	0.3	72.0	88.4	
NI 335	BR	64.3	33.0	48.4	2.2	22.0	26.8	
NI 337	WM	13.1	4.6	24.2	0.3	80.7	100.2	
NI 347	BR	104.2	44.8	77.7	3.6	21.3	26.0	Bore depth -9.7m (b.s.l.)
NI 350	WM	27.4	0.7	194.4	Nil(.05)	3888.0	9418.4	Creek recharge
NI 351	BR	106.7	35.4	51.8	4.3	12.1	14.7	Bore depth -30.5m (b.s.l.)
NI 353	WM	43.6	1.5	129.6	4.0	32.4	41.5	
NI 363	BR	35.3	8.8	48.8	18.6	2.6	3.2	Bore depth -29.2m (b.s.l.)
NI 365	BR	55.5	28.1	64.8	Nil(.05)	1296.0	1581.1	
NI 370	WM	19.5	2.7	114.1	Nil(.05)	2282.0	2789.6	Creek recharge
NI 375	BR	38.1	11.6	25.9	4.0	6.5	7.9	
NI 380	WM	27.1	21.9	12.9	Nil(.05)	259.2	317.5	
NI 396	BR	129.5	85.6	112.3	Nil(.05)	2246.6	2740.6	Bore depth -28.2m (b.s.l.)
NI 397	BR	83.8	56.1	47.5	24.1	1.9	2.4	
NI 399	BR	108.5	60.9	129.6	Nil(.05)	2592.0	3162.2	Bore depth -20.1m (b.s.l.)
NI 401	BR	76.5	47.5	86.4	12.0	7.2	8.8	Drawdown data by AGC (1986) gives T = $2.43m^2d$ and storage coefficient (S) = 0.000038
NI 402	WM	39.6	23.2	25.9	6.1	4.2	6.3	
NI 407	WM	44.2	13.7	34.5	22.8	1.8	2.9	
NI 414	BR	79.2	43.0	64.8	Nil(.05)	1296.0	1581.1	
NI 415	BR	62.5	38.9	59.6	11.3	5.2	6.3	
NI 447	BR	49.7	15.0	62.4	1.5	41.6	50.7	

Code: WM = Weathered mantle; BR = Bedrock
[1]Water level measured from the topographic surface.

is developed close to a seepage, care should be exercised not to excessively disturb the ground, so as not to locally alter the permeability and reduce discharge to a well or shallow bore.

Deep groundwater

For practical water supply considerations, the time and space distribution patterns of groundwater recharge that operates on Norfolk Island — although causing fluctuations in water levels in the weathered mantle — is unlikely to have any appreciable effect other than to maintain a deep storage system.

At present, deep groundwater on Norfolk Island is largely undeveloped and exists more or less in a condition of equilibrium with submarine seepage-loss, balanced by natural groundwater recharge. As at June 1988, thirty-six bores were known to extend to sea level and below (Table 10). Most of these bores have been sited on the southern side of the island in an arc stretching from Rocky Point to Steels Point (Fig. 31). Eight of the deep bores range in depth from 0–5 m b.s.l, while 28 holes have depths exceeding 5 m b.s.l. Five of the holes drilled below sea level were dry. In most cases, water enters the productive bores below sea level.

As most bores and wells do not reach sea level, the effects of tides on the quality of deep groundwater is poorly known. The bores that might be subjected to tidal influence are those at or below sea level, where natural mixing may take place at the saline/freshwater interface. The mixing is dependent on the permeability distribution of the volcanic rocks, the landward effect of tidal fluctuation, and the size of the island. Ocean tide fluctuations on Norfolk Island average 1.5 m, with a maximum fluctuation of 2.8 m (based on data from 1969–1988 supplied by the CSIRO Division of Oceanography, Hobart). Tidal fluctuations remain fairly constant through the year, but are probably large enough to cause mixing of freshwater and seawater at the island perimeter and perhaps farther inland (Fig. 16 and Table 4). Tidal influences on groundwater and water quality levels are known to extend at least 1 km from the coast on the volcanic island of Tenerife with an area of 2058 km^2 (Ecker, 1976), and to extend throughout Niue, a limestone island, 259 km^2 in area (Jacobson & Hill, 1980). Providing there is sufficient permeability, tidal fluctuations will tend to thicken the mixing zone at the

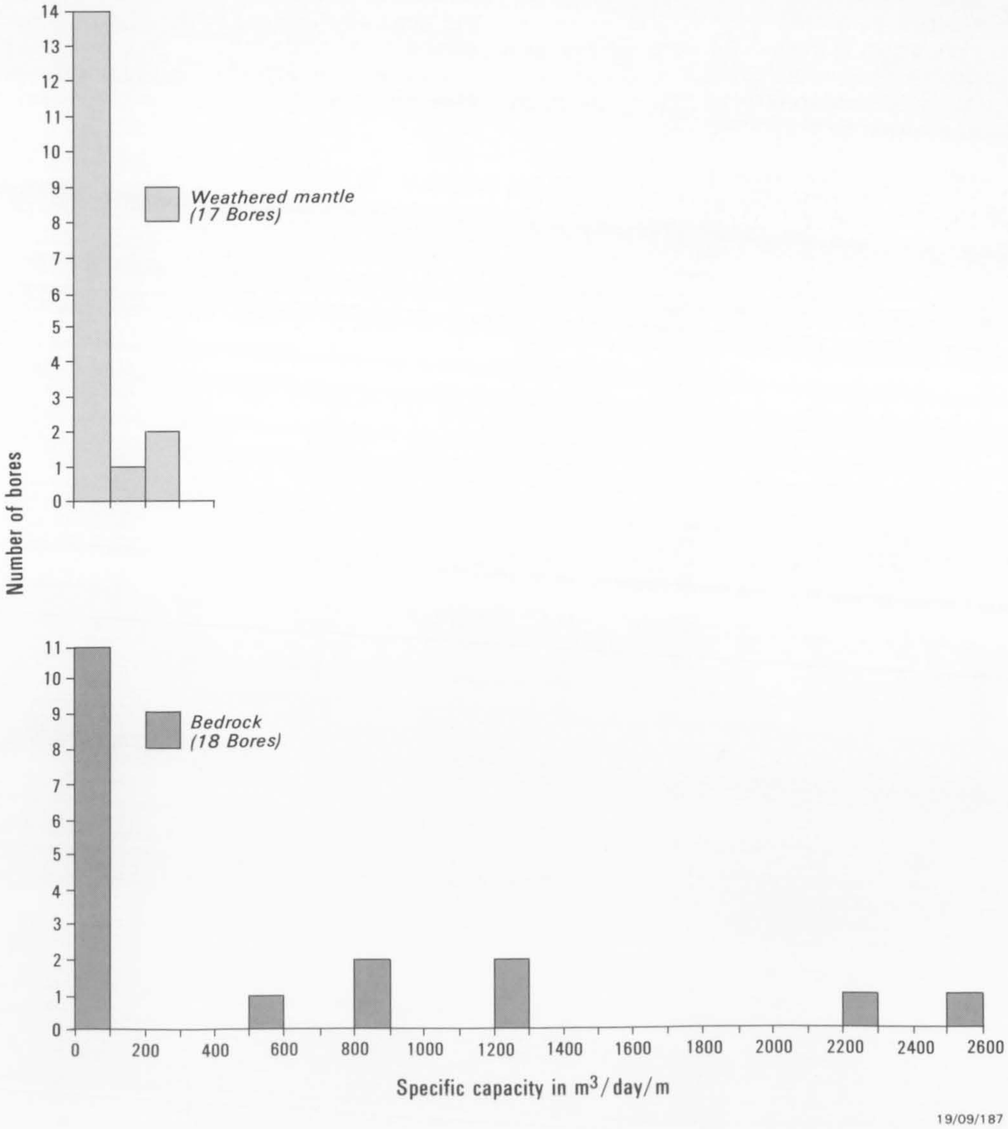

Fig. 32. Histogram of specific capacities for bores in basaltic rocks on Norfolk Island.

base of the freshwater layer. On Norfolk Island, with only 35 km², tidal fluctuations must be expected to have some influence on salinity levels in deep groundwater, particularly where there is a strong hydraulic connection along permeable zones and open fractures. This suggests that initial development of deep groundwater ought to be limited to bedrock aquifers above sea level to ensure a safe water supply (refer to Fig. 16 and Table 4).

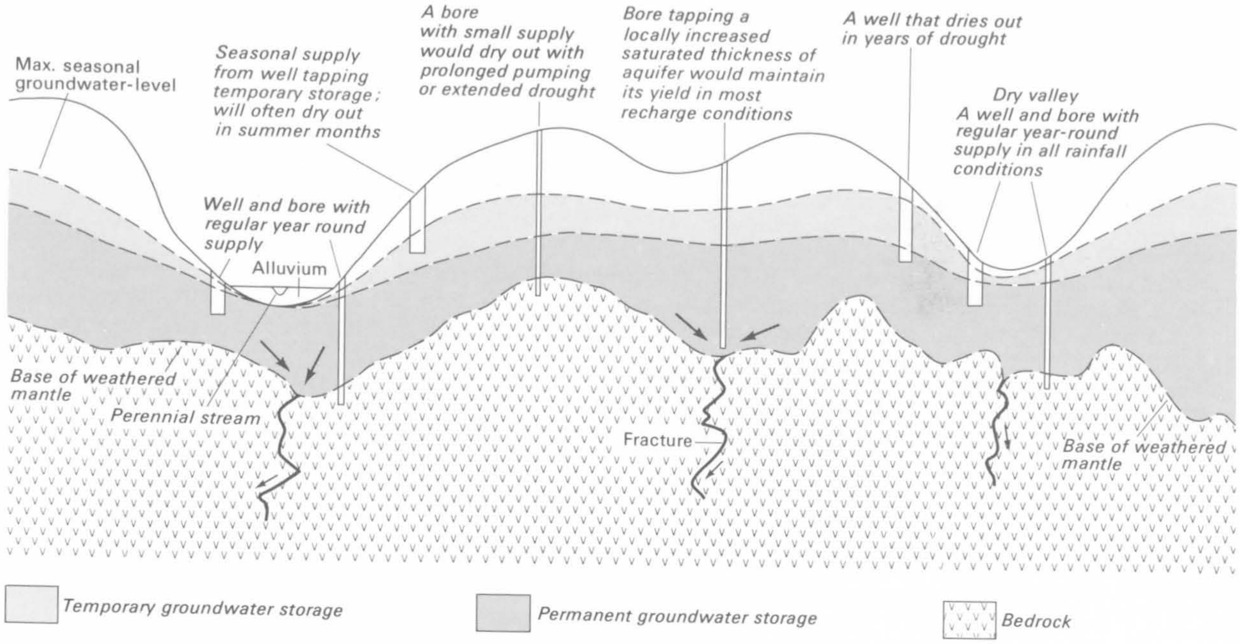

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Fig. 33. Groundwater development in the weathered mantle and alluvium.

TABLE 10. INVENTORY OF BORES AT OR BELOW SEA LEVEL

No.[1]	*Completion date*	*Elevation (m)*	*Depth*[2] *(m)*	*Depth b.s.l.*[3] *(m)*	*Depth of water entry*[4] *(m)*	*Water level*[5] *(m)*	*Yield*[6] *(l/sec)*
83/226	31/07/74	24.4	38.4	−14.0	25.9	18.5	1.00 (no drawdown)
121/297	12/12/75	14.0	24.0	−10.0	23.2	3.0	0.50 (no drawdown)
128/302	09/09/76	91.4	91.4	0	—	—	Dry
134/308	20/04/77	19.8	29.2	−9.4	24.4	7.6	0.35
138/313	26/10/77	42.7	45.0	−2.3	41.1	14.0	0.30 (no drawdown)
170/342	24/07/81	88.4	103.6	−15.2	100.6	32.0	Not in use
178/347	06/04/81	94.5	104.2	−9.7	100.6	44.8	0.90
183/351	26/01/82	76.2	106.7	−30.5	105.8	35.4	0.60
197/363	29/11/82	6.1	35.3	−29.2	15.0	8.8	0.55
200/366	08/03/83	85.4	104.2	−18.8	100.5	60.9	0.45
207/372	20/05/83	76.2	95.4	−19.2	91.4	76.2	Poor (saline after pumping)
208/373	02/06/83	73.2	73.2	0	—	—	Dry
218/384	09/02/84	70.1	80.7	−10.6	80.7	57.3	0.75
219/385	19/01/84	67.0	85.3	−18.3	77.7	39.3	Not in use
224/389	14/12/83	12.2	43.6	−31.4	29.0	0.6	1.00
226/391	02/02/84	91.4	121.9	−30.5	116.0	95.7	0.90 (saline after pumping)
231/394	26/03/84	79.3	79.8	−0.5	74.7	42.1	Not in use
233/396	07/06/84	100.6	129.5	−28.9	126.5	85.6	1.30 (saline after pumping)
236/399	20/07/84	88.4	108.5	−20.1	101.5	60.9	1.50 (no drawdown)
237/400	03/02/86	88.4	90.2	−1.8	—	—	Dry
241/403	24/10/84	67.0	83.8	−16.8	82.9	58.8	0.65
242/404	27/11/84	82.3	109.7	−27.4	106.7	80.2	0.75
249/409	29/01/85	100.6	134.1	−33.5	131.0	102.1	0.75
251/411	14/03/85	118.9	152.4	−33.5	149.3	112.7	Not in use
252/412	19/03/85	61.0	79.3	−18.3	80.7	65.2	0.65
256/416	13/11/85	121.9	164.6	−42.7	—	—	Dry
261/420	10/10/85	106.7	126.5	−19.8	125.0	105.2	0.75
263/422	28/11/85	85.3	100.6	−15.3	98.1	68.6	Not in use
264/423	17/01/86	119.0	154.3	−35.3	152.4	91.4	0.75
272/427	04/08/86	67.0	96.0	−27.0	93.0	73.5	Not in use
274/429	07/10/86	85.3	118.9	−33.6	116.1	82.9	0.75
279/433	12/12/86	54.9	83.0	−28.1	82.0	40.5	0.75
286/439	25/09/87	94.5	117.6	−23.1	112.0	76.5	1.25 (saline after pumping)
291/443	07/07/87	100.6	105.0	−4.4	105.0	57.9	1.00
244/448	06/03/87	129.5	159.1	−29.6	141.7	121.9	Not in use
276/455	19/10/86	97.5	120.4	−22.9	—	—	Dry

[1]Dual numbering system: first number is Duvall's, second is BMR's scheme — the latter without the prefix NI. Refer to text on page 1.
[2]Depth of borehole measured from the topographic surface.
[3]Depth refers to corrected depth to sea level; i.e. b.s.l. = below sea level.
[4]Depth of water entry measured from the topographic surface.
[5]Water level measured from the topographic surface.
[6]Yields are approximate and indicate pump capacity rather than aquifer potential.

Geophysics

Resistivity and magnetic surveys were undertaken in 1981 to obtain subsurface hydrogeologic controls which affect the development and occurrence of groundwater in bedrock aquifers (Abell & Taylor, 1981).

The resistivity survey, using an Atlas Copco SAS 300 Terrameter, consisted of 12.5 km of Wenner profiling in the Broken Bridge–Mission Creek area and three Wenner depth probes at Kingston, Simons Water, and Broken Bridge Creek (see Figs 6 and 7 in Abell & Taylor, 1981). This survey successfully provided information on prospective shallow groundwater occurrences. Low resistivity values indicate zones of saturated, deeply weathered rock with shallow groundwater and, if coincident with fractures, can contribute to the recharge of deeper aquifers. Measurement of the hydrogeophysical response of bedrock was hampered by the dissected terrain which restricted the electrode spacing that was used for profiling and depth probes. The interpretation of resistivity results was made difficult by the low resistivity contrasts that characterise the volcanic sequence; however, on the Kingston lowland a depth probe confirmed salt water at a depth of 17 m with an overlying zone of brackish water 15 m thick.

Magnetic measurements were taken with a proton magnetometer (Geometrics 816) along the same lines used for resistivity. The intense amplitude fluctuations in the magnetic profiles broadly range from 51 000–54 000 nT (nanotessler units). The recorded total magnetic field is typical of a basaltic lava and tuff sequence; the high noise level is due to variations in remanent magnetism rather than man-made interference (metal, powerlines, etc.). The reconnaisance nature of the survey provided some interpretative leads on rock types, depth of weathered mantle, and possible existence of structural discontinuities (Abell & Taylor, 1981).

Prospective areas

Good prospects exist for adequate groundwater supplies south and west of the airport, i.e. areas 1 to 3 in Figure 34. These three areas have the potential to provide good-quality water based on deep storage in bedrock aquifers. The selection of these areas is based on: (a) high drilling success rate with proven water supplies obtained within a depth of 150 m (the limit of the island rig); (b) presence of baseflow along drainage lines indicating aquifer leakage (drainage line contours intersect upper portion of groundwater storage); (c) a suitable vertical and horizontal permeability framework, which retains groundwater in a sequence of interbedded lava and tuff; and (d) adequate distance from known pollution areas in Burnt Pine–Middlegate.

Two other unexplored areas, in Figure 34 along the lower reaches of Watermill Creek (4)and Mission Creek (5), have the potential to provide potable groundwater at shallow depths (< 50 m). An unusually large number of dry bores and wells on the eastern side of the island (6) outlines an area of highly permeable bedrock with poor groundwater availability.

Areas 1 to 5 require more detailed study before drilling sites are chosen to develop groundwater on the scale of a reticulated water supply. Substantial hydraulic gradients directed towards the coastal perimeter suggest that these areas have the potential to produce substantial groundwater, providing the risk of saltwater intrusion is closely monitored.

Conclusions

(1) The hydrogeology of Norfolk Island is summarised in Table 11. There are clear differences between the vent area and the plateau.

(2) A conceptual model is proposed for the Norfolk Island groundwater system. The upper hydrologic boundary in this model is an elevated water table in the weathered mantle. Hydraulic continuity through fresh volcanic rocks to sea level and below is maintained primarily by a network of fractures and interconnected openings. The Ghyben–Herzberg model applies only partly to Norfolk Island. The extent of deep groundwater underlying the island is still unknown, but considering the heterogeneous permeability (including major fractures) evident in volcanic bedrock, the

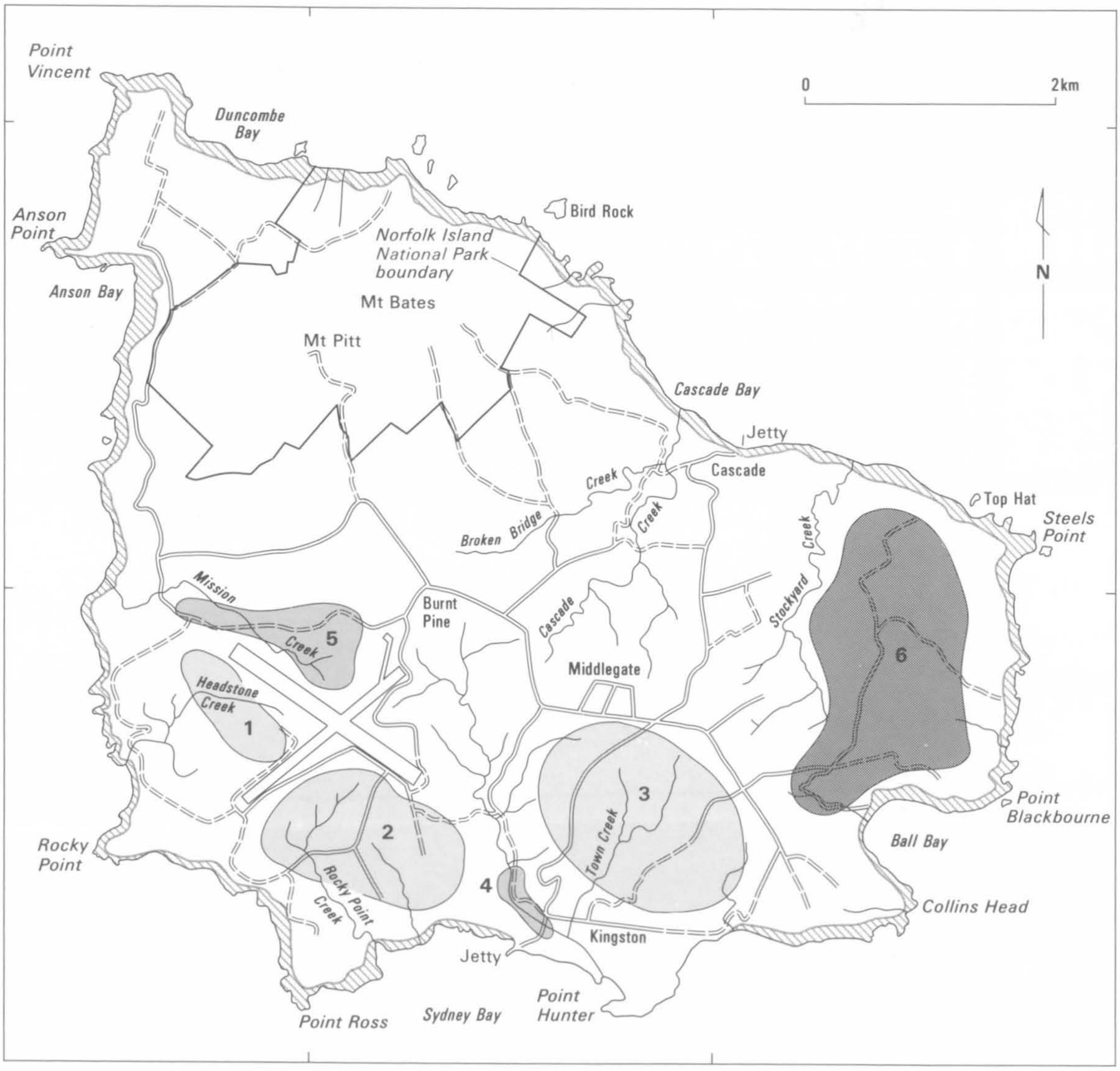

Fig. 34. Prospective areas for deep groundwater development.

effect of tidal fluctuations, and the size of the island, it is expected that the thickness and distribution of the transitional zone between fresh and saline water may be substantial.

(3) Available hydrometeorological data suggest that about 30% of average annual rainfall is available for groundwater recharge. The deuterium/oxygen-18 correlation does not show evaporative effects associated with groundwater recharge or mixing with saline water. On the other hand, low tritium values indicate residence times for groundwater that commonly exceed 25 years and maybe as much as 50 years old.

(4) Norfolk Island groundwater is of the NaCl-type, with the salt derived initially from oceanic spray. The water is generally of good quality and suitable for domestic and irrigation use. However, high levels of chemical and bacteriological pollution occur in the Burnt Pine–Middlegate residential and business area. Around the island perimeter, there is some evidence that pumping can induce seawater intrusion to bores tapping bedrock aquifers at or below sea level.

(5) Water resource development on Norfolk Island is by the conjunctive use of rainwater and groundwater. Exploitation of the latter is limited to the southern and northwestern plateau. Unconfined groundwater in weathered volcanic rock and alluvium is extracted by wells and shallow bores. Deeper semi-confined groundwater in fractured basalt and interbedded tuff is recovered from boreholes which reach up to 35 m below sea level.

(6) Hydrogeological factors and water balance data suggest that sufficient resources of groundwater probably exist for future exploitation. Deep groundwater below the weathered mantle appears to offer the best potential for development.

Future exploration and development of deep groundwater as a viable water supply will depend on the following factors:

- The highly variable geology of the volcanic rocks, which makes it difficult to identify the subsurface components that control groundwater occurrences.
- Effective aquifer testing, since most bores are only completed for local uses.
- The availability of drilling technology on the island that will enable holes to be drilled to depths > 150 m and ability to overcome lost circulation problems in fractured basaltic rock.
- The recognition that pollution will always be a potential environmental hazard for island communities that live above an exploitable groundwater resource. Pollution threats from the disposal of sanitary waste and free-ranging livestock can in part be rectified by the newly installed effluent disposal scheme for the Burnt Pine–Middlegate area and consistent application of health surveillance techniques and water-quality monitoring.
- Consideration of the type of water supply best suited for the needs of Norfolk Island (DHC 1987). The extent and quality of a deep groundwater resource has yet to be proved in detail. If such a resource is found to be adequate, then its exploitation can be phased in with proposals for water reticulation and effluent disposal schemes.

TABLE 11. HYDROGEOLOGIC DIVISIONS

	Vent area	*Southern and northwest plateaux*
GEOLOGY	Basaltic tuff with minor basalt flows	Basalt lavas with interbedded tuffs
LAND USE	National Park; protected area	Populated; land development
VEGETATION	Forested	Grassed
GEOMORPHOLOGY	Topographically high (100–300 m); radial drainage with dry valleys; no permanent runoff	Topographically flat (0–100 m) with incised, fracture controlled drainage; larger creeks support year-round runoff
GROUNDWATER	Permeable ($K_v > K_H$); minimal ground water discharge; average recharge 19% of rainfall; poorly explored area with limited water supply development; pollution free	Moderately permeable ($K_v \geqslant K_H$); groundwater discharge to creeks; average recharge 34% of rainfall; groundwater pollution in Burnt Pine–Middlegate area

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