Some Hydrogeological Problems Peculiar to Various Types of Small Islands

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Abstract

There are many problems associated with the investigation of small island hydrogeology, including (i) the availability of data and the distribution of both spatial and temporal data sets, (ii) the dynamics of the groundwater to sea-water interface and the shape of the so-called groundwater lens, and (iii) the difficulties of evaluating recharge to groundwater and of calculating the volume of groundwater discharge to the sea. These issues are compounded by (a) the ratio of coast to area in small islands, (b) the problems of extreme topography, and (c) the identification of baseflow to rivers and streams. A simple classification of island types assists in evaluating hydrogeological regimes, and the importance of groundwater in an island context cannot be over-emphasised.

Key words: **Islands; recharge; water balance; water resources**

Introduction

Small islands face immense problems with the effective capture and exploitation of renewable resources (water, crops or energy) and for the secure disposal of wastes. Demographic forces can be intense; for example 30 000 people per km^2 live on the tiny island of Malé, which is nearly ten times as densely populated as the Channel Island of Guernsey. Other key problems include groundwater quantity and quality, complexity of the aquifers, limited recharge, sea-water intrusion and pollution caused by improper waste disposal. A principal difficulty is the calculation of the volume of groundwater discharge directly to the sea – an essential component of the water balance[1,2].

Normally, islands have wetter climates than continents[3], but the development of the available surface and groundwater resource is more difficult on an island. This is because of the smaller size of island catchments and aquifers, the significant losses to evapotranspiration from available rainfall, as well as the need to maintain the fresh-water to salt-water interface and the lens of fresh groundwater which occurs particularly beneath low-lying islands. However, these same factors inhibit upland surface-water gathering and storage, and enhance the importance of groundwater.

This paper discusses some of the problems arising in small island hydrogeology. It is not intended as a guideline or a manual, for which reference should be made to Falkland[2]. However, a simple analysis of the factors which control the sustainability of a potable groundwater resource can help to identify problem areas and critical factors.

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Types of Island

Islands can be classified according to a variety of different criteria. Classification by geological origin, for example, highlights the basic or global island settings: continental margins, oceanic ridges, island arcs, sea mounts, and carbonate oceanic banks and reefs.

It is also possible to categorise islands according to a wide range of geographical, hydrological and economical features. The hydrological analysis of 1000 islands used an index of between 1 and 10, which reflected the presence (or otherwise) of perennial streams, perennial springs, wetlands and fresh-water lakes: 181 fell into Class 1 (dry) and 124 were in Class 10 (wet)[4]. Most of the sample set was found to be of an intermediate classification.

A detailed generic classification of small islands has been developed by Falkland[2], based on the key aspects of geology, climate, freshwater lens geometry and water balance. This classification can be reduced to six basic island types (Fig. 1), and classification of an island within these types may help to identify its groundwater flow regime. Further sub-division is always possible. The small, but high-rise, volcanic islands of the Caribbean fall into three sub-classes which distinguish islands with pyroclastic deposits which are saturated to high elevations, e.g. Grenada; islands with pyroclastics but where the rainfall cannot maintain throughflow to the coast, e.g. Beef in the British Virgin Islands; and islands without pyroclastic deposits in which groundwater occurs only in the fractured volcanic rocks, e.g. the Grenadines, or Tortola[5].

Each of the six main island types can be analysed by the adequacy of four key characteristics: (i) recharge, (ii) storage, (iii) yield, and (iv) quality (Table 1). Examples of islands and their island type are given in Table 2. Adequacy, although subjective, is used here as 'ability to sustain normal demand levels for potable water supply and is partly a function of population density'. Of the four characteristics, recharge depends principally on climate, but it also relates to island size, soil cover, vegetation, elevation and topography. Storage depends on the effective porosity of the aquifer, and also on the elevation of the water table and the location of the saline interface. Secondary features, such as the development of weathering and active and fossil karstic horizons in limestone aquifers, are also important. Yield, or more particularly sustainable yield, relates to recharge, storage

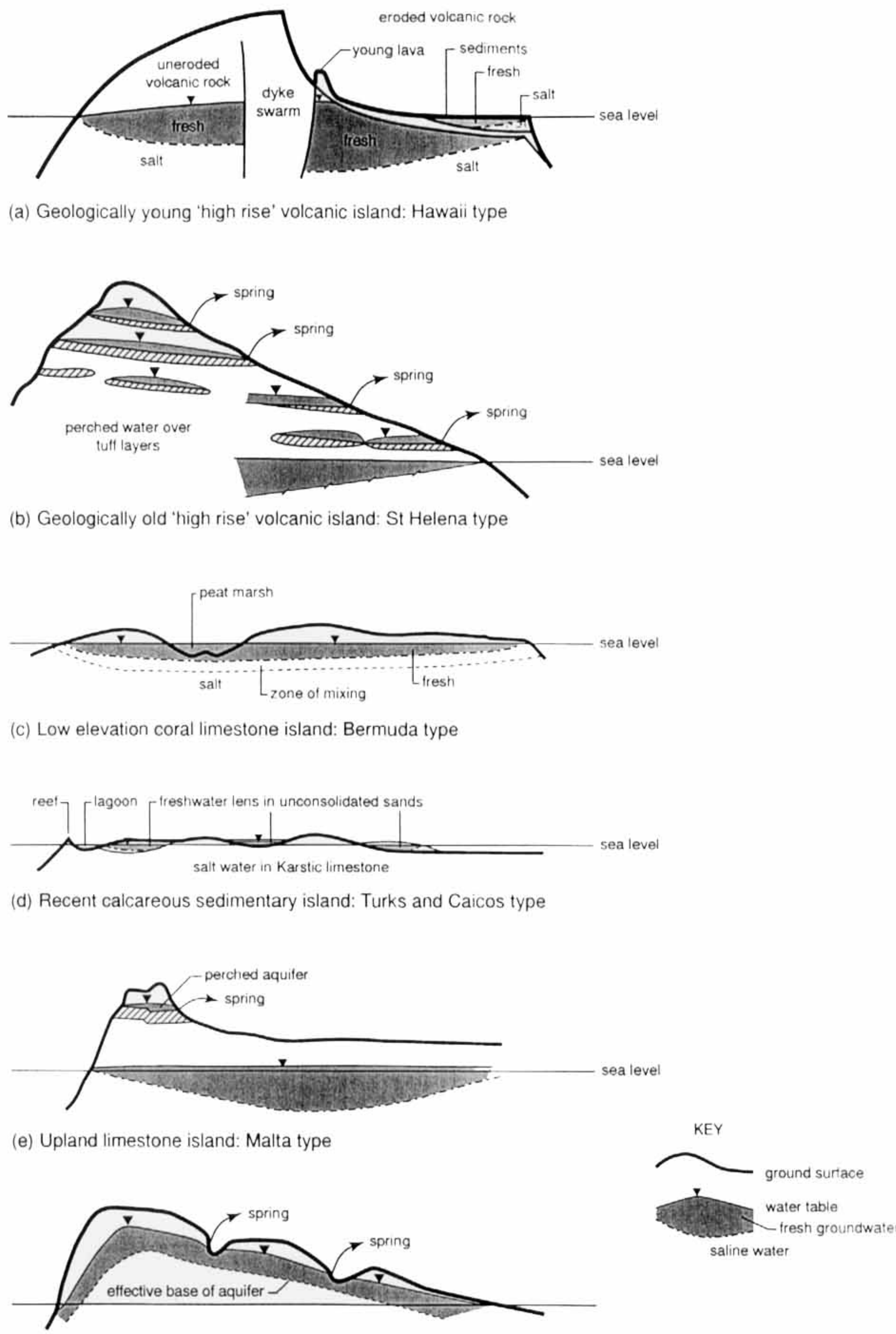

Fig. 1. Hydrogeological type relationships between island fresh groundwater and sea

Table 1. Key characteristics of islands (and their ability to meet 'normal' demand–problem areas are emboldened)

Island type	Recharge	Storage	Yield	Water quality	Examples
Geologically young 'high rise' volcanic island	Adequate	Adequate	Adequate	Adequate	Hawaii St Vincent
Geologically old 'high rise' volcanic island	Adequate	Possibly adequate	**Possibly inadequate**	Adequate	St Helena
Low elevation coral limestone island	**Possibly inadequate**	**Inadequate**	Adequate	**Possibly inadequate**	Many – Caribbean and Pacific, e.g. Bermuda
Recent calcareous sedimentary island	**Inadequate**	Possibly adequate	Adequate	Possibly adequate	Turcs and Caicos, Many – Pacific
Upland limestone island	Adequate	**Inadequate**	**Inadequate**	Adequate	Malta
Near-continental bedrock island	Possibly adequate	Possibly adequate	**Possibly inadequate**	Adequate	Jersey

and transmissivity. Higher transmissivity produces higher borehole yields, but also increases the hydraulic gradient, the thickness of the freshwater lens, and the quantity of groundwater discharge to the sea. Groundwater quality is normally related to sea-water intrusion and mixing, but may also relate to land-based pollution as is the case in Jersey and Guernsey.

Volcanic islands and low-lying karstic limestone islands are hydraulically complex, and aquifers may be thin and of limited areal extent. Islands comprising porous media (such as the calcareous sediments of the Turcs and Caicos) are, by contrast, relatively simple to evaluate. High-rise volcanic islands usually receive plentiful recharge and have good-quality groundwater. Younger volcanic islands may have substantial groundwater storage and transport, and offer useful sustainable borehole yields. However, these generalisations may fail if the geometry of the aquifer cannot be ascertained, especially where aquifers are perched perhaps at high elevations. Groundwater in young volcanic islands may also be subject to geothermal influences.

Observation and monitoring, coupled with the construction of a conceptual groundwater model, is a valuable means of checking generalised classifications. It is also an essential procedure towards developing a resource-management strategy. However, observation and monitoring are expensive, especially as factors of scale require the need for intensive data collection (more data per area or per volume of water required than in an equivalent mainland aquifer). This is because of the sensitivity of the island water balance and because discharge to the coast cannot readily be measured.

If small island water resources are to be effectively monitored and managed, sufficient resources need to be set aside, and this must have implications on water costs and charges. Failure to do so will result in poor understanding of water flow systems, and may lead to serious water resource and quality depletion, which is likely to be even more costly to rectify at a later date. The simple, first pass, classification can help to identify the groundwater regime and therefore likely problem areas to guide where resource monitoring needs to be targeted.

Table 2. Water-balance examples[2,10,13,14,15]

Island	Island type (see Fig. 1)	Mean annual average rainfall (mm)	Actual evapotranspiration (% of rainfall)	Groundwater recharge (% of rainfall)	Runoff (% of rainfall)
Malé	Bermuda	1900	56	42	2
Nauru, Pacific	Bermuda	2000	60	40	0
Guam, Mariana Islands	Bermuda/Malta	2200	62	38	0
Maui, Hawaii	Hawaii	2850	26	34	40
Nuie, Pacific	Bermuda	2050	69	31	0
Norfolk Island, Australia	Hawaii	1320	62	30	8
Bermuda	Bermuda	1450	73	27	0
Kiritimati, Kiribati, Pacific	Bermuda	847	75	25	0
Malta	Malta	500	70	24	6
Menorca, Spain	Malta	600	69	18	13
Santiago, Cape Verde	St Helena	250	50	17	33
Kahoolawe, Hawaii	Hawaii	767	70	10	20
Antigua, Caribbean	Hawaii/Malta	1100	90	2–10	0–8
Anguilla, Caribbean	Bermuda	1100	95	5	0
Jersey, Channel Islands	Jersey	877	60	5	35
St Croix, Caribbean	Bermuda/Turcs & Caicos	750	98	2	0
Zhoushan Islands, China	Jersey	1350	56	0	44

Groundwater/Sea-Water Interface

The Badon Ghyben-Herzberg approximation[6] defines the depth to the freshwater/salt-water interface beneath a coastal aquifer under static conditions. However, groundwater is not static and this simplified relationship is not reliable wherever significant vertical flow occurs. The fresh water and salt water may be separated by a brackish mixing zone in which the interface is defined by the isochlor describing a mixture of 50% sea water and 50% groundwater. The thickness of the mixing zone is a function of the physical agitation of tides and the pumping regime as well as the hydraulic character of the aquifer. Groundwater seeks a discharge area at the coast and flows from beneath the area of highest groundwater head (inland) upwards and outwards along the saline interface with the effect that the mixing zone is constantly flushed to brackish coastal and submarine springs. A strong horizontal discharge maintains the freshwater lens and tends to limit the development of the mixing zone which may be only a few metres thick. In the absence of a significant vertical groundwater flow component, the Badon Ghyben-Herzberg approximation provides a good estimate of the depth to the interface.

Climate change and the potential rise in sea level are critical to many low-lying islands. A 1 m rise in sea level would create an overall increase in the potentiometric head of 1 m throughout an island relative to a fixed datum. However, many islands are low-lying with a shallow water table, which could not universally accommodate a 1 m rise. The overall reduction in the area of a low-lying island will reduce recharge, and consequently also baseflow. According to Darcy's Law, this will, in turn, reduce the hydraulic gradient towards the coast, and the reduced head will cause a reduced depth to the saline interface. It is also possible that a rise in the water table could saturate any higher permeability near-surface weathered zone which would allow more rapid drainage to the coast, inhibiting the water table from rising by the full 1 m. Therefore a rise in sea level of 1 m would cause a reduction in the head of groundwater above the new sea level by some thickness less than 1 m, and the thickness of the freshwater lens would correspondingly be reduced. This might destroy many marginal lenses beneath small low elevation islands.

A small rise in sea level would turn many low-lying islands into potential wetlands. Elevation of the water table into the root zone or to open water would increase evaporation and reduce aquifer storage. In the Bahamas, for example, a 1 m rise in sea level would cause a rise in the top of the fresh-water lens, albeit of only a few centimetres; in addition, the most productive coastal zones of the aquifer would be lost.

The gradual arrival of brackish water in a near-shore well or borehole does not always signal the arrival of sea water because the salinity may arise from another source. However, brackish groundwaters containing sea water can easily be identified on a mixing diagram such as a Piper plot[7].

There are numerous reported examples of fresh-water lenses[8,9]; however, it is not possible to apply the Badon Ghyben-Herzberg approximation to all these examples. The island of Jersey serves to illustrate the problems of dealing with thin coastal aquifers. A small sand aquifer overlies weakly permeable basement rocks (Fig. 2), and attains a maximum thickness of 10 m. It is heavily pumped, with one wellfield until recently taking about 1500 m^3/d with drawdowns of 6.1–7.4 m but limited by the thickness of saturated sand. The catchment is modest in area but runoff is negligible with an effective annual rainfall of about 100 mm. There is a 10 m sea tide, yet no tidal effect is found in any of the boreholes. The saline interface is near vertical beneath the foreshore – its progression inland prevented by the thin nature of the aquifer and by the throughput of groundwater, despite intensive groundwater abstraction.

Fig. 2. Jersey sand aquifer

The limestone and young calcareous sedimentary islands of the Turcs and Caicos provide another example of the limitations of the Badon Ghyben-Herzberg approximation. Fresh water occurs in these low-lying islands as discontinuous lenses in the re-worked limestone (calcarenite) which rests on karstic limestone containing brackish to salt water. The combination of inherently low rainfall, high secondary permeability in the karstic limestone with the mixing influence of sea tides, preclude the application of the Badon Ghyben-Herzberg approximation.

Island Water Balance

The most compact island shape is a circle of radius r, and simple arithmetic shows that the ratio of the length of the coast to the area of a circular island is 2: r. Most islands, however, are irregular in shape and a more realistic ratio is 10: r to 100: r, such that the coastal influence remains important in 'small islands' with an irregular coastline.

Freshwater development on all low-lying islands is susceptible to the location of the groundwater/sea-water interface. Karstic limestone islands are the most delicate because they are both low-lying and may have discrete horizons of high permeability where conduit flow can take place between the coast and the interior. Anguilla, in the Lesser Antilles, for example, is a low-lying karst limestone island which supports a groundwater lens. At the centre of the island is the ultra-saline Cauls Pond, the elevation of which is just above mean sea level, and which is fed by brackish springs. The maximum elevation of the water table on the island is only 0.5–1.0 m above mean sea level, and the average island-wide transmissivity is about 30 m^2/d based on borehole data ranging from 10^{-1} to 10^3 m^2/d[10]. Hydraulic gradients are small and the depth to the saline interface is restricted by the high transmissive properties of the karstic aquifer. These circumstances require specialist management techniques for freshwater production, and these may include minimising pumping drawdowns and distributing the load across the aquifer, and the use of scavenger wells.

The salt-water interface is less critical in higher island situations in which the rock is less permeable and there is significant hydraulic gradient away from the coast. This is particularly the case where the coast is cliff-lined and the rocks are hard and indurated, and less likely to act as an aquifer. The base of the aquifer (for example, the base of weathering in Precambrian rocks of Jersey) may be situated above sea level and entirely secure from saline intrusion (Fig. 1). Not all cliff-lined islands have low permeability; the higher permeability volcanic rocks of Hawaii promote a proper saline interface around the coast of the islands.

Coastal discharge of groundwater from all islands occurs as submarine springs or diffuse flow of brackish water in the zone of mixing, which discharges in coastal areas. It may occur as seepage along the foreshore or as springs at the base of cliffs. In all cases, it is difficult to measure the flow directly and it is necessary to use indirect methods. Coastal discharge can be estimated by one of three methods[2]:

(i) Analogy to other similar islands;
(ii) Simple cross-sectional analysis of the coast by application of Darcy's Law, and the estimation of recharge to groundwater which would sustain groundwater throughput and the water table or freshwater lens; and
(iii) Island-wide modelling.

In all cases, a knowledge of groundwater recharge is essential to support and validate estimates of the water balance. This is because coastal discharge is the main unknown variable, and it cannot readily be measured, as it could be in a land-locked catchment. In the case of Anguilla, the three methods led to a variety of values for island-wide annual recharge. An analogy with other similar islands suggested 18 mm – a value supported by a chloride mass-balance calculation. Simple calculation combining the Dupuit assumption with Darcy's Law and the Badon Ghyben-Herzberg approximation for the freshwater lens suggested 71 mm. Modelling confirmed only that the value was between 20 and 70 mm – this conclusion being dependent on the same data that supported the earlier estimates[2].

In the case of Jersey, a high, hard-rock island, analogy with other islands and the French and British mainlands suggested a mean annual recharge of 60–100 mm. Simple calculation estimated that it should only be about 55 mm, and island-wide modelling was inconclusive[11]. A subsequent estimate based on three years' operation of an experimental catchment on the island indicated that a value normalised for the previous 25 years is about 100 mm/annum[12].

Data, however, are often inadequate to support a useful and validated model. An instrumented catchment, validated with soil-moisture profiling and real-time rainfall and runoff monitoring, may be required to support modelling, but these data are expensive to acquire. Accordingly, it is sufficient to rely on straightforward calculations and island-wide conceptual groundwater flow models rather than trying to force inadequate data into a digital model. Care must be taken over catchment monitoring and baseflow separation. Baseflow varies with groundwater storage in small catchments and reduces to zero in dry periods on semi-arid islands depending on the intensity and elapsed time since the last rains.

Some 'high-rise' islands possess a lowland coastal climate and an interior upland climate. Such is the case in St Kitts in the Caribbean, which has an interior highland characterised by tropical rainforest, but where the leeward coasts are semi-arid. Uneven orographic distribution is not uncommon: for example, from less than 2000 mm mean annual rainfall at the east and north-west coasts of Rarotonga in the Cook Islands, to greater than 4000 mm only 3 km inland, or from 20 to 400 mm on Kauai island, Hawaii – a circular island of about 6 km radius. The effective rainfall over some high-rise islands (such as St Helena) is complicated by the variability of the rainfall, and because low cloud or mist provides a significant contribution to the water balance.

Various water-balance estimates are presented in Table 2. There are two principal types: those islands which experience little if any surface water runoff (such as the Caribbean examples, some of the Pacific islands and Micronesia), and those where surface runoff accounts for part of the overall water balance. The examples are given in descending order of groundwater recharge and range from the very high recharge of the Polynesian islands to zero recharge on Zhoushan Island. The average annual recharge (expressed as a percentage of rainfall) is 18.5% for those islands which experience runoff and 26.5% for those that have little or ephemeral runoff. Groundwater recharge (expressed as a percentage of mean annual rainfall) varies from only 2% on St Croix up to 82% on one island in Micronesia.

Conclusions

1. The water balance is not easy to determine, particularly for small low-lying islands, due to the complex inter-relationship between fresh and saline water, and because monitoring of rainfall, runoff, groundwater chemistry, and groundwater levels may be inadequate.
2. Catchment scale complicates the reliable estimation of recharge and the safe renewable yield of a small island aquifer.
3. A broad classification of six types of small islands indicates the groundwater regimes and potential issues peculiar to the different island types.
4. High-rise volcanic islands generally possess fewer problems in terms of recharge, storage and yield, whereas low-lying karstic limestone islands are likely to involve problems of storage, recharge and management.
5. Average groundwater recharge normally lies in the range 20–25% of rainfall.

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