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Offshore fresh groundwater reserves as a global phenomenon

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The flow of terrestrial groundwater to the sea is an important natural component of the hydrological cycle. This process, however, does not explain the large volumes of low-salinity groundwater that are found below continental shelves. There is mounting evidence for the global occurrence of offshore fresh and brackish groundwater reserves. The potential use of these non-renewable reserves as a freshwater resource provides a clear incentive for future research. But the scope for continental shelf hydrogeology is broader and we envisage that it can contribute to the advancement of other scientific disciplines, in particular sedimentology and marine geochemistry.

Continental shelves are the submerged fringes of the continents and harbour important aquifers beneath the sea floor. Because the shelves are at present covered by sea water, hydrogeology — a scientific discipline with an almost exclusive focus on fresh terrestrial groundwater resources — has conventionally paid little attention to them[1]. But on a geological timescale, the realm of the terrestrial hydrological cycle has been expanding and contracting as coastlines migrated[2] with the falling and rising of global sea levels[3]. The exposure of the shelves reached its most recent maximum during the Last Glacial Maximum, from 26,500 to about 19,000 years ago[4]. Shelf areas that were exposed during sea-level low-stands were covered by freshwater lake and river systems[5,6], and were subject to the infiltration of atmospheric precipitation[2] (also called meteoric water) and glacial meltwater. This led to extensive emplacement and circulation of fresh groundwater.

Groundwater systems are slow to adapt to the reconfiguration of the hydrological conditions at Earth's surface[7–9], and therefore remnants of meteoric groundwater are likely to be found offshore. Now that it is becoming clear that anthropogenic and natural changes in continental water storage affect global sea level[10,11], and that the sequestration of fresh water below continental shelves contributed to the increase of ocean salinity during glacial periods[12], an appraisal of offshore groundwater as an element in global environmental change is warranted. Moreover, because continental shelf aquifers underlie areas that are in a continuous state of transition in response to global climate and sea level, offshore groundwater could hold important clues to the natural variability of the hydrological cycle over thousands of years, or even longer.

In this Review, we discuss overwhelming evidence that vast meteoric groundwater reserves (VMGRs) below the sea floor are a common global phenomenon and review the recent advances in our understanding of the key mechanisms that favour the emplacement, as well as the preservation, of VMGRs. The salinity within VMGRs can range between that of fresh water and that of sea water, and their delineation requires a practical definition. VMGRs are defined in this Review as a groundwater body with a minimum horizontal extent of 10 km, and a minimum concentration of total dissolved solids (TDS) less than $10\,\mathrm{g\,l^{-1}}$, which is about one-third of the salinity of sea water.

The selection of this salinity threshold is deliberate — it coincides with the upper limit of the salinity range used for the definition of brackish water in the area of water desalination[13]. Brackish water is increasingly seen as a resource for water supply[14,15] because the energy needs of reverse osmosis[16], and therefore costs of desalination, are decreasing. The widespread confirmation of the scale of offshore fresh and brackish groundwater reserves therefore provides opportunities for the relief of water scarcity in densely populated coastal regions. Offshore groundwater abstraction can help to mitigate the adverse effects of onshore pumping, such as land subsidence[17,18] and seawater intrusion[19,20]. This provides another important impetus to shift the boundaries of hydrogeology into the offshore domain.

Limits of modern coastal groundwater systems

It has long been known that the coastline does not form a boundary for coastal groundwater systems[14]. Sea water can intrude inland[19,20], and land-derived fresh groundwater may discharge through the sea floor through a process known as submarine groundwater discharge[21,22] (SGD). Myriad studies have highlighted the ubiquitous occurrence of SGD (for example, see ref. 23), but most SGD studies have focused on the near-shore environment[22,24], and we still need to understand the groundwater conditions and processes beneath the continental shelves further offshore[1,24].

Hydrological modelling studies[25,26] have shown that SGD can extend far beyond the coastline in aquifers that are separated from the sea by a confining layer of low permeability. Groundwater from the submarine aquifer discharges slowly by upward flow through the confining layer across extensive areas[22]. The Indian River Bay in Delaware[27] is a well-characterized example, where fresh water occurs up to 1 km offshore in a confined sandy aquifer. For carbonate aquifers (made up of limestone or dolomite) with dissolution-formed flow conduits, discharge in the form of submarine freshwater springs is a well-known phenomenon[22,23].

In the carbonate aquifer system along the eastern seaboard of Florida (Fig. 1), fresh water found in boreholes up to 100 km from the coast[28] (Fig. 2) has also been linked to high water table conditions that existed at the northern seaboard of Florida before the time of major groundwater exploitation[25], suggesting that SGD extends over a distance of 100 km or more. Observed pressures of sub-seafloor fresh waters — fresh water can rise up to 9 m above sea level in boreholes — are consistent[28] with this interpretation. However, the buoyancy of a large freshwater body surrounded by saline groundwater can also account for these observations. In other words, not all fresh groundwater below the sea floor is necessarily related to active SGD systems that originate onshore. This seems a likely

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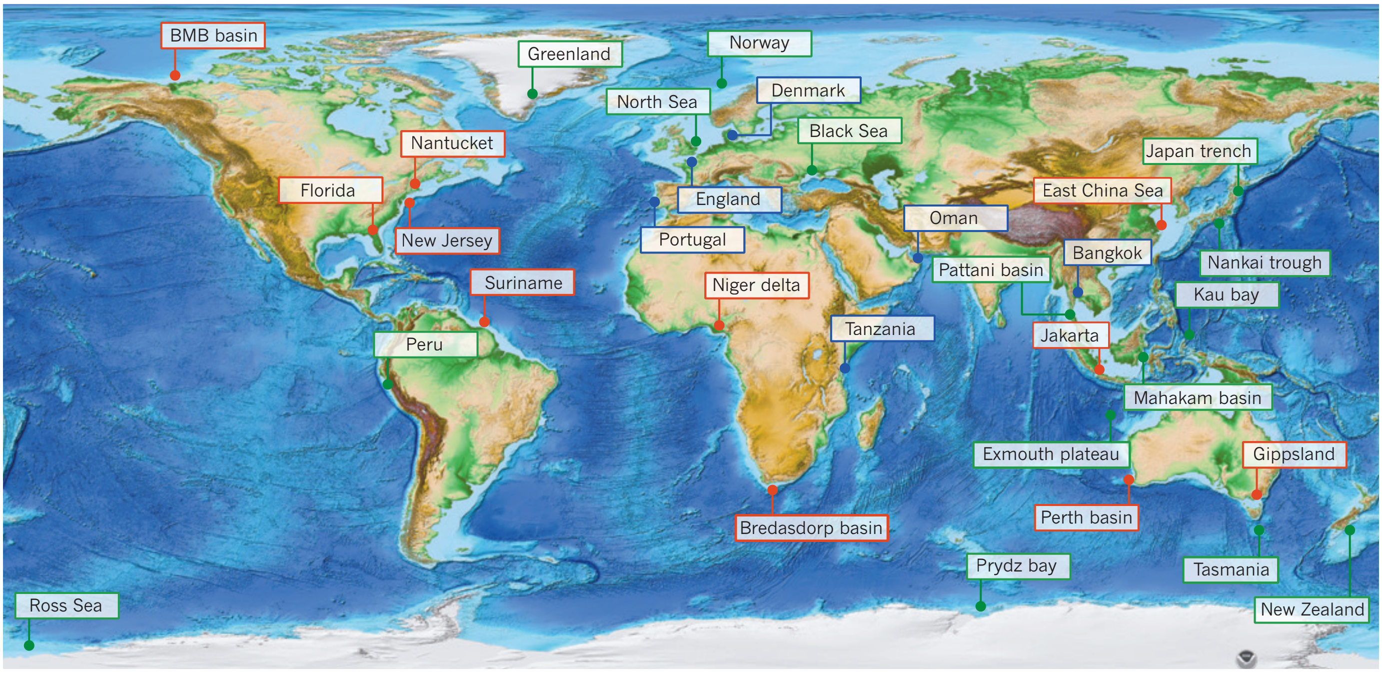

Figure 1 | World map of topography and bathymetry showing known occurrences of fresh and brackish offshore groundwater. Bathymetry from ref. 98. The occurrence of vast meteoric groundwater reserves (VMGRs) proven by direct observational data are shown in red. Offshore groundwater that is not necessarily fresh, but for which a freshwater mixing component has been inferred on the basis of pore-water composition is shown in green. Significant meteoric offshore groundwater with indirect evidence based on onshore palaeo-groundwater is shown in blue. Although no coordinates for the sample locations were provided, it seems probable that the Pattani sedimentary basin in Thailand[96] and the delta sediments of the Mahakam river in Indonesia[97] correspond to the definition of a VMGR that is used here. BMB, Beaufort-Mackenzie Basin

option because low-salinity groundwater has also been encountered in offshore areas in which active SGD is not possible (as indicated by an onshore water table that is too low to provide enough driving force[26] or by the absence of a hydraulic connection with an onshore recharge area[29]). Such low-salinity water occurrences must therefore be relics of flow systems that sequestered fresh water under different climate, morphology and sea-level conditions, and are referred to as palaeo-groundwater.

Global occurrences of offshore VMGRs

The best-documented example of an offshore palaeo-groundwater body is the vast occurrence of low-salinity water extending below the continental shelf of New Jersey[30–32] (Fig. 1). Groundwater with a salinity equal to about a quarter of seawater salinity was found up to 100 km offshore[32], and later drilling documented freshwater influences up to 130 km from the New Jersey coast[30] (Fig. 2 and Table 1). Salinity and pressure data from a deep borehole[29] and geophysical data on Nantucket Island, Massachusetts[33], as well as offshore salinity data[32] provide further indications for the extensive occurrence of low-salinity palaeo-water beneath the continental shelf of the north-eastern United States (Fig. 2 and Table 1).

Although the Atlantic seaboard of North America provided the first documented studies of offshore VMGRs, there is now ample evidence that VMGRs are a global phenomenon[34–41] (Fig. 1 and Table 1). Not all VMGRs seem to be connected to onshore aquifers[40,41], but it has been inferred that those that do are wedge-shaped, becoming thinner and more saline with increasing distance offshore[28,30,32,35–37] (Fig. 2). A conspicuous feature of the Suriname[35]; New Jersey[30]; Gippsland, Australia[36]; and Jakarta[37] VMGRs is that the transition from high salinities below the sea floor to low salinities in the wedge is narrower than the transition zone from fresh water to salt water at greater depth (Fig. 2).

Some studies have found that the distribution of low-salinity water within VMGRs is controlled by geological features, such as faults and low-permeability layers (for example, the Perth Basin[42]) or palaeo-channels (for example, East China Sea[40] or Bredasdorp Basin in South Africa[41]). These examples of implied structural and stratigraphic controls on VMGRs attest to the fact that salinity distributions of VMGRs can be complex and that pervasive, wedge-shaped interpretations[28,30,32,35–37] may be oversimplified. This is borne out by recent borehole data off New Jersey[31], which revealed a complex geometry of vertically alternating freshwater–saltwater intervals that are difficult to correlate at distances of about 10 km.

At various sites around the world, pore-water profiles in low-permeability layers that start just below the sea floor and show a consistent vertical salinity decrease have been documented (Fig. 1 and Table 1). These are found on continental shelves that were exposed during the last glacial period (in the North Sea[43], Peru[44] and New Zealand[45]), or where there used to be lakes when the sea level was lower (Black Sea[5] and Kau Bay, Indonesia[46]). At these locations, they are probably indicators of former meteoric water circulation.

Genesis

Modelling of selected cases has demonstrated that the location of the freshwater and saltwater transition zone is further offshore than would be expected on the basis of current sea-level and hydrological boundary conditions[8,26,29,34,47,48]. On the basis of this, and the overwhelming evidence from the field, the most ubiquitously proposed mechanism to explain the presence of fresh water is that it was emplaced during sea-level low-stands that occurred throughout the Pliocene and Pleistocene epoch[3]. The lower sea level is generally thought to have resulted in steeper water tables[2,49–51], thereby enhancing so-called topography-driven groundwater flow and meteoric recharge that occurs on exposed continental shelves (Fig. 3). This is corroborated by the finding that the volume of offshore fresh water seems to be inversely correlated with present-day sea depth[48], because shelf bathymetry controls the width of shelf exposure during seawater low-stands.

Favourable factors for freshwater emplacement have been inferred from observed salinity patterns and numerical modelling; these include groundwater flow along permeable faults[39] and the existence of distal aquifer outcrops, which allow for lateral groundwater flow rates that are relatively higher than in continental shelf aquifers encased in finer-grained deposits[48]. Some studies have found that a fall in sea level alone

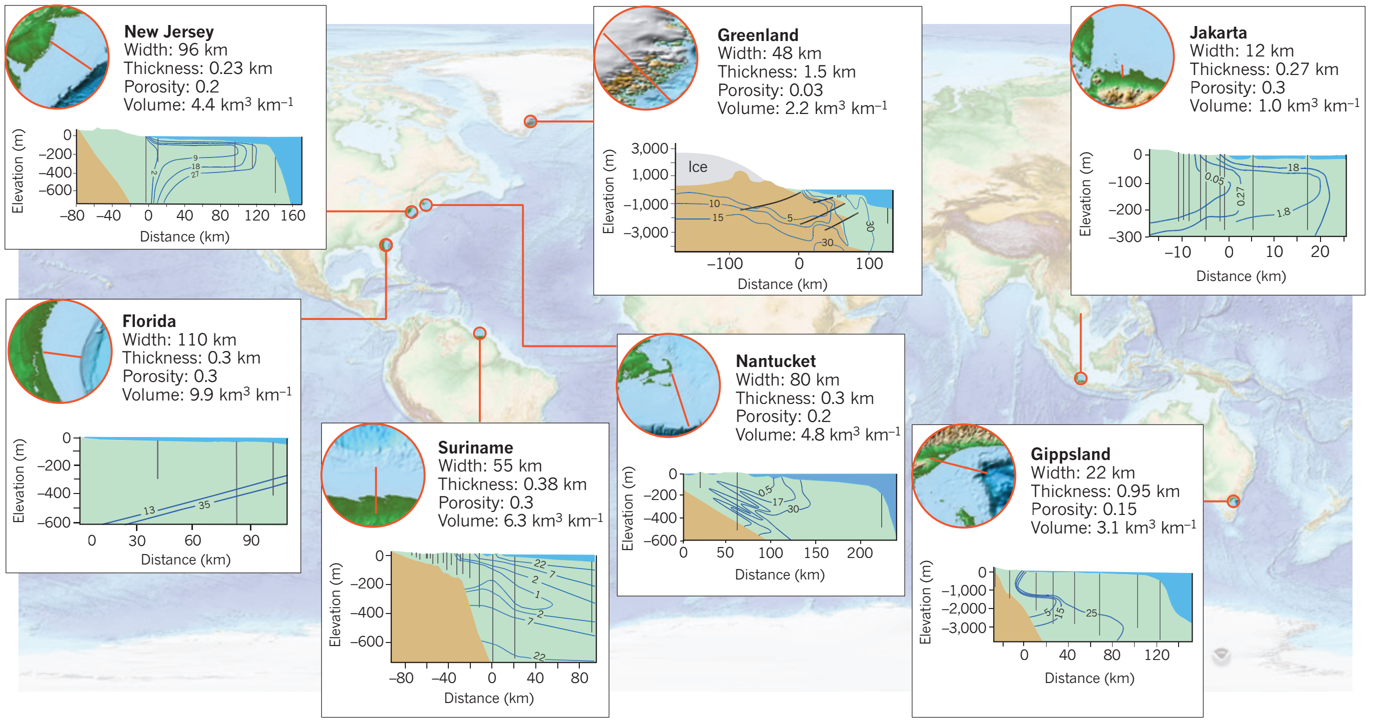

Figure 2 | Global overview of inferred key metrics and cross sections of well-characterised vast meteoric groundwater reserves. Data sourced from refs 28, 30, 32, 35–37, 48, 53. The location of each cross-section is indicated by a red line. In the cross-sections, the blue contour lines indicate total dissolved solid (TDS) concentrations ($g\,l^{-1}$); distance (km) and elevation (m) relative to mean sea level are indicated along the horizontal and vertical axis, respectively; vertical grey lines indicate well locations where salinity is inferred from water samples and borehole logs; crystalline bedrock or low-permeability sedimentary rocks containing salt groundwater are shown in brown; the black, sub-horizontal lines denote faults; undifferentiated continental shelf sediments are in pale green; and sea water is pale blue. Within the Nantucket and Greenland cross sections, salinity contours are based on numerical model results[48,53] and well data. The inferred widths, lengths and volumes per kilometre of coastline pertain to the groundwater with a TDS concentration less than $10\,g\,l^{-1}$ (Box 1).

was not sufficient to drive fresh groundwater to depths and the outward regions of the continental shelf where it is found today[29,34,48]. Incisions by rivers[34] (Fig. 3) and the existence of palaeo-valleys[7] are thought to have provided more localized relief and vigorous topography-driven groundwater flow systems that resulted in deep and extensive flushing of the shelf sediments. This hypothesis is supported by submerged geomorphological features such as spring-derived carbonate mounds[2] and groundwater-related erosion in submarine canyons[52], which testify to past groundwater discharge at continental shelves around the world[2].

At high latitudes, retreating ice sheets probably supplied additional fresh water to the continental shelf environment, a behaviour which has been inferred from numerical modelling[9,29,53], but also, for example, from the composition of groundwater 100 km offshore of southeastern Greenland[53]. The same mechanism could also explain the low pore-water salinity observed at sites off the coast of Antarctica (for example, the Ross Sea[54] and Prydz Bay[55]). The presence of proglacial lakes[33] has also been suggested to play a part in facilitating the emplacement of fresh water below the continental shelf of New England. Former freshwater lakes or inland seas have also been linked to fresh submarine groundwater in warmer regions, such as the Black Sea[5] and Indonesia[46].

The higher than freshwater density of saline groundwater (about 2.5% for sea water) would have impeded the freshening of continental shelf aquifers, because the density limits the depth to which fresh water can flush out saline groundwater. Moreover, it forces fresh water to flow upward along a sloping wedge of saline groundwater, thus reducing the effectiveness of freshwater flow to displace the saline groundwater. Systematic modelling studies of these processes and associated flushing timescales have so far not been published.

Shelf exposure during the last glacial maximum provided an area for terrestrial groundwater recharge that was larger than the area of the present-day land mass by around 10%[12], increasing the potential for recharge. But the propensity for replenishment by meteoric water strongly depended on local conditions of climate and vegetation. In southern Australia, recharge rates between 10,000–20,000 years ago have been inferred to be higher owing to cooler conditions and the concomitant lower evapotranspiration[50], whereas in southwestern Europe, the persistence of Atlantic air circulation resulted in continuity of recharge[56]. But recharge was much reduced in northern Africa owing to declining monsoon rains[56], and in northern Europe because of permafrost conditions[9,56].

Distinct pore-water salinity decreases have also been reported for very deep-water sites where the sea floor did not become dry during the Pliocene and Pleistocene[57–62]. In some cases, for example along convergent plate boundaries (for example, Peru[58], Nankai Trough[58] and the Japan Trench)[60] (Fig. 1 and Table 1), these can be related to water-releasing geochemical processes — such as the dissociation of gas hydrates[63], or the dehydration and transformation of hydrous minerals[58,60]. But in other cases major unresolved issues remain for which such internal water-producing processes cannot account for the observed decrease of pore-water chloride concentrations[58,60,62,63], especially where the distance to a land mass is so great that terrestrial groundwater input is highly improbable (for example, Norway[61], and Tasmania[62] and the Exmouth Plateau[57] in Australia; Fig. 1 and Table 1). Emplacement during as far back as the Miocene epoch has also been proposed for some occurrences[39,59], but it is questionable if preservation of low salinities over such long time frames is tenable[59].

Preservation

The amount of fresh groundwater sequestered in continental shelves during the last glacial period must have been higher than the volume that is found there today, because part of the fresh water was displaced and salinized by the flooding of the exposed shelves during the Holocene[12,29,32,48,64,65], when sea level rose to the present high level. Both

Table 1 | Key metrics of offshore meteoric groundwater occurrences

Location (reference)	Offshore distance (km)	Depth (km)	Minimum TDS ($g\,l^{-1}$)	Observation type	Number of offshore observations	Water depth (m)	Onshore connection
VMGRs							
BMB Basin[39]	<100	3–4.5	1.0	WS	>20	<60	Unclear
Bredasdorp Basin[41]	80–120	2–2.5	2	LOG	>30	100–120	No
Florida[28,32]	100	0.2–0.6	13	WS	3	<100	Yes
Gippsland[36]	70	1–4	5	LOG/WS	6	<100	Yes
Jakarta[37]	18	<0.3	0.3	WS	2	<10	Yes
Nantucket[29,33]	60	<0.6	0.1	WS	3	<100	Yes
New Jersey[30–32]	130	<0.6	1.5	WS	4	<100	Yes
Niger delta[38]	40	0.1–2	0.2	LOG	11	<100	Yes
Perth Basin[42]	50	1.3–4.0	5	LOG/WS	11	<100	Yes
East China Sea[40]	60–100	<0.2	1.0	WS	2	10–15	Unclear
Suriname[35]	90	<0.6	0.9	LOG	3	<50	Yes
Other offshore groundwater							
Black Sea[5]	95	<0.03	2	WS	1	350	Unclear
Exmouth Plateau[57]	225–300	0.85–1	28	WS	2	~1,500	Unclear
Greenland[53]	50	<0.25	26	WS	3	400– 450	Unclear
Kau Bay[46]	10	<0.01	27	WS	3	300– 450	Unclear
Mahakam Basin[97]	20	1–3	2	WS	27	<50	Unclear
Nankai Trough[58]	125	<1.3	29	WS	1	4,675	No
Japan Trench[60]	115	<1.2	19	WS	1	2,681	No
New Zealand[45]	42	<0.3	24	WS	1	84	Unclear
North Sea[43]	100	<0.006	16	WS	1	36	Unlikely
Norway[61]	300	<0.5	30	WS	2	1,300–1,450	Unlikely
Pattani Basin[96]	150–200	1.6–2.65	0.3	WS	20	50–70	Unclear
Peru shelf[44]	20	<0.01	13	WS	1	96	Unclear
Peru shelf[59]	65	<0.35	20	WS	1	460	Unclear
Peru deep[59]	200	<0.6	28	WS	3	3,000–5,000	No
Prydz Bay[55]	60	<0.224	31	WS	1	792	Unclear
Ross Sea[54]	350	<0.380	27	WS	2	619–633	Unclear
Tasmania[62]	70–550	0.2–0.95	28	WS	4	2,147–2,705	No
Onshore indicators							
Denmark[72]	NA	0.06–0.3	0.2	WS	NA	NA	NA
England[70]	NA	0.3–0.4	0.0	WS	NA	NA	NA
Oman[76]	NA	0.2–0.4	0.2	WS	NA	NA	NA
Portugal[71]	NA	~0.3	0.1	WS	NA	NA	NA
Tanzania[73]	NA	0.61	1.3	WS	NA	NA	NA

Depth is relative to the sea floor or land surface for offshore and onshore locations, respectively. Observation type indicates if salinities were inferred from geophysical borehole log data (LOG) or water samples (WS; obtained by either pumping or squeezing of pore water from sediments). When total dissolved solids (TDS) was not reported, it was estimated by multiplying the reported chloride concentration by 1.8 (the TDS/chloride ratio of seawater). Locations are shown in Fig. 1. NA, not applicable.

horizontal, landward migration of the freshwater and saltwater transition zone[8,47,65] and salinization by different modes of vertical, downward transport of salt from the sea floor[29,35,64,65] contributed to the reduction of the freshwater volumes. The upper limit of the driving force for landward migration of the freshwater and saltwater transition zone is controlled by the gradient of the continental shelf[65], and consequently transition zone migration rates are unlikely to have exceeded 10 km per 10 Kyr in high-permeability near-surface (or seafloor) aquifers[65]. Even lower rates are expected to have existed in deeper confined units[9,29,47,66]. Coastline migration, therefore, outpaced transition zone migration during various stages of the Holocene at most continental margins, carrying sea water on top of fresh groundwater, and causing downward salinization (Fig. 3). This is borne out by several cases in which sea water encroached on clay-rich or other low-permeability units, and in which downward salinization occurred by molecular diffusion[5,35,43,46,65] — a slow process in which a time period longer than the Holocene (11 Kyr) would have been required for salinity at a depth of 10 m beneath the sea floor to increase to around one-fifth of seawater salinity. Where the sea flooded more permeable strata, relatively fast downward salinization or seawater intrusion to the base of the seafloor aquifer must have taken place by convective mixing (Fig. 3), whereby dense saltwater plumes sink into the aquifer, displacing fresh water, rising up and discharging through the sea floor[64,65].

The importance of seafloor sediments in controlling vertical salinization during periods of sea-level rise is analogous to and exemplified by their role in SGD[21,22]. The occurrence of fresh groundwater below Indian River Bay, Delaware, for instance, was found to be restricted to areas where low-permeability sediments in palaeo-valleys limit the downward flow of sea water[27]. Conversely, offshore of North Carolina, palaeo-valleys that have cut through confining layers and are filled with permeable sediments were found to form pathways for seawater intrusion into freshwater aquifers[67]. Therefore, it seems very likely that shelf topography (large width and low gradient) and the presence of relatively thick, low-permeability strata at shallow depths beneath the sea floor played a key part in preserving fresh water by preventing major salinization during the Holocene[65]. However, the fact that low-permeability strata also tend to inhibit the emplacement of fresh water during periods of low sea level provides a conundrum that seems to point at asymmetry in the freshening and salinization parts of the glacial cycles. At glaciated margins such asymmetry may be caused by enhanced lateral freshening owing to ice-sheet influences[29,48,53]; in some other settings the fact that the major seafloor-confining unit formed during the Holocene and only inhibited the salinization phase[35] may explain this. However, in general, the integral glacial cycle response needs to be better understood. Recent high-resolution sampling has revealed a distinctly layered structure of salinity distribution of the New Jersey shelf — fresh water occurring preferentially in thick fine-grained layers[31] in which diffusion predominates — that may indicate that freshening existed for much longer periods of time than periods of salinization.

Although onshore water tables[25,26] and offshore salinity gradients[65] are thought to be the main factors that cause the redistribution of fresh and salt groundwater, other drivers of fluid migration in continental shelf aquifers are known to exist. The presence of high-density brines at relatively shallow depth below the New Jersey shelf[31] that probably formed by dissolution of salt layers at greater depth, attest to forces that drive fluid flow upward. Potential processes underlying these flows include fluid expulsion due to sediment compaction[68], and geothermal circulation[69] due to temperature differences.

Onshore indicators

Despite convincing indications for the widespread presence of offshore palaeo-groundwater, direct observations remain limited (Table 1). However, at many locations onshore hydrogeological and hydrochemical conditions add strong indirect evidence for the presence of fresh groundwater seaward of the coastline[49,51,70–76]. Radiocarbon dating of groundwater in the onshore part of the VMGRs in Suriname[34] and Jakarta[75] has shown that this water was recharged during the last glacial period. These time constraints are consistent with the inferred conditions that promoted formation of offshore VMGRs (a greater topographic driving force due to lower sea levels and a larger exposed shelf area)[2].

Fresh coastal groundwater dating back to the last glacial period has further been documented in Florida[49,74], Thailand[51], the United Kingdom[70], Denmark[72], Portugal[71], Oman[76] and Tanzania[17,73] (Fig. 1 and Table 1). Those studies that considered both tracer-based ages and hydrological modelling[9,50,51,72] confirmed that seaward groundwater flow rates were higher during the glacial period, suggesting that fresh groundwater was driven far beyond the present coastline. Thus, where the offshore geological conditions are conducive to preservation, for example where significant layers of marine clay are found at the sea floor, it can be considered likely that onshore palaeo-groundwater reserves extend under the sea[70,71].

Global volume of VMGRs

Two studies[12,48] have estimated global sub-seafloor freshwater volumes, albeit based on very different methods and for different periods. An estimate of 3×10^5 km^3 of fresh water (TDS < 1 g l^{-1}) was reported[48] based on a volume of 3.8 km^3 fresh water per kilometre of shelf length, as obtained from an interpretation of vertical salinity profiles from the eastern seaboard of the United States and Suriname, and an estimated global continental shelf length of 80,000 km. A much higher estimate of 4.5×10^6 km^3 has been suggested[12] as a possible explanation for elevated ocean salinity during the last glacial maximum that cannot be accounted for solely by the water stored in

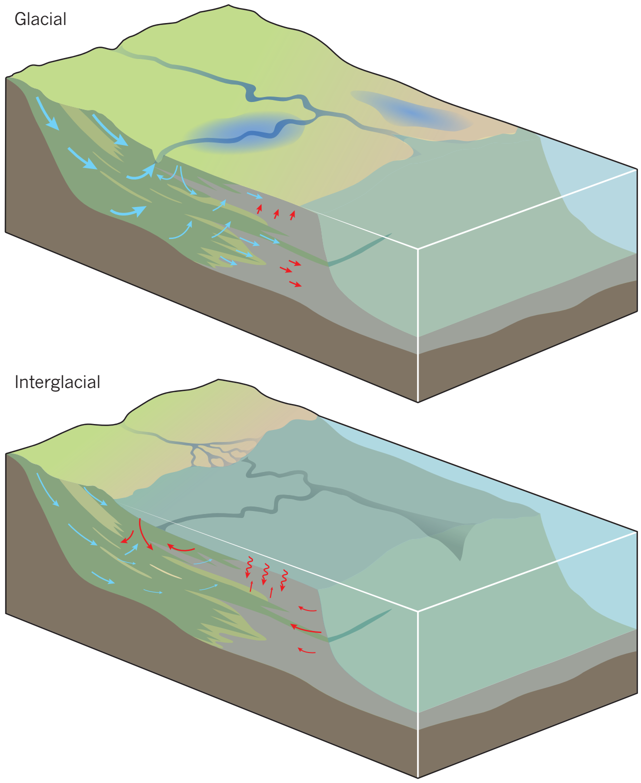

Figure 3 | The geology and the key groundwater flow, and dissolved salt transport processes below the continental shelf. Lower sea levels during glacial periods promote further penetration and recharge of groundwater below continental shelves, whereas incised rivers provide a driving force for topographic flow systems, and saline groundwater retreats seaward. When the shelves are flooded during interglacials, intruded seawater (red arrows) migrates landward as well as downward, while the flow of fresh water (blue arrows) stagnates.

continental ice sheets during that period. To accommodate this large freshwater volume, a continental shelf area corresponding to 5% of the modern ocean surface area would have had to have been flushed to a depth of 500 m with water of negligible salinity when a porosity of 50% is assumed[12]. The markedly higher volume estimate for the last glacial maximum compared with the present can partly be attributed to salinization of shelf groundwater by diffusion and density-driven vertical seawater intrusion[65] owing to sea-level rise. However, modelling has shown that for the massive salinization, implied by the difference between the two volumes, to occur the required timescales approach, or even exceed, the duration of interglacial periods[8,9,48]. Therefore, the estimate that 4.5×10^6 km^3 of fresh water was sequestered is probably too high, and alternative freshwater stores such as ice sheets need to be considered to be able to explain the observed higher ocean salinity[12] during the last glacial maximum.

Using observational data from Greenland[53], Jakarta Bay[37] and the Gippsland Basin[36] that were not included in the previous study[48], we estimate the present volume of continental shelf groundwater with a TDS concentration less than 10 g l^{-1} to be 5×10^5 km^3 (Fig. 2 and Box 1). The greatest uncertainty associated with this figure arises from the lack of observational data. There are vast shelf areas, for example the Sunda Shelf in southeast Asia, that were exposed during the last glacial period[6], but for which there are no groundwater salinity data. New discoveries in these areas could significantly alter the global volume calculations. Despite their very large uncertainty, the calculations show that the volume of fresh and brackish water stored in offshore aquifers may be two orders of magnitude greater than has been extracted globally from continental aquifers since 1900 (4,500 km^3)[10], and about one-tenth the global volume of shallow

BOX 1

Global volume of VMGRs

The global volume of brackish water (TDS <10 g l^{-1}) stored in offshore VMGRs was estimated by analysing seven shore-normal cross sections (Fig. 2), each of which had a relatively high observation data density so that salinity contour lines could be drawn manually and, for the Nantucket and Greenland cross-sections, derived partly from numerical model simulations. For each cross-section, the volume of brackish water per unit width of shoreline (Vf, km^3 km^{-1}) was calculated using:

$$Vf = b \times L \times \varphi$$

where b is the brackish water body's average thickness (km) over its shore-normal horizontal width L (km), and φ is the aquifer porosity, which was estimated from other studies[28,33,37,48,61,68,75]. For the complex geometry of the Nantucket cross-section, Vf was calculated as the sum of four individual sub-layers.

Adopted values for b and L, and calculated values of Vf for each cross-section are displayed in Fig. 2. Brackish-water volumes ranged from 1.0 to 9.9 km^3 km^{-1} between the cross-sections, with an average of about 4.5 km^3 km^{-1}. Multiplying this number by the total length of passive margins (105,000 km)[99] yielded a global volume estimate of 5×10^5 km^3. Adopting a threshold TDS concentration of less than 1 g l^{-1} yielded a volume of 3×10^5 km^3. These figures could vary up or down by a factor of about two, owing to the uncertainty of sediment porosity.

(less than 750 m) groundwater (4.2×10^6 km^3)[77]. These order-of-magnitude calculations suggest that passive margins may represent an important unconventional groundwater resource.

Exploitation

The exploitation of fresh groundwater resources has been pushed beyond sustainable limits in many coastal areas[19,20,78], driven by population pressures and increasing economic standards. Moreover, in many coastal cities groundwater extraction from coastal aquifers is inducing considerable and irreversible land subsidence, damaging infrastructure and increasing the incidence of riverine and coastal flooding[18]. With more than 40% of the global population within 100 km from the coast[79], the demand for fresh water will only become more acute in the coming decades, particularly in coastal megacities, and existing problems are likely to be compounded by sea-level rise[74] and severe drought[80]. Analogous to major inland agricultural areas in India, China and the United States, where current regional strategies are insufficient to address problems with groundwater depletion[81], new or complementary strategies for water provision and management are also required in coastal areas.

As offshore palaeo-groundwaters form on timescales of tens of thousands, if not hundreds of thousands, of years, their production should be considered to be a form of mining, with the same ethical dilemmas as the depletion of non-renewable onshore groundwater resources[82]. Nevertheless, where onshore resources become depleted, exploitation of offshore groundwater could become an option. At the same time, due consideration must be given to the broader spectrum of sustainable water management alternatives, including usage reductions and alternative water sources. Offshore groundwater is not the answer to global water crises, but it has a strategic value that should be acknowledged so that it can be weighed against other options in long-term strategies.

Driven by advances in reverse-osmosis technology, there has been a recent rapid growth of seawater desalination facilities[16] in many coastal regions to augment water supply. The economic feasibility of offshore meteoric groundwater exploitation is therefore best evaluated against seawater desalination. Desalination costs fluctuate with energy prices, but the costs to desalinate brackish water (TDS <10 g l^{-1}) sourced from VMGRs by reverse osmosis vary between US\$0.10 m^{-3} and \$1.00 m^{-3}, compared with \$0.53 m^{-3} and \$1.50 m^{-3} for sea water[13]. Offshore development necessitates additional infrastructural costs for sea-borne production sites, wells and submarine pipelines[17]. These additional investment and operational costs can become prohibitive from an economic perspective; but, if taken into account in the unit water cost, they remain below the higher operational costs for seawater desalination, and the use of offshore low-salinity groundwater may be feasible. If offshore groundwater can be recovered by onshore wells the economics are even more favourable. An example of such a facility already exists in Cape May, New Jersey[83], where drinking water has been produced by the desalination of water sourced from an aquifer with an offshore extension since 1998.

Apart from economics, environmental factors need to be considered when investigating the possible use of offshore fresh groundwater[17]. Large offshore groundwater abstraction for oil and gas production in Gippsland (Fig. 1), for instance, has seen a considerable drawdown of onshore water tables[36]. As with seawater desalination, the reject brine from the desalination process needs to be disposed of[13]. Although the use of offshore brackish groundwater has the advantage that the volumes and salinity of the brine are relatively low, disposal will still have an environmental impact. Moreover, the water quality characteristics of groundwater may cause precipitation of salts on the reverse-osmosis membranes, which necessitates the use of chemicals during the production process[13]. From the perspective of drinking water safety, the use of groundwater could mean that concentrations of individual elements such as radium or boron exceed permissible levels[15].

Greater awareness is needed of the adverse impacts of anthropogenic activities on offshore groundwater reserves. The potential of continental shelf aquifers for carbon-dioxide disposal[36,42] is being assessed. It is quite possible that degradation of offshore VMGRs is already occurring by contamination and enhanced salinization as a result of cross-formational flow along exploration drillholes and wells, or by fluid abstraction for petroleum production[36]. Moreover, in some areas, offshore groundwater is probably already used, albeit inadvertently, because pumping onshore and on islands draws in groundwater from the offshore parts of aquifers[8,20,28,32]. The low economic value of water may mean that this is perceived as being of secondary importance at present, but offshore groundwater could prove to be a resource of strategic importance when conventional water management scenarios in coastal areas are no longer adequate or sustainable.

Offshore hydrogeological frontiers

The numerous studies that testify to sub-sea, low-salinity groundwater published[35–42] since Hathaway and colleagues[32] found "anomalous fresh and brackish water" below the New Jersey continental shelf demonstrate that, rather than being an anomaly, low-salinity water below the sea floor is a common phenomenon. It is an expression of the non-stationary nature of the terrestrial hydrological cycle, which spanned a significantly greater surface area throughout much of the Quaternary period compared with the present day, and emphasizes the ever-evolving nature of coastal groundwater systems in response to the dynamics of sea level, landscapes and climate. It also means that addressing the concerns over pressures on coastal water resources, including the adverse effects of predicted sea-level rise[19,84], needs to be done with this long-term view in mind; considering future trends as deviations from a static, present-day equilibrium could lead to sub-optimal or even misguided management strategies.

Although the potential benefit of submarine groundwater may form the main impetus for future hydrogeological research of the offshore domain, a better knowledge of groundwater processes under continental shelves will also contribute to the advancement of other fields of research. At present, the links between continental shelf hydrogeology and sub-seafloor ecology and microbiology[85,86]; material budgets of the oceans, including those of radioisotopes to assess submarine groundwater discharge[22]; and seafloor geomorphology[2] are unclear. The role of groundwater discharge on exposed continental shelves has even been discussed within the context of the interpretation of the pre-Cambrian fossil record[87]. This places continental shelf hydrogeology at the nexus of other geoscientific disciplines, such as sedimentology, marine geochemistry and reservoir characterization. It is also likely that geochemical and isotopic signatures contained in offshore fresh waters will provide new palaeoclimatic proxies, consistent with such data found in onshore aquifers[49,88]. Continental shelf hydrogeology could even contribute to advancing our understanding of archaeology, because human settlement and migration patterns may be linked to fresh groundwater discharge zones on exposed continental shelves[89] in some areas of the world.

Perhaps most importantly from an economic perspective, the circulation of meteoric waters in continental shelf sediments has been found to have an important role in the evolution of sedimentary basins[90,91] and is key to our understanding of the migration of the oil and gas entrapped in them[36,41,85]. Improved models of the response of groundwater systems to sea-level variations, as well as the length and timescales associated with meteoric water circulation, can place better constraints on past fluid migration histories.

Although this Review has consolidated evidence for the global occurrence of VMGRs, a paucity of data remains. A wealth of geophysical borehole log data from the hydrocarbon industry probably exists that may still be exploited to better constrain known offshore freshwater occurrences and to reveal numerous unknown ones. Study of these data is both complex and time consuming because of dispersed ownership, data confidentiality and that often most industry borehole measurements only start below the depth at which low-salinity groundwater resources can be expected[72]. New geophysical methods developed for petroleum exploration[92] also hold great promise for identifying offshore fresh water in continental shelf environments[93].

Geophysical methods are of great value but are limited in the sense that they only provide constraints on salinity. More comprehensive data are essential to allow the testing of hypotheses regarding emplacment and preservation. Notably, so far, offshore equivalents of existing onshore studies of noble gases and isotopic tracers[49,88] have not been carried out, but are much needed to determine the timing and duration of VMGR formation. Improved offshore drilling methods by the International Ocean Discovery Program (formally the Integrated Ocean Drilling Program) have led to better sediment and fluid recovery, allowing detailed profiles of pore-water chemistry[94] and bringing such studies within reach. Moreover, petrographic and isotopic analysis of diagenetic minerals, which are routinely applied in petroleum reservoir studies to understand fluid migration patterns[95–97], have not seen much uptake by the hydrogeological research community, but could be vital to strengthen interpretations about past groundwater flow conditions.

Conversely, hydrogeological studies of present-day groundwater systems could be useful analogues for understanding the relict flow conditions in offshore sedimentary basins, and the preservation potential of offshore freshwater occurrences. This includes onshore areas where vertical seawater intrusion led to aquifer salinization when the coastline was located further inland earlier during the present interglacial period than today[64]. Furthermore, the interpretation of fluid pressures and submarine pore-water chemistries can be aided by numerical modelling of regional-scale groundwater flow[9,29,48,53], a technique routinely applied in onshore hydrogeology. From this, it seems clear that scientific advancements can be made when hydrogeologists step across the boundaries of their discipline and team up with other scientists to explore the hidden depths of the continental shelves. ■

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