were previously occupied by fresh ground water causes desorption of divalent metals. Thus, the total SGWD flux estimated by Moore[2] necessarily includes a substantial marine component. From the estimate of SGWD given above, however, the most dilute mixture emanating from the mixing zone would still comprise more than 90% sea water. This implies either that the total SGWD flux estimated by Moore is too high, or that the bulk of the total SGWD is indeed of marine origin. If the latter is the case, then Moore's deduction that SGWD is the equivalent of 40% of river flow arises from a failure to compare like with like. In other words, the SGWD entering the South Atlantic Bight is unremarkable, and would not in itself prompt a reappraisal of the oceanic chemical mass balance, or of water resources engineering practice.

Turning to my second point, that of the width of the zone of SGWD: using inverse deduction from the spatial distribution of ^{226}Ra in the near-shore waters of the South Atlantic Bight, Moore infers that the zone of total SGWD extends up to 20 km out to sea. How does this estimate compare with independent evaluations based on groundwater flow around fresh–saline water interfaces?

Density-dependent flow has been analysed for more than a century using simplified analytical solutions[3,5], and more realistic solutions are increasingly being obtained by numerical methods[6]. Such studies demonstrate that the distance (D_{SGWD}) out to sea over which SGWD generally persists can be expressed (for the case of a homogeneous aquifer at steady-state)[3] as; $D_{SGWD} = (20q') / K$, where q' is SGWD per unit width of coastline and K is aquifer hydraulic conductivity (permeability with respect to water).

Scoping calculations show that, for the overwhelming majority of cases, D_{SGWD} will never exceed a few hundred metres. In the case of the South Atlantic Bight, we can estimate the likely maximum value of D_{SGWD} by combining a minimum estimate of local hydraulic conductivity[4] (10 m per day) with an upper-bound q' value (93,750 $\mathrm{l\ d^{-1}\ m^{-1}}$, obtained by dividing Moore's value of $3 \times 10^{10}\ \mathrm{l\ d^{-1}}$ by 320 km). This yields a maximum estimate for D_{SGWD} of 188 m. Although this agrees well with direct observations of D_{SGWD} elsewhere on the eastern seaboard of the United States[7], it is two orders of magnitude smaller than the 20 km suggested by Moore.

Whatever the width of the zone of SGWD, it is necessary also to consider the likely width of the zone of fresh–saline water mixing which separates the terrestrial and marine ground waters. Direct observations of such zones reveal that they are typically a few metres wide, and seldom exceed a few hundred metres[7]. Consequently, D_{SGWD} probably underestimates the width of the zone of total SGWD by a very small margin. In other words, it is physically unreasonable to postulate a mixing zone of 19,812 m extending seawards from a 188-m zone of SGWD to make a total SGWD discharge belt 20 km wide, as proposed by Moore.

Paul L. Younger
Department of Civil Engineering,
University of Newcastle,
Newcastle Upon Tyne NE1 7RU, UK

1. Moore, W. S. *Nature* **380**, 612–614 (1996).
2. Church, T. M. *Nature* **380**, 579–580 (1996).
3. Fetter, C. W. *Applied Hydrogeology* (Macmillan, London, 1994).
4. Back, W., Rosenshein, J. S. & Seaber, P. R. (eds) *Hydrogeology. Geology of North America* Volume 0-2 (Geol. Soc. Am., Boulder, 1988).
5. Ghybens W. B. *Tijdschrift van Let Koninklijk* (Inst. van Ing. Amsterdam, 1888).
6. Aliewi, A. S. thesis, Univ. Newcastle (1993).
7. Kohout, F. A. *J. geophys. Res.* **65**, 2133–2141 (1960).

MOORE AND CHURCH REPLY — Younger questions whether there is adequate terrestrial groundwater recharge to sustain significant fluxes of fresh ground water to the ocean. He argues that almost all of the recharge is captured by streams and little remains to discharge to the ocean. The reference he cites[1] for infiltration of 180–250 mm per yr states that these estimates are derived from an analysis of the base flow component of stream flow. In other words, if almost all the infiltration is captured by streams, 180–250 mm per yr are required to maintain stream flow at observed levels. Because the streams are assumed to capture almost all the infiltration, this assumption drives the infiltration models in a circular argument.

We question this assumption and maintain that there is ample uncertainty in estimates of water balance and associated below-ground inventories to allow significant fresh groundwater fluxes to enter the ocean. Younger should also be aware that the catchment area of the major rivers draining into the South Atlantic Bight is controlled by the Appalachian divide and is only about a factor of three larger than the catchment area of the coastal aquifers, not several orders of magnitude as he estimates.

The answer to this question also depends on your viewpoint. To a terrestrial hydrologist, an annual toss of a few per cent of fresh ground water to the ocean may seem trivial. But, to a chemical oceanographer, discharge of this amount of fresh water with larger volumes of salty submarine ground water (SGWD) may cause a re-evaluation of chemical inputs to the ocean[2]. Therefore, we must take issue with Younger's opinions that even if SGWD is largely of marine origin, its input to the ocean is "unremarkable". The SGWD has chemical characteristics remarkably different from fresh groundwater or ocean water[3] The material flux to the ocean derived from SGWD is the product of its volume times the difference in concentration from ocean water.

If SGWD to the South Carolina coast is of the order of $3 \times 10^{10}\ \mathrm{l\ d^{-1}}$ (ref. 3), it must contain about 100 times more ^{226}Ra than surface ocean water; if the flow is only 10% of that estimated, the ^{226}Ra enrichment must be a factor of 1,000, much higher than we have measured[4]. Flow of large volumes of this chemically altered water may have an enormous impact on coastal ocean chemistry and productivity[2]. As we and others have shown[3–6], SGWD also carries high concentrations of Ba, P, N, Mn, Fe, Cu, Zn, Cd, Pb and Ni. The power of the Ra tracer in quantifying the regional effect of SGWD lies in the conservative behaviour of ^{226}Ra once it is injected into the coastal ocean. Thus, ^{226}Ra fluxes offshore should serve as a proxy for inputs of other elements via SGWD.

Younger's second point concerns the width of the zone of SGWD The input width of 20 km was chosen to correspond to a strong pycnocline (density gradient in the water column) during the period of investigation[3]. Input of ^{226}Ra below the pycnocline from SGWD further off shore was not considered in the mass balance. Simmons[4] measured substantial fluxes (2–20 $\mathrm{l\ m^{-2}\ d^{-1}}$) of SGWD at sites 15–37 km from the South Carolina coast. He also measured fluxes of ocean water into the sediments in this area. We have recently found large ^{226}Ra enrichments at a site 60 km from shore. Drilling has confirmed the presence of brackish water beneath the continental shelf all along the east coast of the United States[7,8]. Clearly, SGWD is occurring throughout the continental shelf, not just from the inner 0.2 km as Younger calculates. When we quantify SGWD from these deeper sites, its impact on the coastal ocean will have to be revised upward.

The challenge to hydrologists is to develop SGWD models that include tidal pumping due to diurnal, monthly, seasonal or longer changes of sea level; saltwater intrusion and changes in groundwater usage; mixing and chemical reactions within coastal aquifers; and the expulsion of a saline end-member.

Willard S. Moore
Department of Geological Sciences
University of South Carolina
Columbia, South Carolina 29208, USA
Thomas M. Church
College of Marine Studies
University of Delaware
Newark, Delaware 19716, USA

1. Back, W., Rosenshein, J. S. & Seaber, P. R. (eds) *Hydrogeology. Geology of North America* Volume 0-2. (Geol. Soc. Am., Boulder, !988).
2. Church, T. M. *Nature* **380**, 579–580 (1996)
3. Moore, W. S. *Nature* **380**, 612–614 (1996).
4. Simmons, G. M. *Mar. Ecol. Prog. Ser.* **84**, 173–184 (1992).
5. Shaw, T. J. *et al. EOS* **76**, F318 (1995).
6. Krest J. M. & Moore W. S. *EOS* **77**, 5153 (1996).
7. Hathaway, J. C. *et al. Science* **206**, 515–527 (1979).
8. Manheim, F. T. *Trans. N. Y. Acad. Sci.* **2**, 839–853 (1967).