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WATER RESOURCES AND THE REGIME OF WATER BODIES

Estimation of Submarine Groundwater Discharge

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Abstract—Leading methods for the evaluation of submarine groundwater discharge are presented, and their possible application under different hydrogeological conditions is discussed.

INTRODUCTION

Studying the submarine groundwater discharge, which bypasses river networks, is a part of a complex hydrological and hydrogeological problem in studying subsurface water exchange between land and ocean [2–4, 6, 7, 22, 24]. The groundwater that forms on land and discharges in the coastal zone of seas often have a significant effect on the hydrochemical, thermal, and hydrobiological regimes of seawater in the coastal zone. Submarine groundwater discharge and its associated chemical fluxes in coastal karst aquifers may be larger than those associated with river discharge, in particular during low stream flow [14]. Thus, the interest in developing methods to estimate submarine groundwater discharge accurately [15]. Its estimation, however, poses unique challenges because it often involves the deployment of measurement equipment in coastal waters as well as on land. The highly dynamic nature of groundwater/seawater interactions in the coastal zone hampers the accurate quantification of submarine groundwater discharge [6, 9, 13]. The evaluation of submarine groundwater discharge by hydrodynamic methods, including modeling, is often limited by the lack or insufficient reliability of the available estimates of hydrogeological parameters.

THE COASTAL ZONE ENVIRONMENT

Figure 1 shows a schematic cross section of the coastal zone and surrounding terrestrial and marine environments. Shown there are the water fluxes that are important in the coastal zone, where submarine groundwater discharge takes place. The coastal zone extends from the lowland region bordering the coastline to the end of the continental shelf. It includes estuaries and the inter-tidal zone, and, in spite of its overall worldwide small size compared to the continental area, it plays a disproportionately important role from ecological and economic standpoints. Its importance is highlighted by the discharge of human waste and the natural export of terrestrial sediments and nutrients to it, by the abundance of fisheries within it, by its rich biodiversity, and by the concentration of human enclaves in it [16].

THE CURRENT STATE OF THE PROBLEM

Submarine groundwater discharge into the seas is the least studied component of the existing and anticipated water and salt balance of seas, especially their coastal zones. However, the water balance of individual seas and oceans cannot be completed unless data on the groundwater runoff are available. A number of important questions are to be answered: what is the volume of submarine discharge; has it any effect on the water and salt balance of the sea and the hydrological, hydrochemical, and temperature regime in the coastal zone; what changes will be caused in the future groundwater discharge by the anticipated climate changes and an increase in the anthropogenic load on the coastal zone; and to what extent the groundwater component should be taken into account in studying and predicting the water and heat balance of seas?

It should be emphasized that the methodology and practical role of studying submarine groundwater discharge have no principal difference from groundwater discharge into large lakes (the so-called subaqual groundwater discharge); therefore, all the information in this paper is applicable to lakes as well [21].

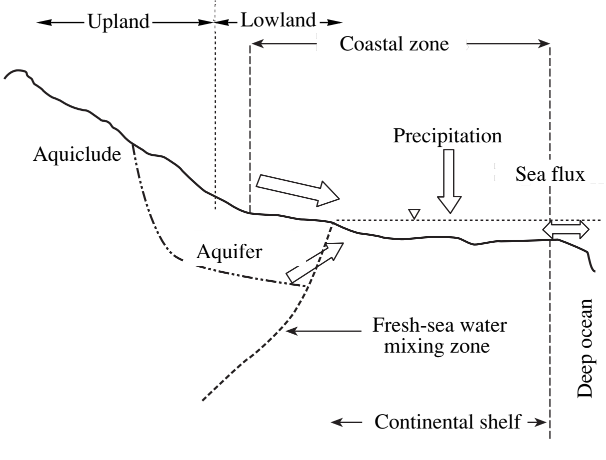

Fig. 1. Schematic cross-section of the coastal zone, q is submarine groundwater discharge.

A number of hydrogeological problems is known to require studying submarine groundwater discharge. Many water intakes developing groundwater are located in the coastal zone, and the conditions of their operation are to a great extent dependent on the character of interaction between groundwater and seawater, which eventually determines the optimal discharge rate of such water intakes. Active operation of water intakes affects water exchange in the sea–groundwater system. An important problem in this case is evaluating the position of the fresh groundwater–salt seawater interface and therefore predicting the quality of groundwater intakes in coastal zones.

Submarine groundwater discharge is a characteristic of groundwater resources. The deficiency of fresh water with appropriate quality in coastal zones can be often reduced or even eliminated at the expense of the development of groundwater, which now uselessly discharges into the sea. Some countries have already accumulated positive experience in the development of large submarine sources discharging into the sea near the shore, as well as experience in the development of wells drilled on the shelf and tapping fresh groundwater for water supply to populated localities in the coastal zone.

Submarine groundwater discharge takes place in the form of concentrated release through dislocations and in the zones of occurrence of fissured and karstic rocks, as well as in the form of diffuse leakage through a low-permeability aquifer top and marine bottom deposits. The leakage processes can control the groundwater dynamics in a large artesian basin as a whole or its large part and play significant and even key role in the submarine discharge of such waters.

Considerable experience in the quantitative assessment of groundwater runoff into closed and marginal seas, large lakes, and oceans has been accumulated [2, 3, 23].

It should be emphasized that the World Map of Hydrogeological Conditions and Groundwater Flow (scale 1 : 10 000 000), compiled by an international group of experts in accordance with the UNESCO International Hydrological Program [20], for the first time presents the characteristics of submarine groundwater runoff into the seas and World Ocean.

The role of groundwater in the water and salt balance of seas and oceans is analyzed with different details depending primarily on the aim of the specific study, the size of the coastal area under study, and, what is most important, on the available hydrological and hydrogeological data. A common and principally important feature of all these studies is the use of direct methods of hydrogeological and hydrological calculations, which do not depend on the accuracy of evaluation of precipitation, evaporation, and river runoff.

The authors of these paper do not mean to consider the experience of studying submarine groundwater discharge reflected in numerous publications and just mention that sufficiently detailed studies of it, including quantitative estimates, have been made for the Caspian and Aral seas; the southern coast of France; some areas in the coastal zone of the Mediterranean Sea; individual areas in the Atlantic coast of the USA, Japan, and Australia; in lakes Ontario, Utah, and Michigan (USA), Baikal (Russia), Issyk-Kul (Kirgizia), Balkhash (Kazakhstan), Taupo (New Zealand), and others.

Any study or quantitative estimate of submarine groundwater discharge is based on reliable methods of investigation, which allow one to establish the sites of submarine groundwater discharge and evaluate its rate. These methods can be divided into two groups: methods based on the quantitative analysis of the formation conditions of groundwater runoff into the sea within a watershed, first of all in the coastal zone, and methods of marine hydrogeological studies based on direct examination of the sea areas [1, 22].

The methods based on the examination of sea-side watersheds include the analysis of the geological and hydrogeological conditions in the coastal part of the sea and incorporate hydrodynamic calculations of flow rates (analytically or through simulation), comprehensive hydrological–hydrogeological method, and the method of normal annual water balance for groundwater recharge zones. These methods, which are based on the results of studying groundwater flows, form the basis for direct quantitative estimation of groundwater discharge into the sea within that part of the geological section, the hydrogeological characteristics of which are available.

The second group of methods includes a large number of visual, aerospace, geophysical, geochemical, and other studies of anomalies in the seawater and bottom sediment that are brought about by the submarine groundwater discharge (anomalies in the temperature and chemistry of seawater, the composition and properties of bottom deposits, the gas, chemical, and isotopic composition of the near-bed layer and the coastal part of the sea, and so on). These methods allow one to distinguish and characterize at a qualitative level the zones of submarine groundwater discharge and, in some cases, yield reliable estimates of the submarine groundwater discharge that causes such anomalies. This group of methods, which are often referred to as marine hydrogeological studies, includes direct measurements of groundwater flow through bottom sediments in the coastal zone made using special instruments.

WATER BALANCE

This method is used to estimate long-term average annual submarine discharge. Let P, E, Q, and G be precipitation, evapotranspiration, surface runoff (the sum of streamflow, overland flow, and interflow) and submarine discharge, respectively, in a coastal basin of area A. All the previous fluxes are long-term annual averages, expressed in units of length per unit area of basin. In the absence of human intervention to increase storage in the basin, water balance dictates the following relationship:

$$G = P - E - Q. \qquad (1)$$

Thus, independent measurements or estimates of the fluxes in the right-hand side of equation (1) produce an estimate of the long-term average submarine discharge. The average annual volume of submarine discharge is then $q = G\,A$. It is assumed that the basin area A is the same for surface and subsurface water storage and flow, an acceptable approximation (although there are occasional exceptions) [18].

The water balance method yields reliable results when (i) the annual average fluxes that enter in its calculation are accurately determined based on long-term data, and (ii) the submarine discharge is substantially larger than (and therefore discernible from) the measurement errors inherent in E, P, and Q (at least two or three times larger). The United States Geological Survey rates as “very good” those measurements of hydrologic fluxes that are within ±5% of their true (but unknown) values. It is not uncommon for those measurements, however, to be only ±10% (or less) accurate. This implies that for an estimate of submarine discharge to have any degree of statistical confidence it would have to be distinctively larger than the errors inherent in measuring E, P, and Q. Recent studies have shown that submarine discharge is less than 10% of average annual streamflow in most coastal aquifers of the world. Considering also the poor accuracy of measurements and even poorer accuracy of evaporation estimates, we can conclude that the water balance method has a very limited application. It can be used mainly for studying coastal zones with a wide occurrence of karst, where the submarine groundwater discharge is comparable with other components of water balance.

FLOW NETS

Flow nets are widely used to analyze regional flow problems in a variety of hydrogeologic settings. It is a simple, yet, potentially effective, method to obtain preliminary estimates of runoff. Figure 2 depicts the elements that enter the flow-net approach.

The total submarine groundwater discharge to the ocean ($q = q_1 + q_2 + q_3 + q_4$, in Fig. 2) is given by the flow-net equation:

$$q = Kp\Delta hb/n, \qquad (2)$$

in which K, m/day, is hydraulic conductivity, p is the number of streamtubes in the flow net ($p = 4$ in Fig. 2), Δh is the change in hydraulic head between the two boundary equipotential contours $\Delta h = 6 - 0 = 6$ m in Fig. 2); b is the thickness of the coastal aquifer perpendicular to the plane of Fig. 2; and n is the number of equipotential head drops in the flow net ($n = 3$ in Fig. 2: between 6 m and 4 m, 4 m and 2 m, and 2 m and 0 m). Assuming that $b = 10$ m and $K = 1$ m/day, the submarine discharge would be $q = 80$ m^3/day. That is the total discharge integrated along the coastal zone of sea–aquifer hydraulic exchange.

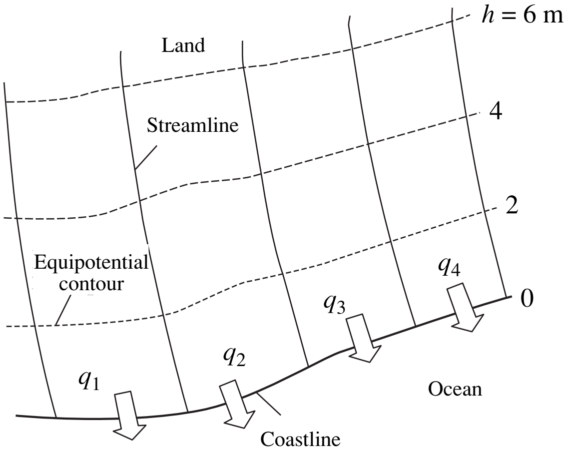

Fig. 2. Plan view of a flow net in the coastal zone.

The construction of the coastal flow net requires groundwater level data. A common problem is the area averaging of the estimated hydrogeological parameters, which is directly related to the accuracy of averaging the submarine groundwater discharge. In addition, the flow-net equation (2) is based on simplifying hydrogeologic assumptions that may be too restrictive in many coastal zones (e.g., the assumption of homogeneous/isotropic hydraulic conductivity). It also assumes steady-state submarine discharge.

NUMERICAL SIMULATION

This method is based on a solution of the 3-dimensional equation of groundwater flow (it may also be applied to regional—two-dimensional flow), which is given by the following expression:

$$\left(\partial K\frac{\partial h}{\partial x}\right)/\partial x + \left(\partial K\frac{\partial h}{\partial y}\right)/\partial y + \left(\partial K\frac{\partial h}{\partial z}\right)/\partial z \pm N = S\frac{\partial h}{\partial t}, \qquad (3)$$

in which K, m/day, is hydraulic conductivity; h, m, is hydraulic head; N is external water input or output (such as groundwater pumping); S is the storage coefficient (dimensionless); x, y, z are Cartesian orthogonal coordinates; and t is the time, independent variable. Equation (3) is supplemented by initial hydraulic head conditions and boundary conditions that render it a well-defined problem. Typical boundary conditions are no-flow values at the bottom and lateral sides of the aquifer and a constant-head value in the freshwater/seawater mixing zone (see Fig. 1). If solved as a steady-state problem, its right-hand side term is equal to zero. Equation (3) is discretized and expressed in finite-difference form using a stable solution algorithm [19].

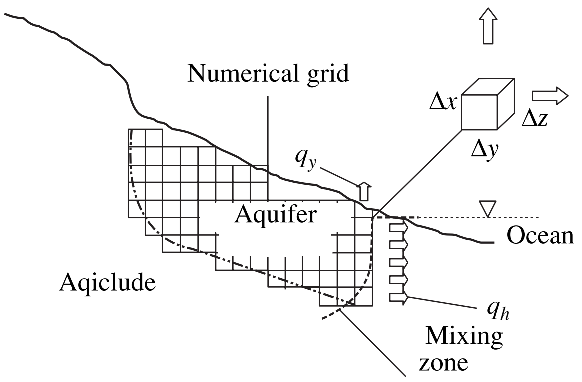

Fig. 3. Cross-sectional view of a finite-difference grid to simulate coastal groundwater flow.

Figure 3 shows a typical cross-section of a finite-difference grid in a coastal aquifer.

Upon solution of equation (3) for the hydraulic heads in the downstream boundary of the aquifer (named mixing zone in Fig. 3), the submarine groundwater discharge equals the sum of the Darcian fluxes in each of the finite-difference cells that make up that boundary. Explicitly, the horizontal component of the submarine groundwater discharge equals:

$$q_h = \sum_{i=1}^{n} K_i^h \Delta z_i \Delta x_i \left(\frac{h_i - d_i}{\Delta y_{id}}\right), \tag{4}$$

in which n is the total number of boundary cells in the finite-difference grid that have horizontal discharge to the ocean (see Fig. 3); K_i^h is the horizontal hydraulic conductivity of the ith cell ($i = 1, 2, \ldots, n$); Δz_i is the vertical dimension of the ith cell; Δx_i is the horizontal dimension of the ith cell (perpendicular to the plane of Fig. 3); Δy_{id} is the horizontal distance between the cell centers where the hydraulic heads h_i and d_i are calculated; d_i is the constant-head hydraulic head at the downstream boundary.

Likewise, the vertical component of the submarine groundwater discharge equals:

$$q_v = \sum_{j=1}^{m} K_j^v \Delta y_j \Delta x_j \left(\frac{h_j - d_j}{\Delta z_{jd}}\right),$$

in which m is the number of top boundary cells where there is upward vertical discharge to the coastal zone (see Fig. 3); K_i^v is the horizontal hydraulic conductivity of the jth cell ($j = 1, 2, \ldots, m$); Δy_j is the horizontal dimension of the jth cell (in the same plane of Fig. 3); (xj = horizontal dimension of the jth cell (perpendicular to the plane of Figure 3); Δz_{jd} is the vertical distance between the cell centers where the hydraulic heads h_i and d_j are calculated; d_j is the constant-head hydraulic head at the downstream boundary. The magnitude of the total submarine groundwater discharge is

$$q = \sqrt{q_n^2 + q_v^2}, \tag{5}$$

This method neglects the effect of density variations of groundwater as it approaches the ocean floor. Thus, the mixing zone of fresh water and sea water is viewed as a very narrow surface with waters of distinct densities on both sides of it. To illustrate this method, assume that the submarine discharge is predominantly horizontal driven by a hydraulic gradient $i = 1/1000$, that the aquifer is homogeneous (with conductivity $K = 1$ m/day), and that the thickness through which the aquifer discharges into the ocean and the length of the aquifer along the coast are 10 m and 8000 m, respectively. Substitution of the former values into equation (4) produces a submarine discharge $q = 80$ m^3/day.

PIEZOMETERS

The estimation of submarine groundwater discharge by the piezometer method relies on the measurement of the gradient of hydraulic head and the application of Darcy’s law [22]. Consider Fig. 4, which shows the measurement approach for a particular deployment of the piezometer system. Nested piezometers (in Fig. 4 each nested piezometer consists of a cluster of two side-by-side piezometers) are located along a transect of the coastal zone to estimate the submarine groundwater discharge. The vertical (q_v) and horizontal (q_h) components of submarine discharge are calculated separately from piezometric data. The width of the aquifer perpendicular to the plane of Fig. 4 is denoted by L. The vertical and horizontal components are:

$$q_v = \sum_{j=1}^{n} K_{vj} w L \frac{\Delta h_{vj}}{\Delta z_j}, \quad q_h = K_h b L \frac{\Delta h_{\mathrm{H}}}{\Delta r},$$

in which n is the number of nested piezometers; K_{vj} is the vertical hydraulic conductivity of the sediments where the jth piezometer is opened to groundwater flow; w is the width of the zone of influence of the nested piezometers in the plane of Fig. 4; Δh_{vj} is the vertical hydraulic head difference at the jth nested piezometer; Δz_j is the vertical distance between the piezometers' screen intervals; K_h is the horizontal hydraulic conductivity of the sediments; b is the thickness of aquifer through which horizontal discharge takes place; Δh_{H} is the horizontal hydraulic head difference; Δr is the distance between two piezometer nests used to calculate horizontal discharge.

Having the vertical (q_v) and horizontal (q_h) components of the groundwater discharge, the total flux is computed by (5). As an example, let $K_v = 1$ m/day, hydraulic gradient = 1/1000, $L = 1000$ m, and $w = 100$ m for one piezometer cluster, then $q_v = 100$ m^3/day.

The piezometer method requires the determination of the hydraulic conductivity of the costal-zone sedi-

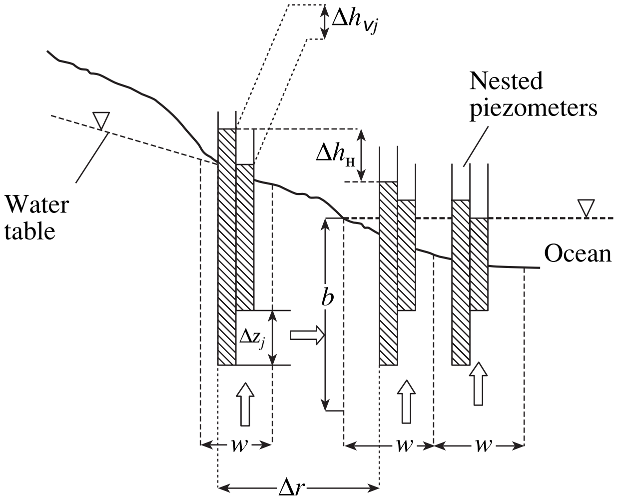

Fig. 4. Nested piezometers in the cross-section of the coastal zone.

ments, which may prove an arduous undertaking [11]. Other complications are brought about by the deployment, anchoring, and maintenance of, and access to, the piezometers, which may become onerous except in coastal environments with minimal surf. The cyclical nature of tides may cause reversal of seepage direction in parts of the coastal zone, which may introduce analytical difficulties in the estimation of the net submarine discharge [17].

SEEPAGE METERS

The classical seepage meter is illustrated in Fig. 5. Applications that involve seepage meters are described in [8, 10–12].

The collector box is inserted into the ocean sediments as shown in Fig 5. Previous researchers have used a cylindrical collector box [12], to which a short tube is attached leading to a plastic bag where the submarine discharge accumulates. The average submarine groundwater discharge $\bar{q}$ during a period of time t is given by the following equation:

$$\bar{q} = V/A_x t, \tag{6}$$

in which V is the volume of groundwater captured inside the plastic bag during the time t; A_x is the cross-sectional area of the collector box perpendicular to the direction of the discharge $\bar{q}$. Assuming that $\bar{q}$ holds over an area A of the coastal zone, then the total submarine discharge is $q = \bar{q}A$. To illustrate, suppose that a volume $V = 10$ l fills up in $t = 1$ day, and that the capture area is $A_x = 1$ m^2; then $q = 0.01$ m/day. Assuming further that the area A over which q takes place is 10^4 m^2, then $q = 100$ m^3/day.

This method yields an average discharge over the time period t, instead of a temporal record of the actual

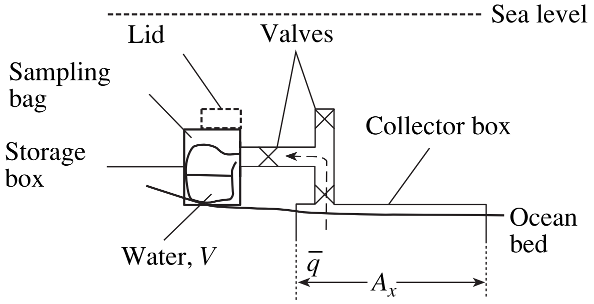

Fig. 5. Schematic of a seepage meter; $\bar{q}$ is the average seepage measured in the meter.

discharge. To avoid energy losses between the collector box and the plastic bag that might yield an underestimate of the average discharge, a digital seepage meter was introduced [15] that measures the velocity of submarine discharge in the tube that connects the collector box to the sampling bag at small intervals, thus providing a nearly continuous record of the submarine groundwater discharge at the measurement location. Notice also that this method provides a local-scale measurement of submarine groundwater discharge. An estimate of the regional submarine discharge requires multiple measurements of the kind illustrated in Fig. 5 spread throughout the coastal zone. A large volume of field and experimental works and considerable expenses are needed in this case.

TRACERS

Natural radioactive tracers found in groundwater, such as radon-222 (^{222}Rn) and radium-226 (^{226}Ra), have been used to estimate submarine groundwater discharge [4, 5]. Other natural non-radioactive groundwater constituents, such as methane (CH$_4$), have been used as well [4]. The approach is based on the conservation of tracer mass in the coastal zone, to which submarine groundwater flux is a contributor.

The reader may recall that ^{222}Rn is the daughter product of ^{226}Ra. Therefore, the net production term of ^{222}Rn in the deep ocean layer of volume V is the radium production minus the radon decay:

$$(\lambda_{^{226}\mathrm{Ra}} C_{^{226}\mathrm{Ra}} - \lambda_{^{222}\mathrm{Rn}} C_{^{222}\mathrm{Rn}})V \equiv (\lambda_{\mathrm{Ra}} C_{\mathrm{Ra}} - \lambda C)V,$$

in which (is the decay constant, equal to 4.278×10^{-4} and 66.56 years^{-1} for ^{226}Ra and ^{222}Rn, respectively, and C denotes isotope concentration.

To the net production term, one must add radon fluxes in and out of this layer. The input fluxes are the diffusive/advective flux across the sediments F_s (through the area A_s) and the offshore radon concentration C_i advected by the current velocity (v) through the area A_i. The output fluxes are the radon concentration C advected to the shallow region of the continental shell by the current velocity v through the area A_o and the diffusive/advective flux (F_p) across the pycnocline (through the area A_p):

$$F_p = \left(K_v \frac{dC}{dz} + v_{\mathrm{up}} C\right) A_p,$$

$$F_s = \left(D_s \frac{dC_s}{dz} + q' C_s\right) A_s,$$

where K_v and D_s are the eddy diffusivity through the pycnocline and the sediments diffusivity, respectively; v_{up} is the upward velocity; q' is the vertical advective groundwater velocity across the sediments; C_s is radon concentration in the sediments. The water balance in the deep layer implies the following equation for the upward velocity v_{up}:

$$v_{\mathrm{up}} = \frac{q' A_s + v(A_i - A_o)}{A_p}. \qquad (7)$$

Equation (7) is combined with the mass-balance equation for radon in the deep layer. If the radon concentration is at steady state one obtains:

$$\begin{aligned} &vC_iA_i + F_s + (\lambda_{\mathrm{Ra}} C_{\mathrm{Ra}} - \lambda C)V - vCA_0 \\ &\quad - K_v \frac{dC}{dz} A_p - v_{\mathrm{up}} C A_p = 0, \end{aligned} \qquad (8)$$

Equation (8) is solved for the radon concentration C in terms of other variables and parameters in it, including the velocity of groundwater, q' (which is contained in v_{up}, see equation (7)):

$$\begin{aligned} C &= \left(vC_iA_i + F_s + \lambda_{\mathrm{Ra}} C_{\mathrm{Ra}} V - K_v \frac{dC}{dz} A_p\right) / (vA_0 \\ &\quad + v_{\mathrm{up}} A_p + \lambda V) = \left(vC_iA_i + F_s + \lambda_{\mathrm{Ra}} C_{\mathrm{Ra}} V \right. \\ &\quad \left. - K_v \frac{dC}{dz} A_p\right) / (q' A_s + vA_i + \lambda V). \end{aligned} \qquad (9)$$

Measured radon concentrations (C) in the deep layer are then fitted to the right-hand side of equation (9). The value of q' which gives the best fit is the estimate of groundwater velocity. The submarine groundwater discharge is then:

$$q = q'A,$$

in which A is the area of coastal zone sampled and perpendicular to the direction of submarine groundwater discharge (typically in km^2 or 10^6 m^2).

The tracer method just described yields a regional average of submarine discharge. The field experimental sampling design to estimate tracer concentrations, velocities, and diffusivities must be carefully chosen so that regional average estimates be statistically representative.

CONCLUSIONS

All the estimation methods presented above provide estimates of submarine groundwater discharge that are hindered by uncertainty. That uncertainty arises from model parameters, from the complexity of the coastal environment, and from approximate measurements of variables such as hydraulic head and coastal-zone water velocities and tracer concentrations. These limitations call for sensitivity analysis designed to reveal the variability inherent to the estimation of submarine groundwater discharge.

Another important consideration is the scale at which the presented methods best capture the process of submarine groundwater discharge. The seepage-meter and piezometer approaches are best suited to problems with flow paths of tens to hundreds of meters in length, or flow areas at the scale of hectares or less. The tracers method has been applied with some success in coastal areas of several squared kilometers, even tens of squared kilometers. The flow-net approach can be applied along the coastline for as long as the hydraulic data are available and the model assumptions hold. A typical scale of linear distance along the coastline within which the flow-net assumptions apply is the kilometer.

The numerical simulation method can handle complex hydrogeology as well as three-dimensional flow patterns in coastal areas of variable size. The water-balance method is applicable at basin-wide scales, in which all fluxes represent long-term annual averages under steady state climatic and natural conditions.

Cost is another key issue. The flow-net method requires the least amount of data, although the study area must have a well-characterized hydraulic-head map. Numerical simulation requires detailed data and substantial modeling sophistication. The piezometer and the seepage-meter methods rely on a network of piezometers and collector boxes in the coastal zone, respectively, some of which are subject to tidal effects. This poses measurement challenges and accessibility limitations. The tracers method relies on measurements made entirely in the ocean, which requires research vessels, probes, and other analytical equipment of a cost much greater than that encountered in the other methods reviewed here. The water balance is the more expeditious, provided that representative data to calculate all the intervening long-term fluxes are available for that task.

It should be emphasized that all the methods for submarine groundwater discharge assessment, including those described above, are not rival but supplement each other. The most reliable result can be obtained through the combined use of several estimation methods.

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