

Summary

Groundwater intensive use in the coastal areas caused lessening of its reserves and sea water intrusion into coastal aquifers, that became a pressing problem in many countries of the world. A mathematical model of sea water intrusion into fresh coastal inhomogeneous and anisotropic, confined and unconfined layers is given in the paper. A formulated problem of intrusion is solved, using numerical methods, results of calculations and their comparison with field data and calculations of other authors are given.

Coastal zones of sea and oceans are characterised with the highest population density, that is caused by the availability of large plain areas of fertile soils, high biological productivity of estuaries and coastal water areas, convenient transport communications. From a hydrogeological point of view, coastal areas are transitional ones where interaction occurs between continental fresh water discharge and sea water. In the latest decades problems of aquifers use are paid great attention to that is caused by a growing importance of groundwater reserves for economics, and particularly, for water supply and irrigation. Intensive groundwater exploitation has caused its reserves lessening and salt water intrusion into the coastal aquifers in many near-shore areas.

The study of sea water intrusion into fresh aquifers in the coastal areas in an important hydrogeological problem in many countries of the world with an extended coastal line. Sea water intrusion is observed in the USA, Canada, Mexico, Venezuela, Italy, Netherlands, Yugoslavia, Belgium, Germany, France, Great Britain, India, Marrakech, Tunis, Algeria, Japan, Australia and other countries (Groundwater, 1987).

In the former USSR countries is very acute in some areas of Baltic, Kamchatka, the Black and the Caspian sea coasts of the Caucasus, where a real threat of sea water leakage by coastal well fields does exist (Khublaryan, Frolov, 1988).

Sea water intrusion immediately into an aquifer in the place of its discharge into the sea or sea water blowing up into rivers and channels and its further filtration into aquifers are the main ways of sea water intrusion. Besides, sea water intrusion into an aquifer can be caused by the sea water leakage through poorly permeable deposits. Sea water intrusion are also caused by irrigation of the adjacent territories, making quarries and other engineering arrangements. Intensive water with drawl in the Baltic territory has resulted in a considerable groundwater level decline and vast depression cones with in land shelf. Sea water intrusion into exploited aquifers has

already occurred in some coastal well fields a hydrogeological situation, providing for the intrusion is developing.

Seaside part of the Baltic artesian basin, Kaliningrad area, Russia, is characterised with complex hydrogeological conditions. The availability, in the zone, of active water exchange between some interconnected aquifers, heterogeneity of their filtration properties, diversity of conditions for forming seaside well fields safe yield and necessity to predict to sea water intrusion force to use mathematical modelling methods (Gregorauskas et al., 1987). A very complex intrusion structure has been discovered in the Long-Island (USA) (Cohen, Kimmel, 1974). Salt water intrusion zone consists of four wedges, indicating a complex hydrogeological structure of water bearing rocks. An anomalously quick contamination of water withdrawing exiles with chlorides was observed in 1969-1970 in the Lebanon (Bucsi, 1978), where chlorine ions concentration exceeded permissible value - 0,25 g/l. Investigations (electrical physical sounding) showed that intensive fresh water with drawing from water saturated rocks of the senoman limestone snit has resulted in formation of vast depression zones in very loosened and karstified rocks and intensive sea water movement through them to a distance of 3 km from a coastal line. Here, places not disturbed geologically are saturated with fresh water due to their low porosity, and hence, permeability.

In the limestone deposits of the southern England, constituted with fine grained fissured white limestone's of the Upper Cretaceous period, sea water intrusion was initiated by fresh water with drawl for supplying the population. Process of intrusion was intensified due to a well developed fissure system, in the water enclosing rocks, immediately connected with the sea. The availability of fissures greatly affected the dependence of fresh and salt water interface on tidal fluctuations. Movement of the interface boundary reached 86 m for some wells (Monkhouse, Fleet, 1985).

Special attention in the latest years is centered on the problem of sea water intrusion in the tidal line of the coast, where hydrodynamic interaction of salt and fresh groundwater of the continental discharge is essentially affected by sea level fluctuations. This when studying intrusion in the area of Bengal Bay (Goswami 1986), where water bearing rocks are constituted by alluvial sands and soft clays, due to the grained material prevalence of the surface, groundwater recharge of the studied aquifer was realized by direct rain water seepage into it. Ground water in this aquifer discharges into the sea and with in a tidal zone of the coastal area fresh ground water is underlain by salt water wedge. Thus, within the aquifer, fresh water zone is between two wedges of salt water, one of them being placed at the top, the other - at the bottom of the aquifer. The upper zone is formed due to the sea water intrusion into the layer during maximum tidal sea levels, and fresh water.

The main attention in studying the sea salt water intrusion into fresh aquifers is paid to predicting groundwater quality in the sea coast well fields. Sea water intrusion into the ground water is a complex hydrodynamic process of joint salt and fresh water movement, that are characterized with different density and other physical properties (Reilly, Goodman, 1985). Processes of dispersion, diffusion and convective fluids occur in the salt - fresh water interface zone. Place, form and extent of a diffusional zone depend on many factors, including a ratio between salt and fresh water densities, fresh water discharge or head, dispersion parameters and water - bearing layer structure. In multi-layered systems, that can be visualized as some layers, separated by semi - permeable aquitards, there appears a "tongue" of intrusion, in this case a hydrodynamic analysis of the system becomes more complex, if there occurs a leakage between the adjacent layers through the aquitards. Adaptable enough mathematical models are needed for studying complex structures. A system of equations for dissolved salt filtration and diffusion is the most general mathematical model for describing the sea water intrusion. This model is based on a generalized law for fluid filtration, with density depending on dissolved materials concentration, that can be characterized both confined and unconfined groundwater flows in heterogeneous and anisotropic water - bearing layers.

By introducing into consideration fresh water head,

$$\phi(x, y, T) = \frac{P(x, y, T)}{\rho_f g} + y, \quad (1)$$

and relative dissolved sea salts concentration,

$$\zeta = (S - S_f) / (S_s - S_f), \quad (2)$$

a system of sea water intrusion equations, basing equations for continuity and convective diffusion, can be written in the form

$$\nabla(\rho Q) = 0, \quad (3)$$

$$\nabla(D \nabla C) - \nabla\left(\frac{QC}{n}\right) = \frac{\partial c}{\partial T}, \quad (4)$$

where ρ - is density, g - gravity acceleration, x and y are horizontal and vertical coordinates in a vertical plane, perpendicular to the shore line (axis y is directed upward), $P(x, y, T)$ - is pressure, S - is salts content in water, D - is a tensor of hydrodynamic dispersion (Huyakorn et al., 1987; Souza, Voss, 1987), n - effective porosity, of water bearing rocks, T - time. A generalized Darcy's filtration law for heterogeneous anisotropic layer and fluid with varying density is the following

$$\bar{Q} = -\frac{A}{\mu(\rho)}(\nabla p + \rho \bar{g}), \quad (5)$$

where \bar{Q} - is rate of filtration with constituents Q_x, Q_y in directions x, y , $\mu(\rho)$ - is fluid viscosity, A is a tensor of water bearing rocks permeability. When axes of water - bearing rocks anisotropy coincide with axes of coordinate system, then tensor A can be written in the form of

$$A = \begin{bmatrix} \kappa_x & 0 \\ 0 & \kappa_y \end{bmatrix}, \quad (6)$$

Index "f" is related to fresh water, index "s" - to sea one, a line above characterizes a vector value.

Equations (3) - (4) are connected by dependence of fluid density on dissolved sea salts concentration; and hence cannot be solved separately. Boundary conditions, in the case of sea water intrusion into confined aquifers, are assumed to be usual. When considering unconfined flows, that is particularly important for studying processes of land and sea interaction in the coastal zone, $y = \delta(x, t)$ is given by pressure $p = 0$, on a free surface of filtration flow, i.e. $\psi = y = \delta$.

For the equation of dissolved salts transport (4) on the free surface under availability of infiltration flow with contaminants concentration C_{inf} , a boundary condition (for isotropic media) is the following

$$D \frac{\partial C}{\partial N} = E_N (C - C_{inf}), \quad E_N = w / (1 + (\partial \phi / \partial x)^2)^{-1/2}$$

where D - is a coefficient of diffusion, $\partial / \partial N$ - is the inner normal to the boundary derivative, E_N - is infiltrational recharge for a unit of free surface length, $w(x, t)$ - is infiltrational recharge for the soil horizontal surface.

Initial distribution of concentration $C(x, y, 0) = C_0(x, y)$ is initial condition of the problem and in the case of studying unconfined layers it is a free surface location $\phi(x, 0) = \phi_0(x)$.

Free surface moving is described in the following equation

$$n \frac{\partial \phi}{\partial t} = -\kappa_y \left[\frac{\partial \psi}{\partial y} + \varepsilon c \right] + \kappa_x \frac{\partial \psi}{\partial x} \frac{\partial \phi}{\partial x} + w$$

A formulated boundary problem has been solved using numerical methods. Equation of elliptic type was solved with iteration method

(Yanenko , 1967). All the equations in partial derivatives were solved by the method of spatial variables division (Khublaryan et al, 1984).

Figure 1 gives a structure of a concentration field under intrusion in a multilayered aquifer in the Baltic aquifer (Gregorauskas et al., 1987).

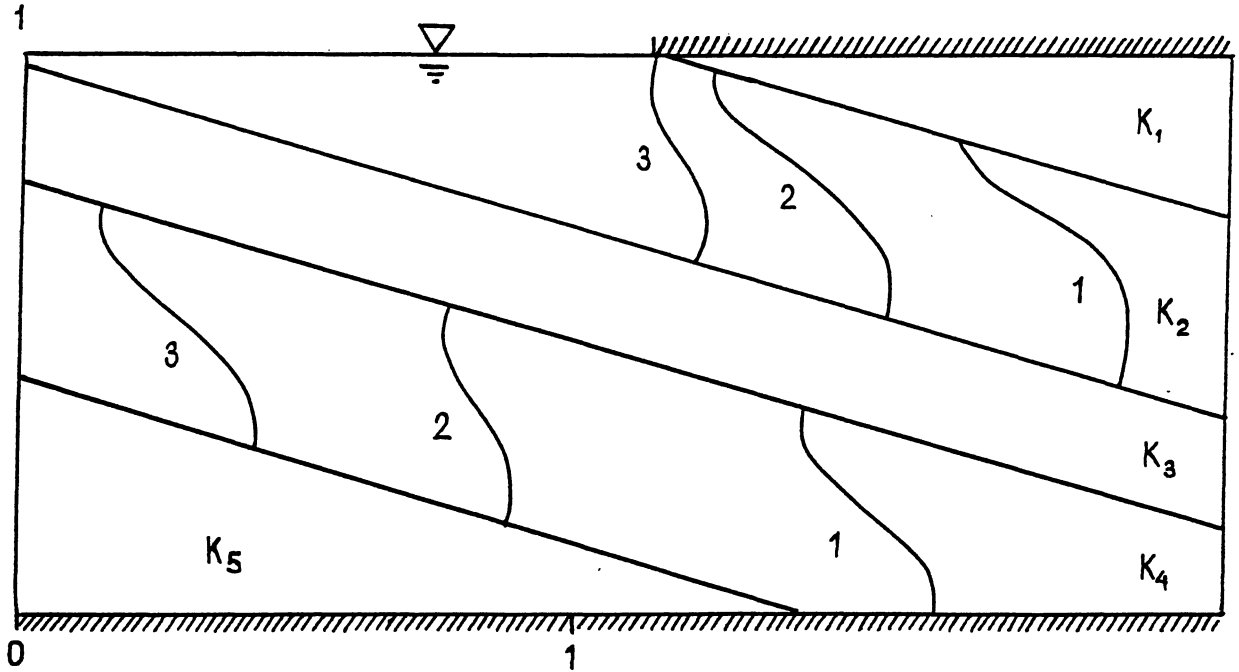


Figure 1. Lines of equal sea salts concentrations under intrusion into a layered aquifer : 1 - $c = 0,27$; 2 - $c = 0,51$; 3 - $c = 0,76$, with the following meanings permeability coefficient for layers and diffusion coefficient: $\kappa_1 = 0.001$ m/d, $\kappa_2 = 10$ m/d, $\kappa_3 = 0.001$ m/d, $\kappa_4 = 1$ m/d, $\kappa_5 = 0.001$ m/d, $D = 7,0 \cdot 10^{-2}$ m /d.

It is evident, that under an essential difference is the values of layers permeability, intrusion zone is subdivided into some separated parts. Sea salts penetration into poorly permeable layers is not actually observed calculations were made, using a developed technique, of the sea water intrusion into heterogeneous confined water layers and filtration coefficients and dispersion impact on the intrusion zone. Calculations made were correlated with the field data for intrusion into the Biscayne aquifer (Florida, USA) and calculations of other authors (Figure 2).

The investigations carried out show that a designed model for calculating intrusion in heterogeneous layers and its me, allow us to effectively model different hydrogeological conditions applicable to the problems of water consumption in the coastal areas and groundwater protection from sea salts contamination.

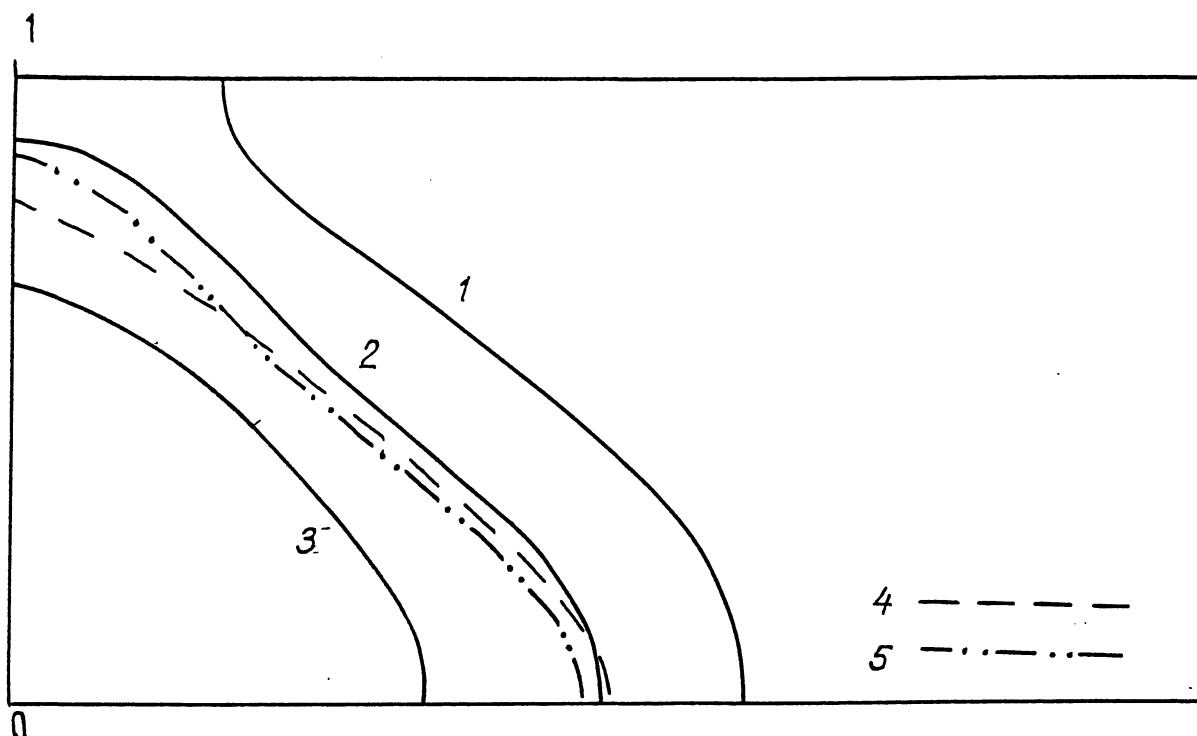


Figure 2. Correlation of field data with the results of finite-difference and finite-element methods for calculating the distribution of sea salts concentration in the intrusion zone in natural layers: 1- 3 - $c = 0,25; 0,5; 0,75$ correspondingly (according to the authors), 4 - $c = 0,5$ (Lee, Cheng, 1974) - Natural isochlorine $c = 0,5$ (Kohout , 1960).

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1. Introduction

Direct ground water flux reaches the ocean floor bypassing the river network. Zektser and Loaiciga (1993) have estimated that the global mean annual direct ground water flux to the oceans is approximately $2,400 \text{ km}^3 \cdot \text{yr}^{-1}$, and that the global dissolved salt throughput carried by direct ground water flux is approximately $1,300 \times 10^6 \text{ t} \cdot \text{yr}^{-1}$ ($1 \text{ t} \cdot \text{yr}^{-1} \equiv 1 \text{ metric ton per year} = 1,000 \text{ kg per year}$). The estimated annual ground water volumetric flux compares with an estimated $38,000 \text{ km}^3 \cdot \text{yr}^{-1}$ mean streamflow reaching the oceans via the drainage network (Shiklomanov, 1993; Postel, *et al.*, 1996). Furthermore, Zektser and Loaiciga (1993) have estimated that the global direct salt discharge to the oceans ranges from 40 % to 60 % of the mean annual salt discharge carried by streamflow. Therefore, even though on a volumetric basis the direct ground water flux is equal to about 6.3 % of the streamflow reaching the oceans, on a chemical basis it amounts to about 50 % of the salt discharge carried by streamflow to the oceans. In a recent symposium on ground water discharge to the coastal zone (Land Ocean Interactions in the Coastal Zone Core Project Office -LOICZ-, 1996), newly reviewed data reaffirmed the significant role of direct ground water on ocean chemistry and nutrient cycles in the coastal areas of many regions of the world. In regions where karstic coastal aquifers are important features of the coastal landscape, direct ground water flux may become the dominant delivery mechanism of matter -water or chemical species- to the coastal zone. The Mediterranean Sea is a case in point. Other well-known examples are the Black and Baltic Seas.

Zektser and Loaiciga (1993) pioneered the study of potential changes in direct ground water flux induced by global warming trends in the earth-atmosphere system. A mass/energy conservation method is developed in this article. The newly developed method yields estimates of direct ground water and salt discharge to the oceans under the “double- CO_2 ” global warming scenario (i.e., that corresponding to a doubling of CO_2 by the end of year 2100, the so-called $2 \times \text{CO}_2$ scenario). This study focuses on mean global streamflow, direct ground water flux, and direct salt discharge. Continental- and regional-scale estimates may be obtained similarly by modifying a few essential parameters as one scales down from global to continental or regional scales.

2. Methodology

Let us consider the first law of thermodynamics (i.e., conservation of matter and energy), as it applies to global hydroclimatic processes. For the continents of the world as a whole, there is a statement of the conservation of (water) mass written in differential form to represent changes in (water) fluxes averaged over a representative period of time (e.g., several decades in the context of present-day global warming trends). Assume that P represents continental precipitation, E is the total continental evaporation (or evapotranspiration to be more precise), and R_T is the total runoff discharging to the world's oceans. $R_T = R_S + R_G$, where R_S is streamflow delivered to the oceans by the drainage network and R_G is the direct ground water flux to oceans which bypasses the river network. All variables are mean annual averages taken over representative time periods and are expressed in dimensions of $\text{km}^3 \cdot \text{yr}^{-1}$. The equation of conservation of water mass can then be expressed in differential form as follows (Δ denotes change over time):

$$\Delta P = \Delta E + k_S \cdot \Delta R_S \quad (1)$$

in which $k_S \equiv R_T/R_S$ has been estimated by Zektser and Loaiciga (1993) to be about 1.063. It is assumed that the ratio (k_S) of total runoff to (river) streamflow remains relatively constant, and its changes are negligible compared with changes that may occur in the other variables present in equation (1). If one considers the ratio $k_G \equiv R_T/R_G \approx 16.8$, equation (1) can be expressed in an alternative way, as follows:

$$\Delta P = \Delta E + k_G \cdot \Delta R_G \quad (2)$$

where changes in the ratio k_G are negligible.

Let us consider next the heat balance over the surface of the world's continents. Let A denote the available surface energy (in the form of heat), E be evaporation as before, L the latent heat of vaporization, $L \cdot E$ the latent heat flux from the surface, and H the sensible heat flux. All heat and energy terms have units of watts per m^2 ($\text{W} \cdot \text{m}^{-2}$). The available surface energy is partitioned into latent and sensible heat fluxes. At global scales, and averaged over sufficiently long time periods, the sensible and latent heat fluxes are directed away from the earth's surface (Budyko, 1978). The equation of conservation of heat in differential form is expressible in the following form (where L can be treated as a constant from basic thermodynamic considerations):

$$\Delta A = L \cdot \Delta E + \Delta H \quad (3)$$

The available energy A is also equal to the balance established among net radiant fluxes at the surface (long and short wave) R_n , soil heat flux G, and biospheric heat consumption (mostly through photosynthesis) B. Therefore, an equivalent statement of the equation of conservation of heat in differential form is:

$$\Delta A = \Delta R_n - \Delta G - \Delta B \quad (4)$$

An important modification in the energy balance equations (3) is introduced by the Bowen ratio $\beta \equiv H/L \cdot E$, the ratio of sensible heat flux to latent heat flux. Over wet surfaces, the long-term average Bowen ratio is low (i.e., much less than one) while over dry regions it is close to one. For example, over the world's oceans the available surface energy A is spent mostly as latent heat of vaporization, and the global, oceanic, average Bowen ratio is about 0.11 (Budyko, 1978). On the other hand, over the continents, the long-term average Bowen ratio is about 0.85, signifying a larger expenditure of surface energy as sensible heat flux relative to that consumed as latent heat flux. Introducing the Bowen ratio in equation (3) and solving for the evaporation E yields:

$$\Delta E = \frac{\Delta A}{L(1 + \beta)} \quad (5)$$

where it has been assumed that the Bowen ratio remains relatively constant while the latent heat and sensible heat fluxes change. The impact of Bowen ratio variation on global streamflow, direct ground water, and direct salt discharge calculations under the 2 x CO₂ scenario will be examined in greater depth below. The biospheric heat (B) and soil heat (G) fluxes are relatively small compared to the net radiant fluxes (R_n) in equation (4) at continental scales measured over long periods (Budyko, 1977; 1978; Rosenberg, *et al.*, 1983). Based on this, it is assumed that the changes in B and G are negligible compared to those that may be induced on net radiant fluxes over the world's continents under the 2 x CO₂ global warming scenario. Introducing this last assumption in the right-hand side of equation (4), and then substituting the resulting expression for ΔA in equation (5) leads to an important simplification of the equation of heat conservation over the land:

$$\Delta E \approx \frac{\Delta R_n}{L(1 + \beta)} \quad (6)$$

The approximation error in equation (6) is of the order of $(\Delta G + \Delta B) / (L(1 + \beta))$, which is negligible relative to the net radiant energy term kept in the right-hand side of equation (6). The dimensions of ΔE in (the energy balance) equation (6) are $\text{kg} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$. On the other hand, the ΔE term appearing in (the water balance) equations (1) and (2) has dimensions of $\text{km}^3 \cdot \text{yr}^{-1}$. We seek to substitute the right-hand side term of equation (6) into equations (1) and (2) to obtain coupled mass/energy equations with which to predict changes in streamflow, direct ground water flux, and direct salt discharge. We must then introduce a correction factor in the right-hand side of equation (6) so that its dimensions become $\text{km}^3 \cdot \text{yr}^{-1}$. The transformed equation (6) becomes (L, the latent heat of vaporization, is equal to $2.46 \times 10^6 \text{ J} \cdot \text{kg}^{-1}$ and ΔR_n must be in dimensions of $\text{W} \cdot \text{m}^{-2}$):

$$\Delta E \approx \frac{K \cdot \Delta R_n \cdot S_L}{\rho \cdot L(1 + \beta)} \quad (7)$$

in which S_L is the world's land area ($150 \times 10^6 \text{ km}^2$), ρ is the density of freshwater ($10^3 \text{ kg} \cdot \text{m}^{-3}$), and K is a dimensional conversion factor, $K = 31,536$. Equation (7) is substituted in equations (1) and (2) to obtain expressions for the change in global annual average streamflow, ΔR_s , and the change in direct ground water flux, ΔR_G , (both in $\text{km}^3 \cdot \text{yr}^{-1}$; the change in land precipitation, ΔP , must be in $\text{km}^3 \cdot \text{yr}^{-1}$ also):

$$\Delta R_S \approx \frac{\Delta P - \frac{K \cdot \Delta R_n \cdot S_L}{\rho \cdot L(1 + \beta)}}{k_S} \quad (8)$$

$$\Delta R_G \approx \frac{\Delta P - \frac{K_L \cdot \Delta R_n \cdot S_L}{\rho \cdot L(1 + \beta)}}{k_G} \quad (9)$$

The theoretical framework of this article is completed by recalling that the mass of solute in direct ground water flux, M_G (in $\text{t} \cdot \text{yr}^{-1}$), is equal to the product of the solute's concentration, C_G (in $\text{t} \cdot \text{km}^{-3}$), times the flux of direct ground water discharge, R_G (in $\text{km}^3 \cdot \text{yr}^{-1}$):

$$M_G = C_G \cdot R_G \quad (10)$$

Therefore, assuming that salt concentration in direct ground water flux remains relatively constant as global warming impacts unfold, equation (10), in combination with equation (9) yields:

$$\Delta M_G = C_G \cdot \Delta R_G \cong C_G \cdot \frac{\Delta P - \frac{K \cdot \Delta R_n \cdot S_L}{\rho \cdot L(1 + \beta)}}{k_G} \quad (11)$$

From the work of Zektser and Loaiciga (1993) it can be inferred that the average concentration of salts in direct ground water discharge is approximately $C_G = 542 \times 10^3 \text{ t} \cdot \text{km}^{-3}$ (which is equivalent to $542 \text{ mg} \cdot \text{l}^{-1}$).

3. Specification of model parameters and variables

The key stress posed by global warming on the hydrologic cycle relates perhaps to the potential disruption of the heat balance in the earth-atmosphere system as more long-wave radiation is trapped by increased atmospheric CO_2 . General circulation models, GCMs, estimate that the radiation forcing of the earth-atmosphere system would be about $4 \text{ W} \cdot \text{m}^{-2}$ (Ramanathan, 1988; Ramanathan *et al.*, 1989; Loaiciga *et al.*, 1996), of which about $3 \text{ W} \cdot \text{m}^{-2}$ would directly heat the atmosphere and about $1 \text{ W} \cdot \text{m}^{-2}$ would be directed to the earth's surface. This latter flux of downwelling long-wave radiation would affect the radiant energy balance at the earth's surface and it may modify the available surface energy. As stated above, the best available current data suggest that the change in net radiant energy over the earth's land masses triggered by global warming can be estimated to be about $\Delta R_n = 1 \text{ W} \cdot \text{m}^{-2}$. Based on considerations concerning heat balances at the earth's land surface, stated above, it can be concluded that the change in available surface energy is $\Delta A = \Delta R_n = 1 \text{ W} \cdot \text{m}^{-2}$. This radiation "forcing" induced by global warming and the concomitant change in mean continental precipitation are the driving elements effecting changes in streamflow, direct ground water flux, and direct ground water salt discharge to the oceans as described in equations (8), (9), and (11), respectively. In calculations to follow, the net radiation forcing ΔR_n will be varied from its predicted mean of $1.0 \text{ W} \cdot \text{m}^{-2}$ and assigned values below and above the predicted mean, such as 0.5 and $1.5 \text{ W} \cdot \text{m}^{-2}$, for example. This is intended to elucidate the sensitivity of predicted changes in streamflow, direct ground water, and direct salt discharge to the net radiation forcing.

Another key variable in our analysis is the change in mean annual continental precipitation ΔP which appears in equations (8) - (11). One of the most reliable estimates of mean continental precipitation puts it at $109,500 \text{ km}^3 \cdot \text{yr}^{-1}$, or $73 \text{ cm} \cdot \text{yr}^{-1}$ (Budyko, 1977) over an estimated total land area of $150 \times 10^6 \text{ km}^2$. GCMs predict that under the $2 \times \text{CO}_2$ global warming scenario changes in mean continental gross precipitation may vary from 0 to $+20\%$ of the current mean value, although pronounced spatial variability is predicted by the GCMs (Gates *et al.*, 1990; Mitchell *et al.*, 1990; Loaiciga *et al.*, 1996). This range in the predicted change of mean continental precipitation will be used in our analysis of streamflow, direct ground water, and direct salt discharge to the world's oceans under the $2 \times \text{CO}_2$ scenario. Table 1 lists the variables and parameters introduced above with their respective values and dimensions.

Table 1. Variables and parameters in models of hydrologic change

Parameter or variable	Mean Value	Dimensions
Change in net radiant flux at the land surface, ΔR_n	1 ^(a)	$\text{W}\cdot\text{m}^{-2}$
Salt concentration in direct groundwater, C_G	542×10^3 ^(b)	$\text{t}\cdot\text{km}^{-3}$
Precipitation change over the continents, ΔP	10,950 ^(c)	$\text{km}^3\cdot\text{yr}^{-1}$
Ratio of total runoff to streamflow, k_s	1.063 ^(d)	dimensionless
Ratio of total runoff to direct ground water runoff, k_G	16.8 ^(e)	dimensionless
Latent heat of vaporization, L	2.46×10^6 ^(f)	$\text{J}\cdot\text{kg}^{-1}$
Bowen ratio over the world's continents, β	0.85 ^(g)	dimensionless

Notes:

^(a) From Ramanathan (1988). See also Loaiciga *et al.* (1996).^(b) Inferred from Zektser and Loaiciga (1993);^(c) From Budyko (1977). This is equivalent to a 7.3 cm change in precipitation over the land masses.^(d) Inferred from Zektser and Loaiciga (1993)^(e) Inferred from Zektser and Loaiciga (1993)^(f) For freshwater at 15 °C. L shows a slight variation with salinity and water temperature, but these are negligible for the purpose of global warming impacts.^(g) From Budyko (1978).

4. Sensitivity of model predictions to variables and parameters

One important question that arises in regards to the estimates of changes in streamflow, direct ground water flux, and direct salt discharge (see equations (8), (9), and (11), respectively) associated with global warming, is their sensitivity to model variables and parameters. The key variables are the change in net radiation, ΔR_n and the change in continental mean precipitation, ΔP . The key parameter, in terms of the uncertainty in its estimation, is the Bowen ratio β . The sensitivity of a model prediction with respect to a parameter or variable is defined as the ratio of the percentage change in the prediction to the percentage change in the parameter (or variable) in question, while all other parameters and variables are held constant. Let us take as an example equation (9), which predicts changes in direct ground water flux. The sensitivity of the ΔR_G prediction with respect to, say, changes in the Bowen ratio is mathematically expressed as follows:

$$S_{\Delta R_G} \equiv \frac{\frac{d(\Delta R_G)}{\Delta R_G}}{\frac{d(\beta)}{\beta}} = \frac{\beta}{\Delta R_G} \cdot \frac{K \cdot \Delta R_n \cdot S_L}{\rho \cdot L(1 + \beta)^2 k_G} \quad (12)$$

Similar definitions apply to other prediction equations and parameters. Table 2 contains the expressions for the sensitivities of the model equations that predict changes in streamflow, direct ground water, and direct salt discharge with respect to net radiation change, mean precipitation change, and the (mean) Bowen ratio. It is important to recognize that the sensitivity of model predictions as defined herein is a dimensionless variable.

Table 2. Sensitivities of prediction equations to net radiation change, mean precipitation change, and Bowen ratio.

Model parameter or variable	Model prediction equation		
	streamflow ΔR_S (eq. (8))	direct ground water ΔR_G (eq. (9))	direct salt discharge ΔM_G (eq. (11))
Net radiation change, ΔR_n	$-\frac{\Delta R_n}{\Delta R_S} \cdot \frac{K \cdot S_L}{\rho \cdot L(1 + \beta)k_S}$	$-\frac{\Delta R_n}{\Delta R_G} \cdot \frac{K \cdot S_L}{\rho \cdot L(1 + \beta)k_G}$	$-\frac{\Delta R_n}{\Delta M_G} \cdot \frac{K \cdot C_G \cdot S_L}{\rho \cdot L(1 + \beta)k_G}$
Mean precipitation change, ΔP	$\frac{\Delta P}{\Delta R_S} \cdot \frac{1}{k_S}$	$\frac{\Delta P}{\Delta R_G} \cdot \frac{1}{k_G}$	$\frac{\Delta P}{\Delta M_G} \cdot \frac{C_G}{k_G}$
Bowen ratio, β	$\frac{\beta}{\Delta R_S} \cdot \frac{K \cdot \Delta R_n \cdot S_L}{\rho \cdot L(1 + \beta)^2 k_S}$	$\frac{\beta}{\Delta R_G} \cdot \frac{K \cdot \Delta R_n \cdot S_L}{\rho \cdot L(1 + \beta)^2 k_G}$	$\frac{\beta}{\Delta M_G} \cdot \frac{K \cdot C_G \cdot \Delta R_n \cdot S_L}{\rho \cdot L(1 + \beta)^2 k_G}$

Notes:

- The latent heat of vaporization $L = 2.46 \times 10^6 \text{ J} \cdot \text{kg}^{-1}$;
- The ratio of total runoff to streamflow $k_S = 1.063$
- The ratio of total runoff to direct ground water flux $k_G = 16.8$
- The mean salt concentration in direct ground water $C_G = 542 \times 10^3 \text{ t} \cdot \text{km}^{-3}$
- The freshwater density is $\rho = 1,000 \text{ kg} \cdot \text{m}^{-3}$
- The Bowen ratio $\beta = 0.85$
- The dimensions of ΔR_S and ΔR_G are in $\text{km}^3 \cdot \text{yr}^{-1}$
- The dimensions of ΔR_n are $\text{W} \cdot \text{m}^{-2}$
- The dimensions of ΔM_G are in $\text{t} \cdot \text{yr}^{-1}$
- The dimensional conversion factor $K = 31,536$.
- The sensitivity is a dimensionless coefficient.

5. Results and discussion

Streamflow and land/ocean interactions. Table 3 shows estimates of the change in global mean streamflow, R_S , in $\text{km}^3 \cdot \text{yr}^{-1}$, based on equation (8), for a range of mean continental precipitation and net radiant energy changes. The figures in Table 3 indicate that for a fixed net radiation change, the change in global streamflow increases with increasing mean precipitation change. In contrast, for a fixed mean precipitation change, the change in global streamflow decreases with increasing net radiation change. The predicted change in streamflow associated with a net radiation change of $+1 \text{ W} \cdot \text{m}^{-2}$ and a precipitation change of $+10\%$ from its mean (or $\Delta P = 10,950 \text{ km}^3 \cdot \text{yr}^{-1}$) is $\Delta R_S = +9,300 \text{ km}^3 \cdot \text{yr}^{-1}$. These latter levels of net radiation and continental precipitation change are commonly predicted by GCMs. The figure of $+9,300 \text{ km}^3 \cdot \text{yr}^{-1}$ change in global streamflow can be put in perspective by realizing that it is larger than the mean annual runoff in the Amazon river, the world's largest.

Table 3. Estimates of the change in global mean streamflow, ΔR_s , in $\text{km}^3\cdot\text{yr}^{-1}$, based on equation (8) for a range of mean continental precipitation change, ΔP , and net radiation change, ΔR_n .

% Change in land precipitation ^(a)	Changes in net radiant energy at the land surface		
	$\Delta R_n = +0.5 \text{ W}\cdot\text{m}^{-2}$	$\Delta R_n = +1.0 \text{ W}\cdot\text{m}^{-2} \text{ (b)}$	$\Delta R_n = +1.5 \text{ W}\cdot\text{m}^{-2}$
0	-495	-975	-1,470
+10 ^B (10,950 $\text{km}^3\cdot\text{yr}^{-1}$)	9,900	9,300	8,850
+20 (21,900 $\text{km}^3\cdot\text{yr}^{-1}$)	20,100	19,700	19,200

Notes:

^(a) For a current mean continental precipitation of 109,500 $\text{km}^3\cdot\text{yr}^{-1}$ or 73 $\text{cm}\cdot\text{yr}^{-1}$ distributed over $150 \times 10^6 \text{ km}^2$ of total land area.

^(b) These are values commonly predicted by GCM simulations.

Clearly, there is a fixed total amount of water in the planet earth, and the predicted gain in streamflow must come at the expense of modification of the water balance somewhere else. That somewhere else is partly the oceanic reservoir and partly the atmospheric water reservoir. The gain in streamflow to the oceans must be balanced by changes in oceanic evaporation and precipitation. A conservation equation linking water and heat balances in the oceans can be derived in a form analogous to that used above for the earth's continents. Let P_0 denote the mean global oceanic precipitation (estimated at 410,000 $\text{km}^3\cdot\text{yr}^{-1}$, by Budyko, 1977), L_0 the latent heat of vaporization for sea water (about $2.5 \times 10^6 \text{ J}\cdot\text{kg}^{-1}$), S_0 the ocean surface ($361 \times 10^6 \text{ km}^2$), β_0 the mean oceanic Bowen ratio ($= 0.11$ as stated above), and ρ_0 the mean density of sea water ($1,025 \text{ kg}\cdot\text{m}^{-3}$). The water/energy conservation equation for the ocean, written in differential form, is:

$$\Delta P_0 = \frac{K \cdot \Delta R_n \cdot S_0}{\rho_0 \cdot L_0 (1 + \beta_0)} - k_s \Delta R_s \quad (13)$$

in which $K = 31,536$ is a dimensional conversion factor, as before. The change in streamflow ΔR_s appearing in the right-hand side of equation (13) has been tabulated in Table 3. From equation (13) it can be shown that the streamflow increment $\Delta R_s = + 9,300 \text{ km}^3\cdot\text{yr}^{-1}$ associated with a $+ 10 \%$ continental precipitation change (or $\Delta P = 10.950 \text{ km}^3\cdot\text{yr}^{-1}$) and a net radiation change $\Delta R_n = 1.0 \text{ W}\cdot\text{m}^{-2}$, occurs simultaneously with a drop in mean global oceanic precipitation of about $\Delta P_0 = 5,780 \text{ km}^3\cdot\text{yr}^{-1}$. The balance between the $+ 1.063 \times 9,300 = 9,890 \text{ km}^3\cdot\text{yr}^{-1}$ ($= k_s \Delta R_s = R_T$) gain in total runoff and the $5,780 \text{ km}^3\cdot\text{yr}^{-1}$ loss in precipitation is made up by an increment of $4,110 \text{ km}^3\cdot\text{yr}^{-1}$ in mean oceanic evaporation. The larger input of water vapor to the atmosphere emanating from the oceans must be such that the mass of water vapor in the atmosphere is conserved once $2 \times \text{CO}_2$ equilibrium conditions set in. Letting E_0 denote the mean oceanic evaporation, the equation of conservation of water vapor in the atmosphere expressed in differential form is (all terms are in $\text{km}^3\cdot\text{yr}^{-1}$):

$$\Delta E + \Delta E_0 = \Delta P + \Delta P_0 \quad (14)$$

Given that (i) a 10% increase in continental mean precipitation is equivalent to $10,950 \text{ km}^3\cdot\text{yr}^{-1}$, (ii) the drop in mean oceanic precipitation has been established at $5,780 \text{ km}^3\cdot\text{yr}^{-1}$, and (iii) the rise in mean oceanic evaporation is $4,110 \text{ km}^3\cdot\text{yr}^{-1}$, it follows from equation (14) that the mean continental evapotranspiration rises by $1,060 \text{ km}^3\cdot\text{yr}^{-1}$ under the $2 \times \text{CO}_2$ scenario. It is concluded then that a rise in continental precipitation of $10,950 \text{ km}^3\cdot\text{yr}^{-1}$ (a 10% rise), triggered by $2 \times \text{CO}_2$ warming, is partitioned into a $9,890 \text{ km}^3\cdot\text{yr}^{-1}$ rise in total global runoff and $1,060 \text{ km}^3\cdot\text{yr}^{-1}$ rise in continental evapotranspiration. The rise in total global runoff is divided into a $9,300 \text{ km}^3\cdot\text{yr}^{-1}$ increment in streamflow delivered through the river network and about $590 \text{ km}^3\cdot\text{yr}^{-1}$ is accounted for a larger direct ground water flux.

Direct ground water and salt discharge. Table 4 shows the results for predicted changes in direct ground water (in $\text{km}^3 \cdot \text{yr}^{-1}$) and direct salt discharge (within parentheses, and reported in $10^6 \text{ t} \cdot \text{yr}^{-1}$) associated with a range of mean continental precipitation changes and net radiation changes that may be triggered by $2 \times \text{CO}_2$ warming. Two general trends are deduced from Table 4. First, for a fixed net radiation change, the direct ground water change and the direct salt discharge change increase with increasing precipitation change. Second, for a fixed mean precipitation change, the direct ground water flux change and the direct salt discharge change decrease with increasing net radiation change. For the standard $2 \times \text{CO}_2$ net radiation and mean precipitation changes of $1.0 \text{ W} \cdot \text{m}^{-2}$ and $+10 \%$, respectively, Table 4 indicates that the changes in direct ground water flux and salt discharge are $590 \text{ km}^3 \cdot \text{yr}^{-1}$ and $317 \times 10^6 \text{ t} \cdot \text{yr}^{-1}$, respectively. Using the estimated baseline values of $2,400 \text{ km}^3 \cdot \text{yr}^{-1}$ and $1,300 \times 10^6 \text{ t} \cdot \text{yr}^{-1}$ for direct ground water and salt discharge, respectively, their predicted changes in Table 4 constitute a 24 % increment relative to their baseline values, while the change in mean continental precipitation is only $+10 \%$ from its mean. Thus, the forcing induced by precipitation is amplified through the hydrologic cycle under the standard $2 \times \text{CO}_2$ global warming scenario. It was explained above that the gains in water fluxes to the oceans (streamflow and direct ground water) are intertwined with a set of complex shifts in water balances that must be established in the earth's land masses, oceans, and atmosphere. Likewise, the larger salt discharge to the oceans must be derived from additional chemical weathering and reactions that take place between ground waters and the rock matrix through which they move. Eventually, the larger chemical throughput to the oceans via direct ground water must reach equilibrium with chemical precipitation in the oceans, deposition in the ocean floor, and removal by other processes such as sea spray.

Table 4. Changes in direct ground water flux (ΔR_G , in $\text{km}^3 \cdot \text{yr}^{-1}$) and salt discharge in direct ground water (ΔM_G , within parentheses, in $10^6 \text{ t} \cdot \text{yr}^{-1}$) associated with $2 \times \text{CO}_2$ global warming.

% Change in land precipitation ^(a)	Net radiation change		
		($\text{W} \cdot \text{m}^{-2}$)	
	+ 0.5	+ 1.0 ^(b)	+ 1.5
0	-31.2 (-16.8)	-61.5 (-33.2)	-92.8 (-50.1)
+10 ^B ($10,950 \text{ km}^3 \cdot \text{yr}^{-1}$)	625 (338)	590 (317)	558 (301)
+20 ($21,900 \text{ km}^3 \cdot \text{yr}^{-1}$)	1,268 (685)	1,243 (671)	1,211 (654)

Notes:

^(a) For a current mean continental precipitation of $109,500 \text{ km}^3 \cdot \text{yr}^{-1}$ or $73 \text{ cm} \cdot \text{yr}^{-1}$ distributed over $150 \times 10^6 \text{ km}^2$ of total land area.

^(b) These are values commonly predicted by GCM simulations.

6. Sensitivity of results

Table 5 summarizes the sensitivity of streamflow, direct ground water, and salt discharge predictions with respect to (i) net radiation change, (ii) mean precipitation change, and (iii) Bowen ratio. All sensitivities in Table 5 are calculated for $\Delta R_n = +1.0 \text{ W} \cdot \text{m}^{-2}$, $\Delta P = +10 \%$ from mean value or $10,950 \text{ km}^3 \cdot \text{yr}^{-1}$ and $\beta = 0.85$. The results in Table 5 indicate that the sensitivities of the predicted changes in streamflow, direct ground water, and direct salt discharge with respect to net radiation change are the same and equal to -0.11 . This means that a 1 % increase in net radiation forcing produces a 0.11 % drop in the predicted change of streamflow, direct ground water, and direct salt discharge. The sensitivities of the predicted changes in streamflow, direct ground water, and direct salt discharge with respect to mean precipitation change are the same and equal to 1.11. Therefore, a 1 % increase in mean precipitation forcing leads to a 1.11 % rise in the predicted change of streamflow, direct ground water, and direct salt discharge. Lastly, the sensitivities of all predicted variables with respect to the Bowen ratio are also equal among themselves with a value of 0.05, the smallest of all the calculated prediction sensitivities. Thus, for example, a 100 % increase in the Bowen ratio results in only a 5 % increase in the predicted change of streamflow, direct ground water, and direct salt discharge.

Table 5. Calculated sensitivities of predictions for $\Delta R_n = 1.0 \text{ W}\cdot\text{m}^{-2}$, $\Delta P = + 10 \%$ ($= 10,950 \text{ km}^3\cdot\text{yr}^{-1}$), and $\beta = 0.85$

Model parameter or variable	Predicted variable ^(a)		
	streamflow ΔR_s	direct ground water ΔR_G	direct salt discharge ΔM_G
ΔR_n	-0.11	-0.11	-0.11
ΔP	1.11	1.11	1.11
β	0.05	0.05	0.05

Notes:

^(a) The sensitivity equations for the predicted variables are given in Table 2.

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THE POSSIBILITY OF GROUNDWATER DISCHARGE REGULATION IN THE MEDITERRANEAN COASTAL ZONES FOR FRESHWATER CAPTURE: PROBLEMS ARISING AND SOLUTIONS ADOPTED - CASE HISTORIES
MIJATOVIĆ, B.F.

1. Summary

In the karstic areas of the Mediterranean coastal zones, vast quantities of groundwater discharge through the carbonate formations finally to get lost in the sea. This groundwater discharge and its outcrops - the coastal and submarine springs - represent the most spectacular natural phenomena of littoral karst. The economic potential of these phenomena is not irrelevant, for according to estimates, the annual groundwater discharge flux ranges between 25 km³ (Margat and Forkasiewicz, 1981) and 68 km³ (Zektser *et al.*, 1984) per year. However, in spite of their great frequency in the Mediterranean basin, there are very few successfully realized projects capture of freshwater along the coastal zones.

The unsuccessful capture attempts involving coastal springs, the number of which has increased during last decades (Port-Miou near Marseille, Scurda and Gurdić in the gulf of Kotor in Adriatic, Chekka at Lebanon coast, Almiros near Iraklion in the Crete, Ain Zayana near Benghazi at Lybian coast, etc.), actually reveal the complexity of relationships between the coastal aquifers and their local erosional basis (below sea level), which controls the level of groundwater flow.

Recently, knowledge in this complex domain of hydrogeology has been largely extended owing to great technological development of equipment and research methods, as well as more reliable and quicker ways of field data collection. Yet, one must admit that many problems concerning the capture of freshwater still remain to be solved, because the knowledge of inherent properties of karstic aquifers is insufficient. These properties determine their geometrical organization and hierarchies of preferred orientation of cavities. Therefore, one must consider not only the field distribution of fresh and salt water hydraulic potential, but also the field distribution of the main physical parameters in carbonate rocks - the permeability and effective porosity in the matrix-blocks and in the network of preferred-flow cavities. It is also necessary to obtain reliable data concerning the local erosional basis of karstic aquifers, which controls the level of groundwater flow.

The cases discussed in this paper concern the problems of freshwater capture in karstic coastal zones. Owing to the geological approach in the analysis and synthesis of available data, a typological classification of coastal reservoirs has been formed. It improves the identification of most problems arising in the process of locating and making capture facilities. Solutions adopted involve the two most important tasks: (1) the regulation of groundwater flow, and (2) the system of control of salt water encroachment in the larger influence zone of the capture facility.

2. Introduction

In complex hydrogeological research on karstic coastal zones and their catchment areas (small and medium scale), the application of hydrodynamic rules can be suitable for interpretation of the observed hydraulic potential fields of freshwater and salt water encroachment at the points accessible to measurement (springs, sinkholes, boreholes, etc.). Locating the capture facilities (large scale) involves very important issues, such as: (1) structure of aquifer - reservoir; (2) geometry: relationship between the matrix blocks of great volume but small transmissivity and the very transmissive karstic network responsible for groundwater flow, (3) the depth of erosional base, and (4) the behavior of the transition zone and, in connection with that, the state of residual salinity in the bottom of the aquifer - reservoir.

To define a coastal karstic reservoir, as an aquifer, which feeds all springs on the coast and in the sea, it should be said that such type of reservoir has several important features:

Generally it is extremely karstified, comprising a complex drainage network system, created as a consequence of interactions between general fractures of the carbonate rocks and water circulation. In that way the system of ground water flows is formed, depending on the seasonal feeding of freshwater and sea water oscillations; coastal springs above sea level and submarine springs are the natural outcrops of the system.

The basic porosity of these aquifers, defined through irregular geometrical forms of the karst cavities, is usually associated with the fractures which may be more considerable if the carbonate complex is tectonically damaged (matrix-blocks and network of cavities in the carbonate rocks). A kind of intergranular porosity, most often subordinate (in the case of some dolomites, chalk, etc.) may be associated with it.

The processes of karstification can occur in any emerged carbonate rocks and take place in various geological periods, paleogeographical zones and structures, different from those of today; accordingly, the karst structure of porosity is displaced above and below the current sea level (Figure1).

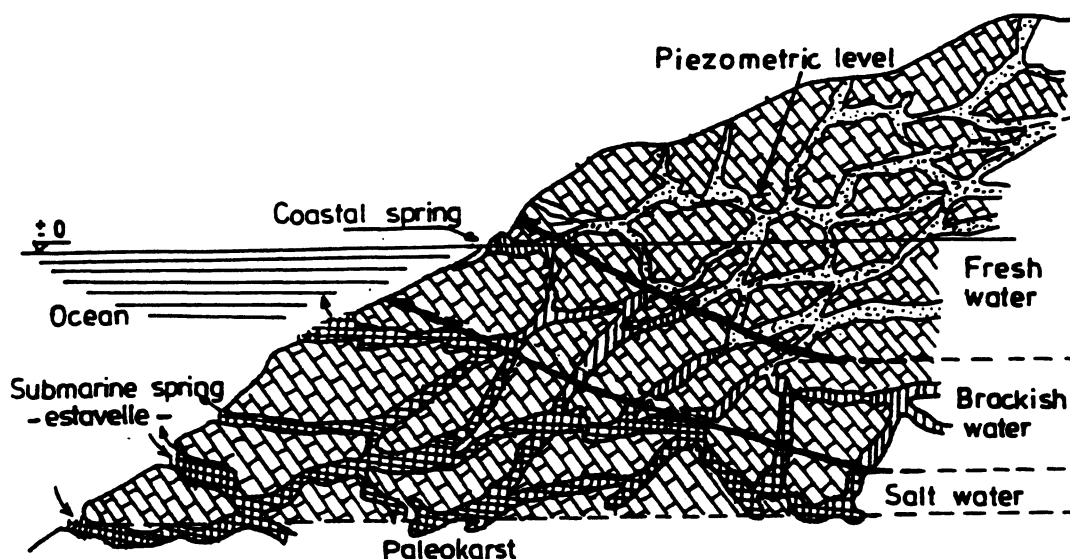


Figure 1. Schematic representation of ground water circulation in the karstic coastal zone.

The above cited attributes are confirmed by numerous observations at coastal karst regions, thus providing the fundamental postulates of hydraulic features and fresh/salt water circulation in karstic aquifers to which many studies are devoted. Figure 1 schematically presents the relationships which are usually dominant in open coastal karst aquifers whose active cavities may extend to the depths of over 50 - 100 m below sea level.

3. Mechanism of Salt Water Encroachment and its Consequences

From a hydraulic point of view, the regime of ground water flow in such karst reservoirs is a function of an equivalent permeability of diverse porosity types which may be found in the given reservoirs, and results in corresponding losses in hydraulic potential.

Mechanisms of recharge and discharge in such a reservoir accordingly have different durations for each type of porosity, so that the velocity of water flow itself varies from several dm/s in karst channels to several mm/s in fissures.

It is important to mention, that in the same karst channels unusually high pressures develop during high water levels and rapidly decrease during recession conditions. At the end of a dry period, values of hydraulic gradients are very low, about $i = 0.001$ or sometimes even less. Under such circumstances the negative consequences of salt water encroachment and expansion of the brackish zone are inevitable.

The established balance relations between freshwater and salt water depend on the following factors:

- overpressure of freshwater (head);
- density of each fluid and their mixtures (ρ - freshwater, ρ_v - brackish water; ρ_s - sea water);
- differences of water temperature, which accelerate the exchange of fluids, modifying their salinity;
- additional movements caused by tides and waves;
- heterogeneity and anisotropy of the karst aquifers, causing extremely irregular distribution of permeability and effective porosity fields in the aquifer.

Depending on the mutual relationships of the factors mentioned above, the contamination of freshwater by salt and brackish water to a greater or lesser degree, will take place at distances more or less close to the sea. Encroachment of salt water may take place far away from the sea coast (several kilometers), and is favored by numerous anastomosis in the karstic network, and by cavities with particularly large cross-sections, in which overpressure of freshwater occurs only during high water levels. When cavities of this kind directly communicate with the sea, it regularly occurs that (due to their large size and shapes - as in the case of the gallery Port Miou and Bestouan), penetration of salt water into the lower parts of cavities and freshwater flows to the sea in the upper parts will take place at the same time.

In the case of several karstic channels of similar dimensions, the flow regime of freshwater towards the sea and the reverse flow of the sea water will depend on locations of various karstic openings in relation to the sea level. The freshwater flow will follow the law of loss of head, namely, the freshwater will enter the sea if the pressure of the sea water is smaller than the freshwater head.

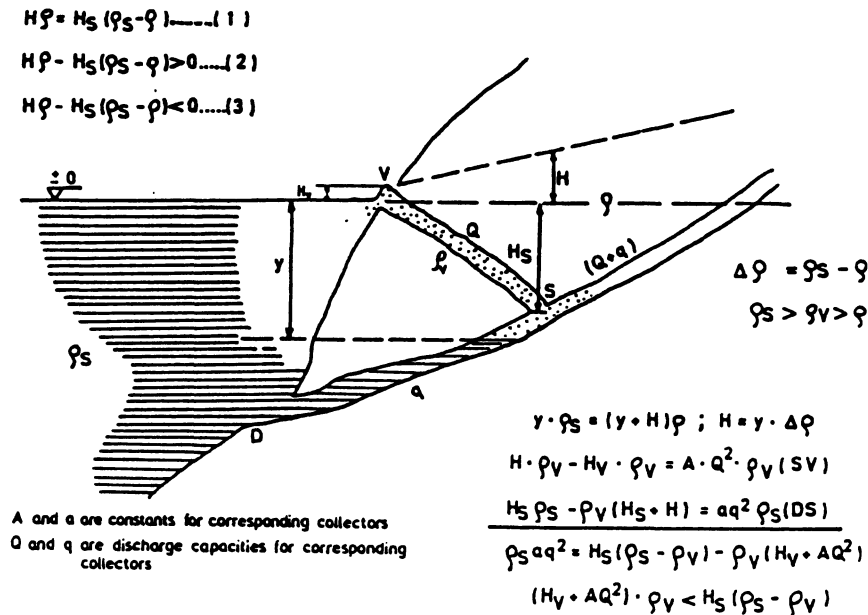


Figure 2. Schematic representation of salting processes in submarine and coastal springs.

Generally, three cases, which are shown schematically in Figure 2, could occur (Djurašin, 1943; Kuščer 1950; Mijatović, 1967):

- freshwater goes out through all openings into the sea;
- freshwater goes out at the upper openings, while at the lower openings there is no net flow;
- sea water enters the aquifer at the lower openings and at the higher openings the brackish water flows out into the sea.

The physical basis of this phenomenon could be easily proved by means of experimental models (Mijatović, 1963). Which of these three cases will take place depends on the special location of the brackish zone in relation to the freshwater spring level. This depends on the hydraulic gradient and the discharge capacity of the spring: the first case occurs when the capacity is large, the second case usually occurs when the capacity is medium, and the third case regularly occurs when the capacity is minimal.

Considering the second case which includes the first and the third one, the following Equation is obtained, (Figure 2):

$$a q^2 \rho_s = H_s (\rho_s - \rho_v) - (H_v \rho_v + A Q^2 \rho_v)$$

From this Equation one can reach certain important conclusions, interesting for practical exploration work and exploitation of freshwater resources in karstic coastal regions. They are the following:

The expression $H_s (\rho_s - \rho_v)$, represents the pressure of the salt water zone, on the freshwater zone in the cavities, and $(H_v + A Q^2) \rho_v$ is an expression (definition) for the pressure of the brackish zone on the salt water in the area of discharge. From the given Equation, it follows that the spring will be more saline if $(H_v + A Q^2) \rho_v < H_s (\rho_s - \rho_v)$, which means that H_v and Q must be as small as possible in absolute values.

The spring will be the most saline in the extreme case when $H_v = 0$ and $Q = 0$, that is, when the spring occurs at the sea level, and dries out. However, for positive values H_v and Q , the spring will be more saline if the depth of interface of the sea water in the collector H_s is greater.

This conclusion, at the same time points to the fruitlessness of the attempts of numerous artificial interventions in the sea and along the coast with the aim of protecting some coastal springs from the damaging influence of the sea by lifting their outflow levels. The danger here is not as much a lateral penetration of the sea water, as a vertical one, which directly originates from submarine springs of the estavelle type, and can often be more intensive, if the coastal spring is captured at a higher level (Figure 3).

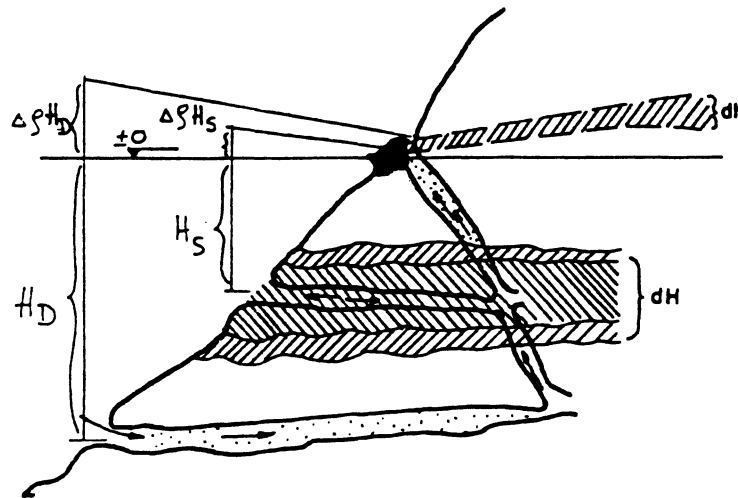


Figure 3. Provocation of the submarine spring by artificial slowing of discharge within the same drainage system.

In the Mediterranean coastal zone the presence of well-developed submarine karst makes illusory any hopes of capturing freshwater outflow into the sea or on the coast, if the geological conditions are not convenient to prevent sea water encroachment into the aquifer. In karstic areas of that kind, the submarine connections of deeper collectors are commonly very complex and open to the sea, to the general depth of - 100 m or more, and thus it is practically impossible to locate the position of a salt water cone affecting the capture. In such cases nothing could be gained by capping those coastal karst springs, for there always remain open deeper cavities, the effects of which are even greater. However, to isolate all these connections in the system would be impossible. The explorations of coastal karst, at various regions of the Mediterranean (Port-Miou, Vrulja, Gurdić, Chekka, Almiros, Ein-Zayana, etc.) have made evident the presence of caves and galleries of large dimensions and easily accessible for divers to the depths of - 45 m in Port-Miou, - 51 m in Gurdić, - 38 m in Pantan, and numerous boreholes have discovered circulation zones of salt water at depths below 100 m. In this respect the case of salting of the well known spring Almiros near Iraklion at the Crete is characteristic. Because of considerable neotectonic activity lowering carbonate blocks by the sea coast, paleokarstic outcrops are activated at the depth of 300-400 m below sea level. That is the reason that the spring is brackish all year round, and so is useless. Consequently, construction of a grouting screen at the coastal spring Almiros is one unsuccessful attempt at freshwater capture along the Mediterranean coast (Figure 4). The hydraulic behavior of certain deep seated karsts is entirely uncertain with respect to making artificial barriers at the sites of coastal springs.

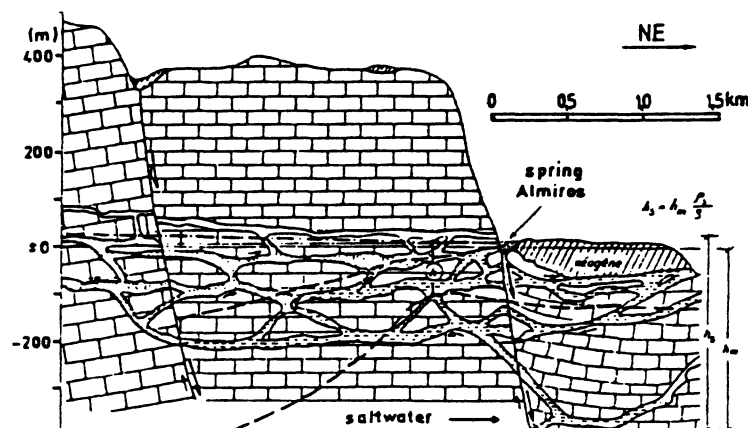


Figure 4. Geological cross-section from carbonate massif of the Keri mountain to the plain of Iraklion and the spring Almiros (Monopolis and Mastopis, 1969).

As the disposition of cavities as a function of depth in the karst drainage network (below the sea level) for each coastal spring is a constant factor, the changeable discharge of the spring regulates its hydraulic mechanism (salting/desalting), throughout the year. Generally, in such cases and under conditions of maximal freshwater flows, the majority of coastal springs become entirely freshwater ones or with Cl contents reduced to negligible levels, depending on the residual salinity ($\rho_s - \rho_v$) for the spring.

In order to prevent damaging salinity, it is essential to prevent the decrease of freshwater head, that is, to create conditions which would make possible a certain overpressure of freshwater which is not in the balance with the transition (brackish) zone (Figure 5).

This could be achieved if the pumping withdrawal is limited, by checking the salinity in the transition zone, or by the monitoring of deep piezometers in the aquifer.

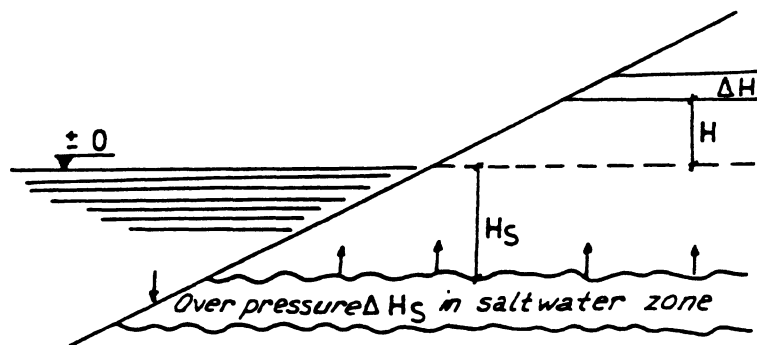


Figure 5. Schematic display of freshwater overpressure, not in balance with the brackish zone.

4. Main aspects of research methodology for freshwater and the protection of its capture in the process of exploitation

The classification of karstic aquifers according to the mechanism of sea water encroachment.

As geological conditions play an important role which evidently affects the hydrogeological features of the coastal karst aquifers and their hydraulic behavior, the possibilities of freshwater capping are different from one area to another. Therefore, geology and hydrogeology studies in their classical sense are indispensable although not sufficient, as they do not always provide results reliable for practical use. So they should be combined with applied methods of explorations.

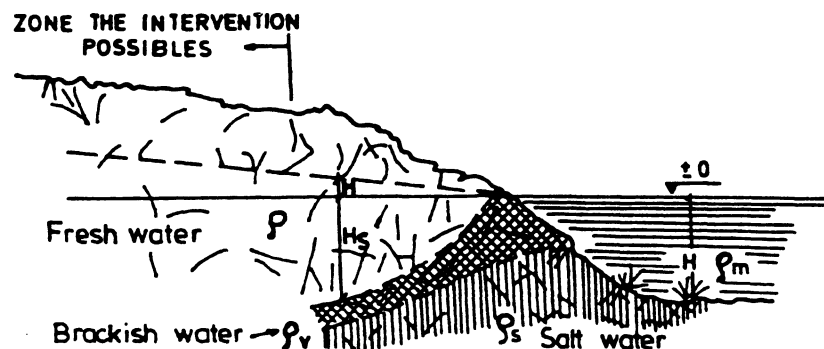


Figure 6. Coastal karst aquifer open to the sea.

If the intrusion of sea water into the coastal zones is considered as the main cause of mixing salt water with freshwater, all littoral karst aquifers can be divided into two basic groups, without regard to their geological age and differences in tectonic structure (Mijatović, 1984):

- aquifers open to the sea, in which hydraulic link between freshwater and sea water is provided through the contact surface between an aquifer and the sea (Figure 6);
- aquifers with incomplete barriers in the sea, in which the hydraulic link between freshwater and sea water is obtained only through localized contact surfaces between the aquifer and the sea, depending on the hypsometric position of the incomplete barrier (Figures 7 and 8).

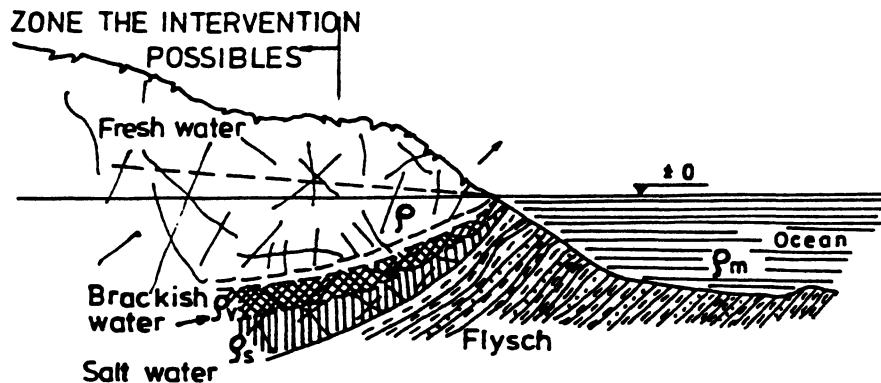


Figure 7. Coastal karst aquifer with incomplete barrier in the sea.

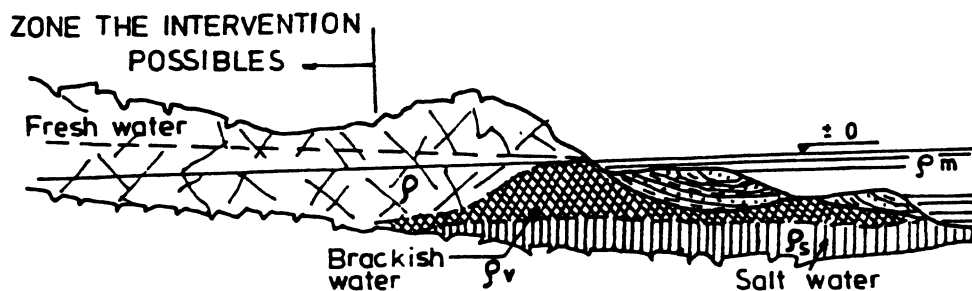


Figure 8. Coastal karst aquifer with hanging barrier.

However, aquifers with complete barriers cannot be the subject of discussion, since they are not affected by salt water intrusion.

Depending on the location and extent of the contact surface between karstified rocks and the sea (geometrical boundary conditions), different processes of salt water intrusion into freshwater zone can occur in the case coastal karst aquifers with incomplete barriers. However, there are only two basic cases:

- aquifers with an incomplete barrier in the sea, in which the sea water intrusion occurs above the barrier (Figure 7) and
- aquifers with a hanging barrier in which the sea water intrusion occurs below the barrier (Figure 8).

By a detailed study of the characteristics cited and typical examples we can get some useful hydrogeological criteria for setting up a calculation scheme for an aquifer. The purpose is to contribute to more rational design of capture projects for the optimum utilization of freshwater in littoral karst on the basis of field monitoring and investigation.

Depending on the location and size of the interface between an aquifer and the sea, various types of mixing occur. This is particularly relevant to the capture and exploitation of freshwater. Therefore, particular attention should be paid to the proper choice of the location of the capture facility and its type:

- the vertical well, or
- the horizontal drainage gallery.

The capture of freshwater in coastal karst aquifers with cavities of large size and preferred directions of drainage involves many risks concerning both capacity and water quality if the capture is based on a system of wells. On the other hand, capture facilities of the horizontal gallery type have proven to be reasonably efficient under such conditions. They obtain maximum capacity through cavities with preferred groundwater flows; they reduce salt water encroachment during withdrawal of freshwater. The balance can be obtained by regulation of pumping or by a radical intervention in the collectors themselves (building an artificial barrier across the direction of water circulation).

Horizontal drainage galleries have played positive roles at several locations in coastal karst regions. Table 1 provides some basic information concerning the capture facilities on the Dalmatian coast and the one near Benghazi on the Libyan coast.

Table 1. Capture facilities on the Dalmatian coast and Libyan coast.

Locality	Distance from the sea (km)	Tech. characteristics		Min. capacity (l/s)	Cl ⁻ content ppm (mg/l)
		Depth of shaft (m)	Length of gallery (m)		
Dubrava 1	3,0	28,0	110,0	35,0	35
Dubrava 2	3,7	40,0	150,0	15,0	50
Kovča	4,0	70,0	50,0	25,0	30
Roman well	2,0	82,0	270,0	100,0	250-300
K ₁ - Brač	0,8	18,0	20,0	1,0	400-500
K ₂ - Brač	1,8	52,0	400,0	5,0	300-400
Žuljana	1,0	18,0	30,0	10,0	300-400
Marina	3,0	33,0	400,0	45,0	200-250
Sidi Mansour - Lybia	11,0	80,0	500,0	400,0	250-300

5. The control system of salt water encroachment in the protective zone of the captages

To protect the operation of capture facilities against intrusion of salt water it is necessary to install a control system for monitoring of brackish and salt water migration into a wide influence zone between the capture facility and the sea. From this purpose, a network of piezometers is set for monitoring the transition zone, both in its horizontal and vertical cross-sections.

Disposition and number of piezometers depend on structure of the aquifer subjected to water exploitation as well as the mechanism of sea water encroachment into the lower karstic cavities. In setting up a system for monitoring contamination effects on extracted freshwater, it is necessary to identify as precisely as possible the following:

- the fields of hydraulic potential in the freshwater, and in salt water encroachment between the capture facility and the sea;
- the fields of permeability and effective porosity;
- the vertical conductivity along the profile from freshwater to salt water, based on measuring the vertical gradient of salinity in piezometers;
- the evolution of salinity in all piezometers on the basis of simultaneous testing of water columns in control wells;
- the delimitation and structure of the transition (brackish) zone;
- the depth of effective groundwater flow in the aquifer - reservoir.

Methods of measurement and testing to be applied must be determined on the basis of the specific geological and hydrogeological conditions of the area.

As successes of this system of control, one can mention the examples of the capture facilities near Pantan spring on the Dalmatian coast and Skurda and Gurdić springs in the Gulf of Kotor, where the directions of salt water encroachments toward the capture facility have been determined by precise monitoring of the field of hydraulic potential.

6. Conclusions

Experiences obtained in investigation and the use of coastal karst aquifers reveal a wide variety of relationships between these aquifers and the sea. Both problems regarding water capacity and water quality are always very closely connected with the phenomenon of sea water encroachment. This phenomenon is still insufficiently defined in the scale of capture facilities, as analyses and tests of the chemical and physical properties which regulate contamination of the freshwater, are usually approximate. Unfortunately, there are not sufficient reliable monitoring data and interpretation to indicate the zones subject to salt water encroachment.

In general, it is recommended freshwater protection in regions of coastal karst should be undertaken by integrated management of water resources, including direct interventions regarding overpressure improvements in the zone of freshwater with convenient gradients; this is actually the most effective protection against the negative influence of the sea water.

For this purpose, complex (interdisciplinary) methods of exploration and choice of the optimal type of capture facilities, appear to be the only possibility. With respect to determination exploitation capacity and control of interactions between the freshwater and the salt water over the wide expanse of the capture zone it is also advisable to proceed on the basis of a synthesis of the results obtained, either theoretical and practical, in investigations of this phenomenon. Practical experience provides more and more justification for this approach, throwing more light on the exploitation problems of freshwater aquifers in the coastal karst regions, and their protection of loss of freshwater to the sea.

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NUMERICAL MODELLING OF COASTAL DISCHARGE: PREDICTING THE EFFECTS OF CLIMATE CHANGE

OBERDORFER, J.A.

1. Summary

Numerical modeling of the Pajaro Valley, California coastal aquifer system for varying climate scenarios tested the sensitivity of groundwater discharge to variations in sea-level, flooding, recharge rates, and pumping rates. For many scenarios, the results varied by only a few percent from what a simple water budget would predict. The main departures were the result of groundwater/surface water interactions which would be difficult to quantify without more complex modeling.

Numerical models are useful tools in groundwater studies, particularly for predicting the consequences of varying global climate change scenarios since these cannot be tested short-term on a field scale. Variations in sea level, in recharge from rainfall, in inflow from surrounding bedrock, and in interactions with surface water bodies can be evaluated rapidly if the aquifer system is well-enough understood to support the detailed approach of numerical modeling.

The coastal aquifer system selected for analysis was the Pajaro Valley located on Monterey Bay, 100 km south of San Francisco, California (Figure 1). The valley forms part of a tectonic depression which is infilled with Quaternary alluvium, terrace deposits and dune sands.

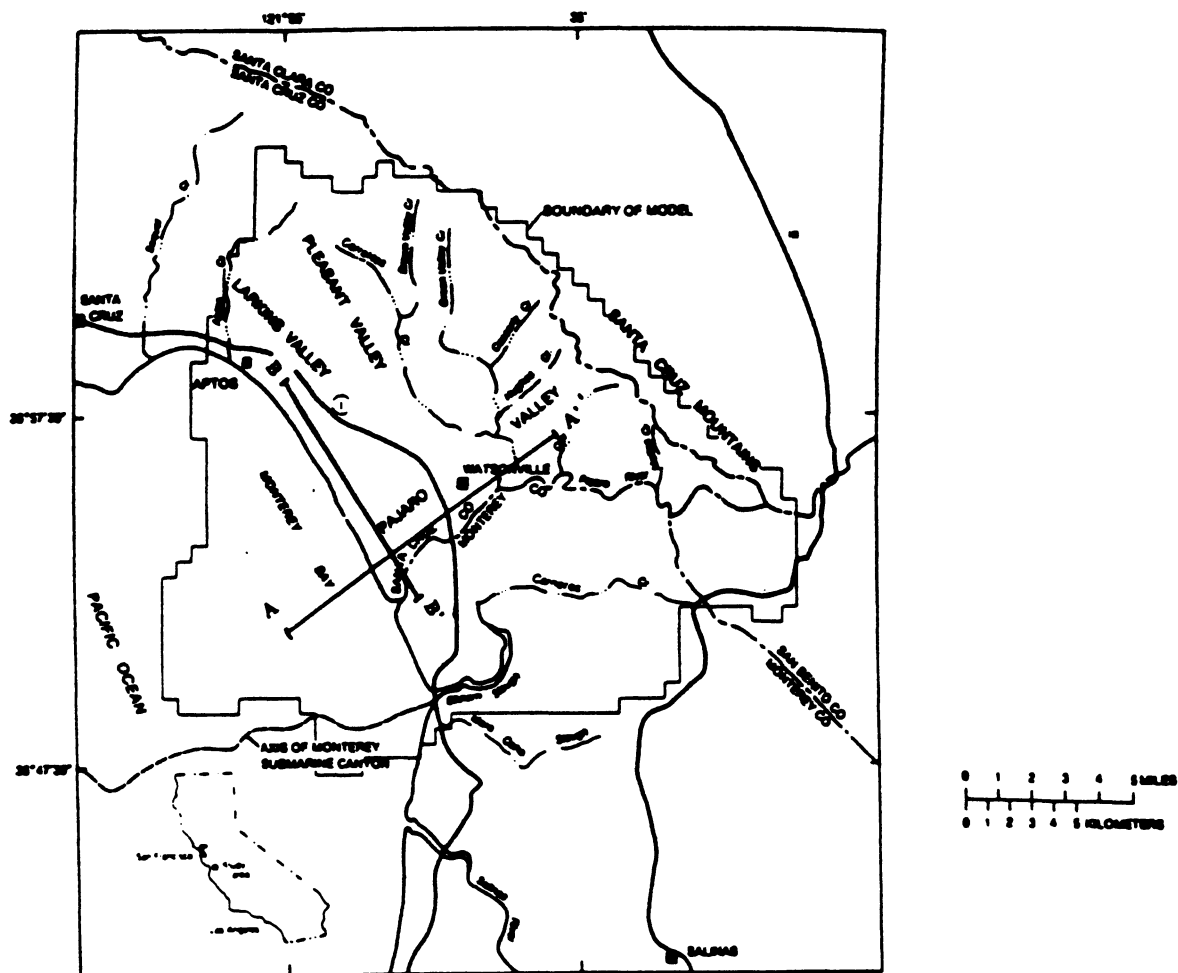


Figure 1. Location map of Pajaro Valley with cross-section locations (after Johnson *et al.*, 1988).

Three aquifers have been identified (Figure 2): a shallow unconfined aquifer which discharges along the shoreline, and two deeper, confined aquifers which discharge to the ocean at outcrop locations along the walls of the Monterey Submarine Canyon. All three aquifers are hydraulically connected through leaky aquitards. The Pajaro River and a number of lesser streams recharge the groundwater in their upper reaches and act as discharge zones for groundwater in their lower reaches. Rainfall in the valley varies with topography from 400 mm/yr near the shore to 1100 mm/yr in the foothills to the north. Groundwater inflow occurs from adjacent, less permeable, bedrock aquifers.

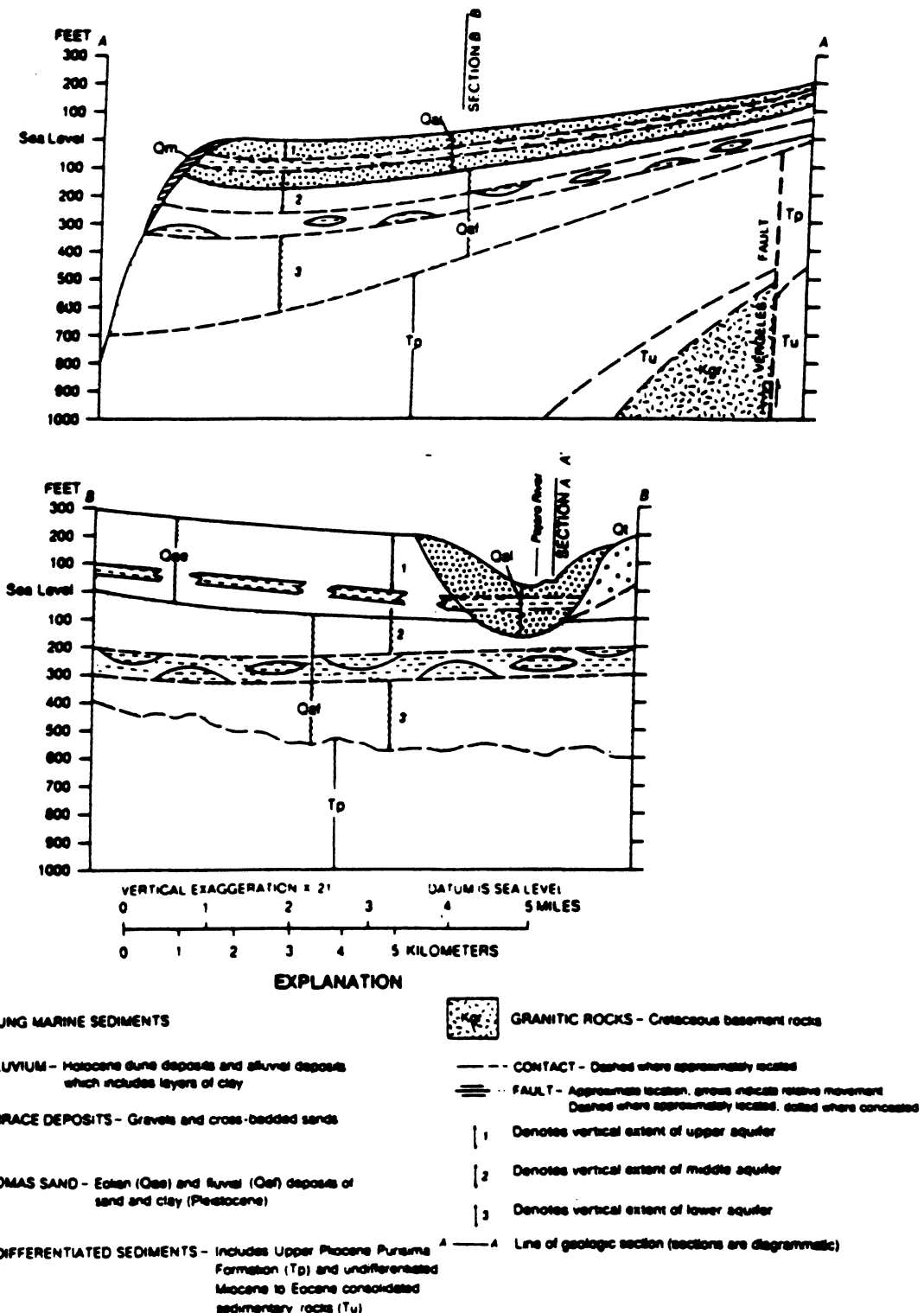


Figure 2. Geologic cross-sections (Johnson *et al.*, 1988).

This study is based on previous modeling work of Johnson *et al.* (1988) who utilized the U. S. Geological Survey groundwater flow code MODFLOW (McDonald and Harbaugh, 1984) to simulate the behavior of the three water-bearing zones under historic stresses. MODFLOW is a modular, finited difference code which is versatile, verified, and can simulate the major hydrogeologic processes examined. The finite element grid (Figure 3) was set up as squares, 610 m long on a side, and consisted of 43 rows and 44 columns. For the base case simulation, inputs to the aquifer were rainfall recharge (73%), inflow from surrounding bedrock (27%), and seepage from the streams (0.2%). Outflows consisted of discharge to the ocean (97%) and discharge to the streams (3%). The total discharge from the aquifer was approximately $1.8 \times 10^5 \text{ m}^3/\text{d}$.

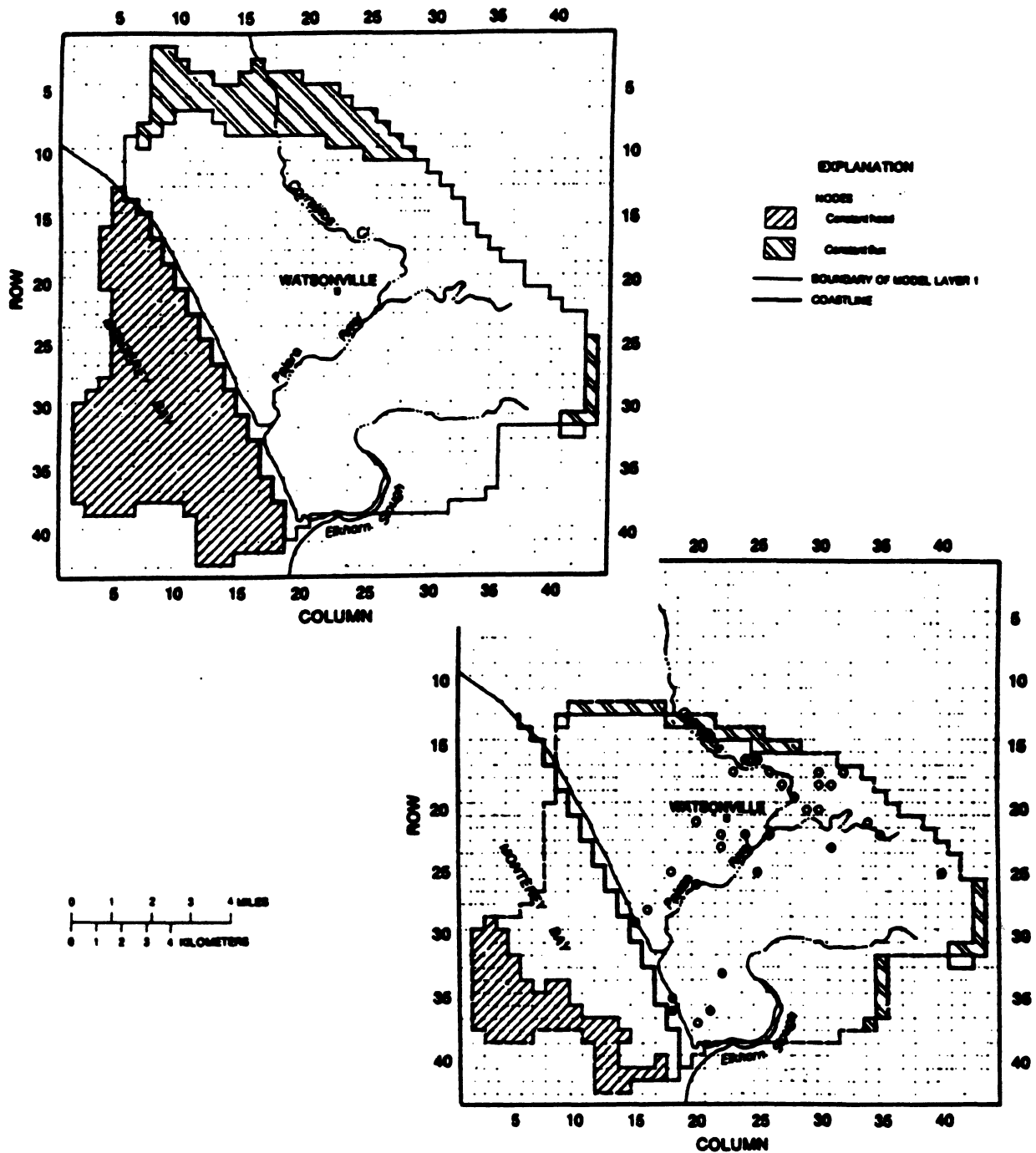


Figure 3. Finite difference grid for Layers 1 and 2; the Layer 3 grid is similar to that for Layer 2 (Johnson *et al.*, 1988).

Four sea-level rise scenarios (1 m, 2 m, 4 m, and 8 m) were tested (Figure 4), which included comparable rises in river stage near the shore. The resultant rise in groundwater levels reduced seepage from the streams and increased groundwater discharge to the stream. As a consequence, direct discharge to the ocean was slightly reduced (1 - 3%). When flooding of low-lying areas was added for the 4 m and 8 m scenarios, recharge was reduced due to loss of surface area. Discharge to streams declined since the lower reaches of the rivers were inundated. Discharge along the coast was reduced (3 - 6%) because of the reduction in recharge.

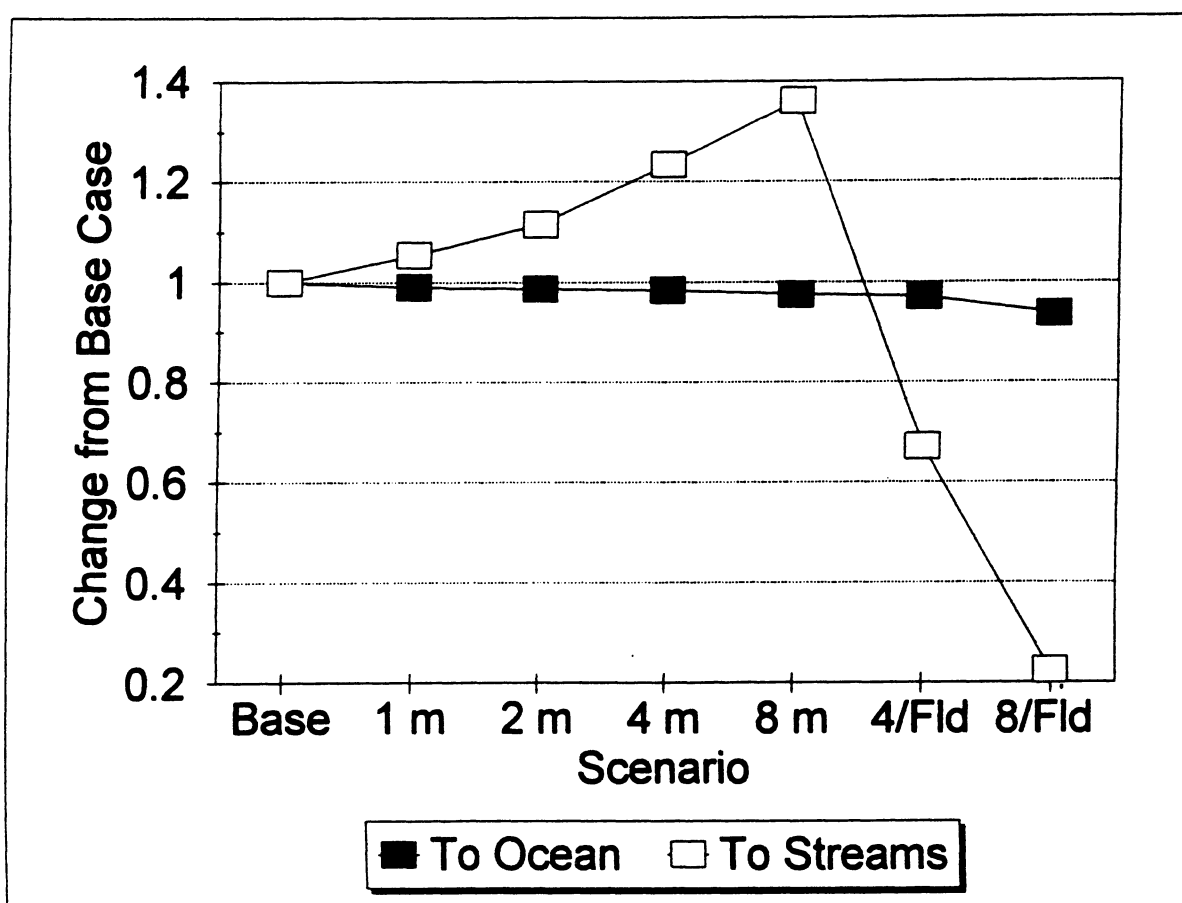


Figure 4. Results for discharge to the ocean of sea level change scenarios (without and with flooding), relative to the base case discharge.

Changes in precipitation rate were simulated by modifying recharge, bedrock inflow, and river stage to represent increases of 25% and 50% and decreases of 25 and 50% relative to the base case water inputs. Increased inputs caused groundwater levels to rise significantly. This resulted in seepage from the river declining and discharge of groundwater to the river augmenting markedly. Discharge to the ocean increased slightly less than the increase in inputs, due to the augmentation of discharge to the river. The scenarios with decreases in inputs to the aquifer system had the opposite results: groundwater levels declined markedly and discharge to the streams decreased. The resulting discharge to the ocean being affected slightly less than proportionally to the decline in inputs, due to the decreased discharge to the streams.

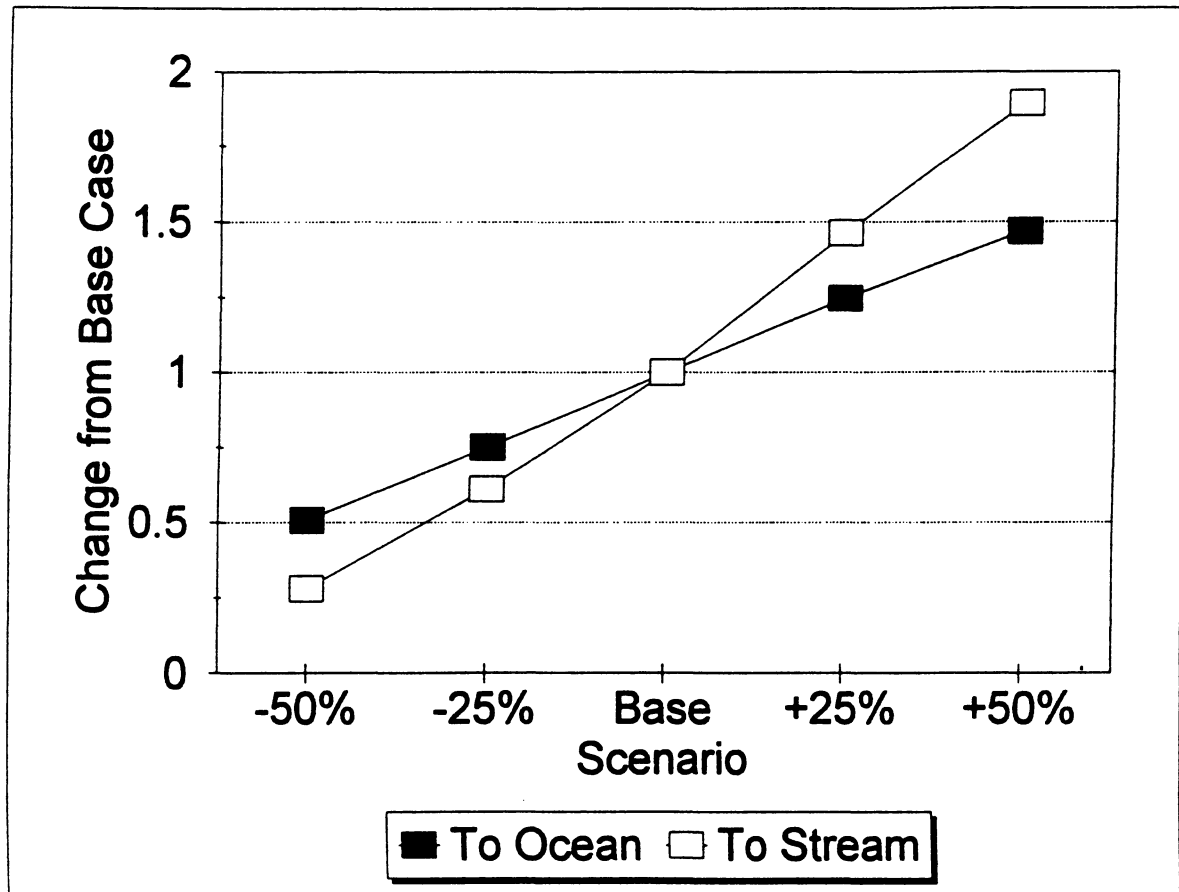


Figure 5. Results for discharge to the ocean of scenarios for changes in recharge, relative to the base case discharge.

A scenario was run in which groundwater pumping (at a rate equal to 25% of the total base case inputs) was initiated to compensate for the decrease in rainfall in the 25%-decrease-in-inputs scenario. Additional water level declines were observed, along with a decrease in groundwater discharge to the streams, an increase in stream recharge of groundwater in the upper reaches, and an increase in inflow from the surrounding bedrock. The discharge at the coast declined (to 58% of the base case), but to a lesser degree than that expected by taking the loss of recharge and the pumping into account (expected to be 50% of the base case). The altered stream recharge and discharge patterns and the increased bedrock seepage account for this difference.

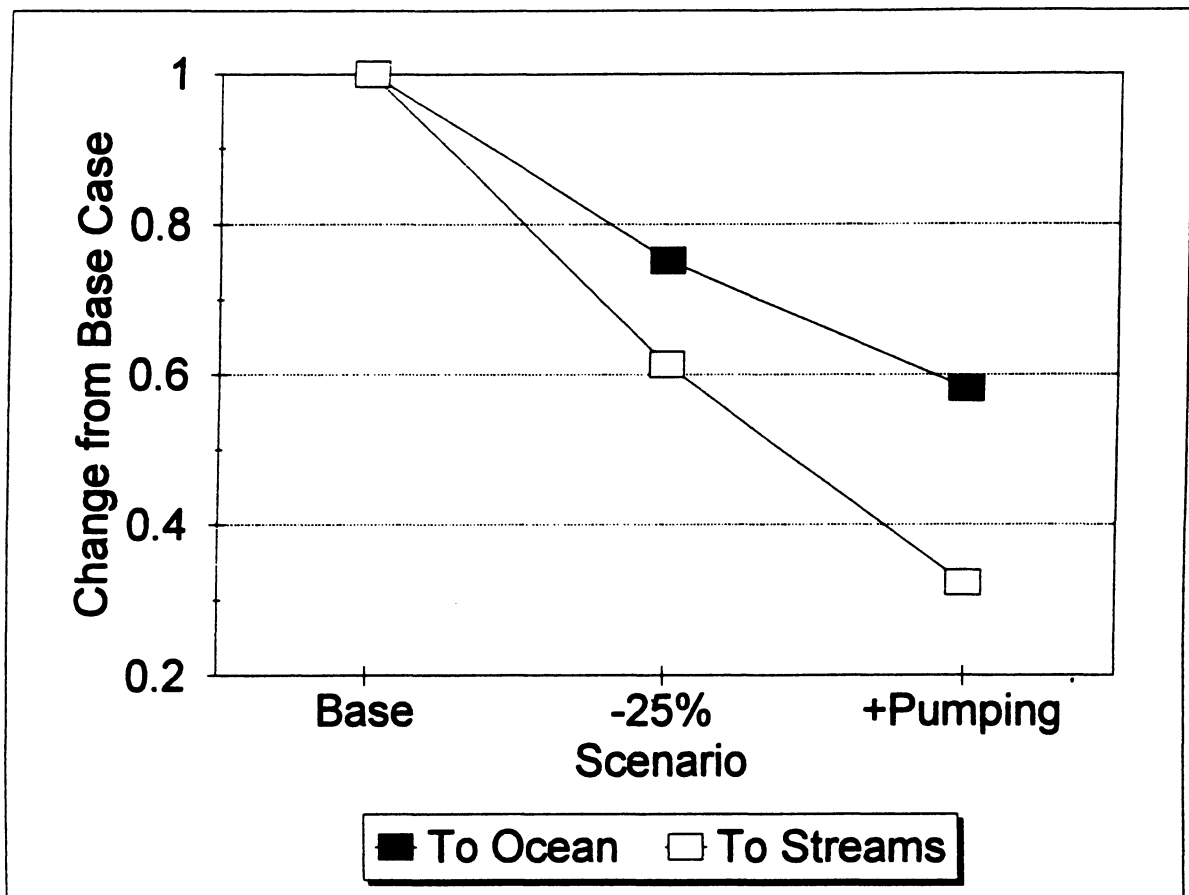


Figure 6. Results for discharge to the ocean of scenarios of 25% decreased recharge (without and with pumping) relative to the base case discharge.

For many of the climate change scenarios, the groundwater discharge to the ocean varied by only a few percent from what would have been predicted with a simple water budget. The main variations from a simple water budget prediction were the result of groundwater/surface water interactions which would be difficult to quantify without knowing the spatial distribution of hydraulic head and its effects on the seepage to and from streams. For very simple groundwater basins, use of a water budget could be an adequate first approach to predicting changes in coastal discharge. For more complex basins with multiple sources and sinks (surface water bodies, inflow from adjacent aquifers), numerical modeling can provide a better quantitative estimate of perturbations to the present groundwater system resulting from climate change.

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THE HYDROGEOLOGY OF THE NORTHERN YUCATAN PENINSULA, MEXICO, WITH SPECIAL REFERENCE TO COASTAL PROCESSES

PERRY, E. C. and VELAZQUEZ-OLIMAN, G.

Northern Yucatan, Mexico (Figure 1) is a platform of Tertiary carbonate rocks dipping northward with a slope that generally is considerably less than a meter per kilometer. Because of this low slope, the coastline has been quite sensitive to the sea level rise of about 110 m in the last 18,000 years (Fairbanks, 1989; Coke *et al.*, 1991). Where undisturbed by human activity, this coast consists of an almost continuous dune ridge (fed by a westward-moving longshore current) that is broken in several places where groundwater discharge is exceptionally high. Behind the dune ridge is a hypersaline swamp. All water discharging from northern Yucatan arrives at the coast as groundwater. There are no surface streams more than a few hundred m long in the northern Peninsula (Perry *et al.*, 1989).

Most of the aquifer system of the northern Yucatan Peninsula is developed in 200-to-1000-m of permeable, mostly flat-lying Tertiary limestone and dolomite, with no persistent aquitards, that overlies the terminal Cretaceous Chicxulub bolide impact crater and its surrounding breccia blanket (Hildebrand *et al.*, 1991, 1995; Sharpton *et al.*, 1993). A lens of fresh groundwater 15 to 100 or more m thick overlies a saline intrusion that extends 90 km or more inland. Hydrogeology in northwest Yucatan is strongly influenced by a 165-km-diameter basin of Tertiary sedimentation bounded by a semicircular fault system marked on the surface by a Cenote (sinkhole) Ring (CR) that acts as a major groundwater conduit (Figure 1). The CR is probably coincident with a faulted ring of the Chicxulub impact crater (Pope *et al.*, 1991; Perry *et al.*, 1995). Because Eocene and Oligocene sedimentation occurred within the Chicxulub basin while karst erosion was occurring outside, interconnected cavern permeability is less developed within the basin than outside.

The CR discharges to the coast at Estuario Celestun and Bocas de Dzilam, two natural breaks in the coastal dune system characterized by abundant brackish water springs (Estuario Celestun) and by springs and four (or more) short streams discharging into a mangrove swamp (Bocas) (Perry and Velazquez, 1995). The western arm of the CR carries water from an evaporite terrain and contains abundant sulfate, a useful tracer. The evaporite component probably originates at a groundwater divide near Lake Chichancanab (Figure 1), a lake whose waters are approximately saturated with respect to gypsum. Sulfate and sulfate-chloride content of groundwater indicate that high-sulfate water moves northwestward along the Ticul Fault (Figure 1) to the western arm of the CR. This sulfate-rich water is discharged from the CR into Estuario Celestun. Sulfate-rich, chloride-poor groundwater also moves southeastward from the area around Lake Chichancanab, surfacing in the 62-m-deep Cenote Azul in southeast Quintana Roo, near the coast (Figure 1). Submarine discharge of this high-sulfate water into nearby Bahia Chetumal is likely.

Groundwater discharge to Estuario Celestun and Bocas de Dzilam is seasonal. At the Celestun bridge over Estuario Celestun, the estuary water had about 30% of the chloride content of seawater in December, 1993 (several months after the rainy season) and 70% of seawater chlorinity in May, 1994 (just before the beginning of the rainy season). To account for this dilution there must be outward flow of fresh water, but the dimensions of the channel are such that the flow produces little or no net measurable current (compared to currents induced by tidal fluctuations of up to 0.8 m. We have suggested (Perry and Velazquez, 1995) that the wide, shallow channels connecting the estuaries to the sea at Bocas de Dzilam and Estuario Celestun are kept open not only by physical currents but also by a process of carbonate dissolution similar to that observed on the east coast of the Yucatan Peninsula at Xel Ha and other places in Quintana Roo (Back *et al.*, 1979, 1986; Stoessell *et al.*, 1989).

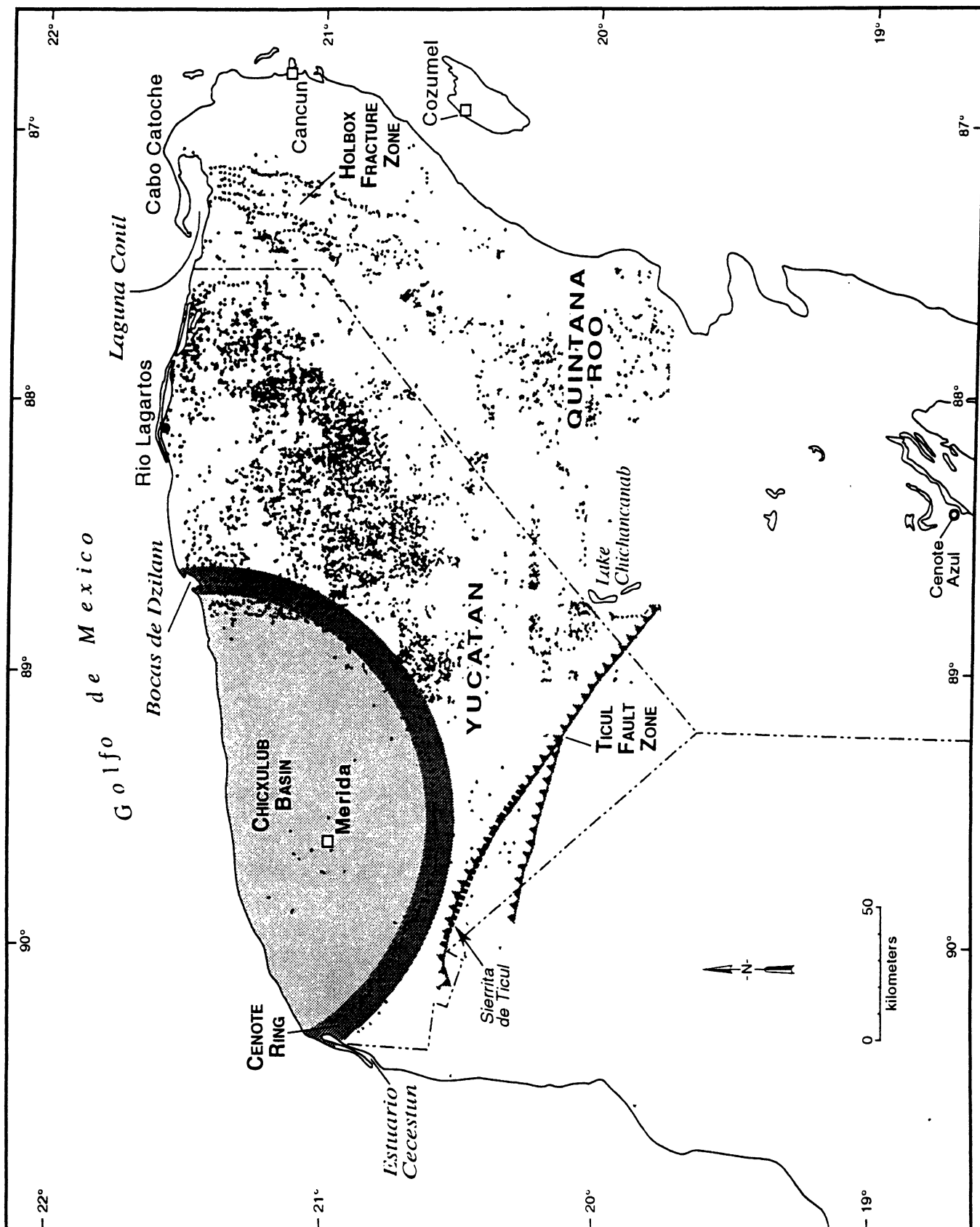


Figure 1. Northern Yucatan Peninsula showing the Cenote Ring, Chicxulub sedimentary basin, Ticul Fault, and Holbox Fracture Zone (as a set of aligned cenotes). Gray dots are cenotes (from Hildebrand *et al.*, 1995). Highest concentration of cenotes (east of Cenote Ring and south of Rio Lagartos) marks zone of extensive Tertiary weathering that may have resulted in solution of gypsum-bearing impact breccia (Perry *et al.*, 1996).

Mixing of fresh groundwater with seawater, both saturated with respect to calcite, can produce an unsaturated water capable of dissolving either calcite or aragonite (Runnels, 1969; Back *et al.*, 1979). For example, groundwater from Kopoma, a town located on the CR, about 50 km from the coast, is near saturation with respect to calcite and somewhat undersaturated with respect to aragonite. Most of the groundwater in the northern Peninsula is approximately saturated with respect to calcite. When Kopoma groundwater is mixed with about 45% normal seawater, the resulting solution is calculated to be aggressively undersaturated with respect to both calcite and aragonite (Figure 2). Consider what must happen to Kopoma groundwater when it is delivered to Estuario Celestun by the CR and discharged into the estuary under confining pressure through bottom silt and mud (composed almost entirely of calcite and aragonite). A measurement made in the estuary in May (at the end of the dry season) showed that Estuario water was strongly evaporated and consequently supersaturated with respect to calcite. At the same time, a piezometer placed in bottom mud became filled with brackish groundwater which rose to a height several centimeters above the level of water in the estuary. This groundwater was slightly supersaturated with respect to aragonite and distinctly supersaturated with respect to calcite. Nevertheless, a mixture of 40% of this bottom groundwater and 60% estuary water is precisely at saturation with respect to aragonite (Figure 3). Thus, a mixture of two waters (Kopoma groundwater and seawater) is calculated to be capable of dissolving carbonate, whereas the mixture of the two waters actually collected at the site of mixing is, in fact, in equilibrium with aragonite, the most soluble carbonate. This saturation suggests that mixing zone dissolution of carbonate material is taking place in the estuary just as has been reported on the east coast by Back *et al.* (1979). However, in contrast to the rocky east coast where erosion is obvious, no rocks are exposed along the northwest coast, and the strong, regular west-moving longshore current delivers a steady supply of carbonate sand and silt that blankets carbonate rock for about a kilometer out from shore (where the water depth is 5 to 8 m).

A distinctive feature of the northern Yucatan coast is the presence there of a calcrete confining layer formed where the groundwater table intersects the nearly flat topographic surface (Perry *et al.*, 1989). Here, evaporation and degassing of CO₂ result in precipitation of CaCO₃ that continuously heals subsidence cracks in the surface calcrete. Slowly rising sea level has propagated this layer inland to produce a 0.5 m coastal aquitard sufficiently impermeable to produce a head (responsive to tides) of up to 40 cm at the coast. This impermeable coastal aquitard is responsible for the phenomenon, mentioned above, of a positive head in groundwater rising through bottom sediment in Estuario Celestun.

On the eastern north coast of the Yucatan Peninsula, significant groundwater discharge occurs to Laguna Conil (Figure 1) through the Holbox Fracture Zone, a region of long, narrow swales parallel to >100 km long chains of elongated solution depressions aligned with offshore tectonic structures related to plate boundaries inactive since the Late Eocene. Channelled discharge along the fault-bounded east coast develops solution inlets such as Xel Ha and Xcaret.

Recent measurement of Sr in a deep cenote on the northeast edge of the CR indicates probable direct water circulation between surface and an evaporite-bearing K/T impact breccia layer 200 m deep or more (Perry *et al.*, 1996). This indicates probable existence of a deep, interconnected cavern system developed during times of lower sea level. In the north this system is occupied by the saline intrusion and is thus not available to carry fresh water discharge. A reconnaissance study of the eastern coast indicates that, perhaps because of greater recharge and/or lower permeability, the fresh water lens is thicker. As noted above, the deep Cenote Azul (Figure 1), practically on the coast, is part of a system that drains a region of evaporite. Its water contains only 1.25 meq/l of Cl but 25.75 meq/l of SO₄ indicating positive flow preventing mixing with seawater. Possibly, groundwater here is moving through a deep, cavernous system.

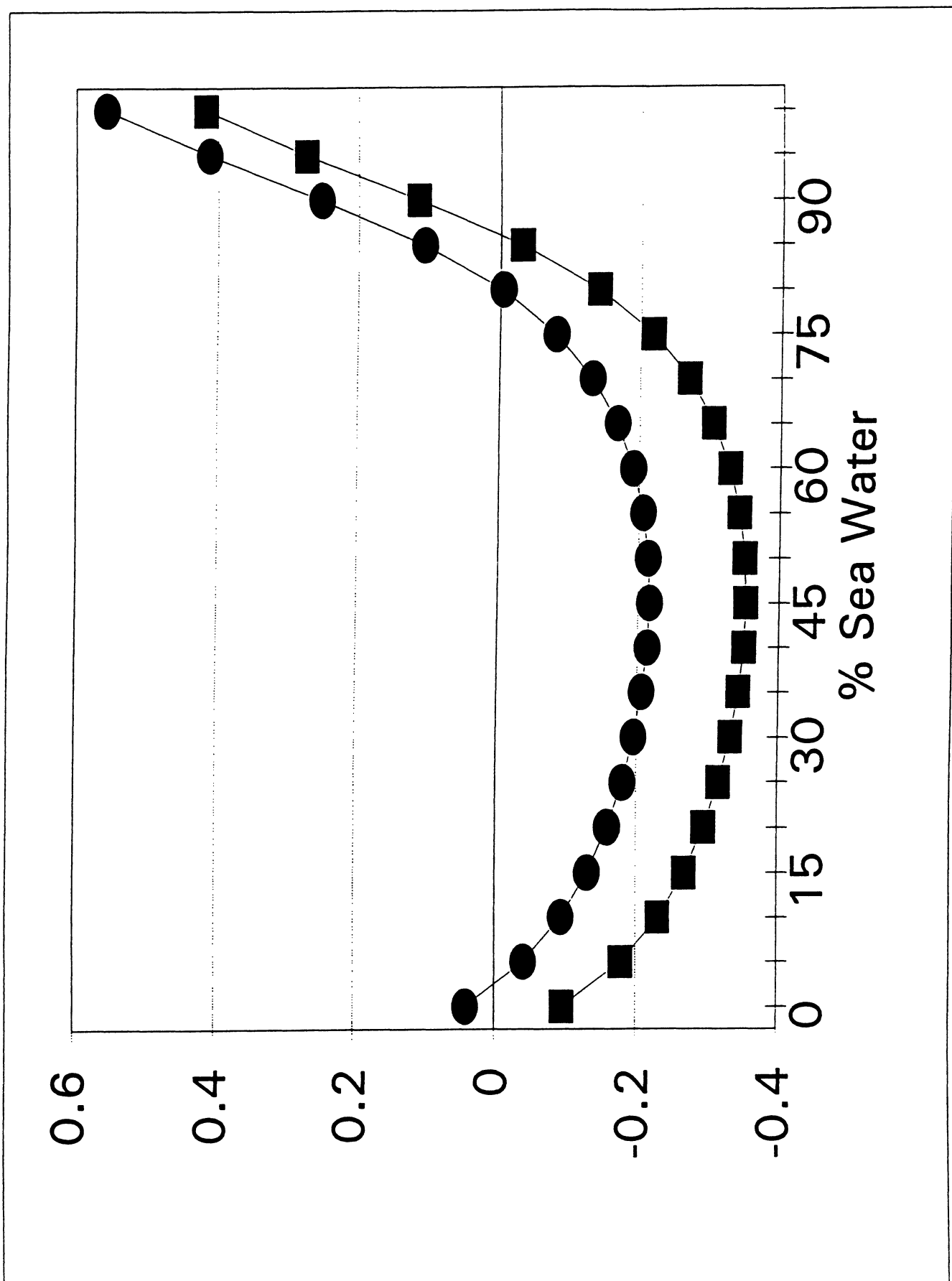


Figure 2. Calculated result (using SOLMIN) of mixing Kopoma groundwater with seawater. Saturation index = $\text{Log}\{[\text{Ca}^{++}] \times [\text{SO}_4^{--}]\} / K_{\text{sp}}$. Positive values indicate supersaturation; negative values indicate undersaturation.

Mixing Estuary with Celestun Bottom*

*Estuary wtr with Bottom wtr (May 94)

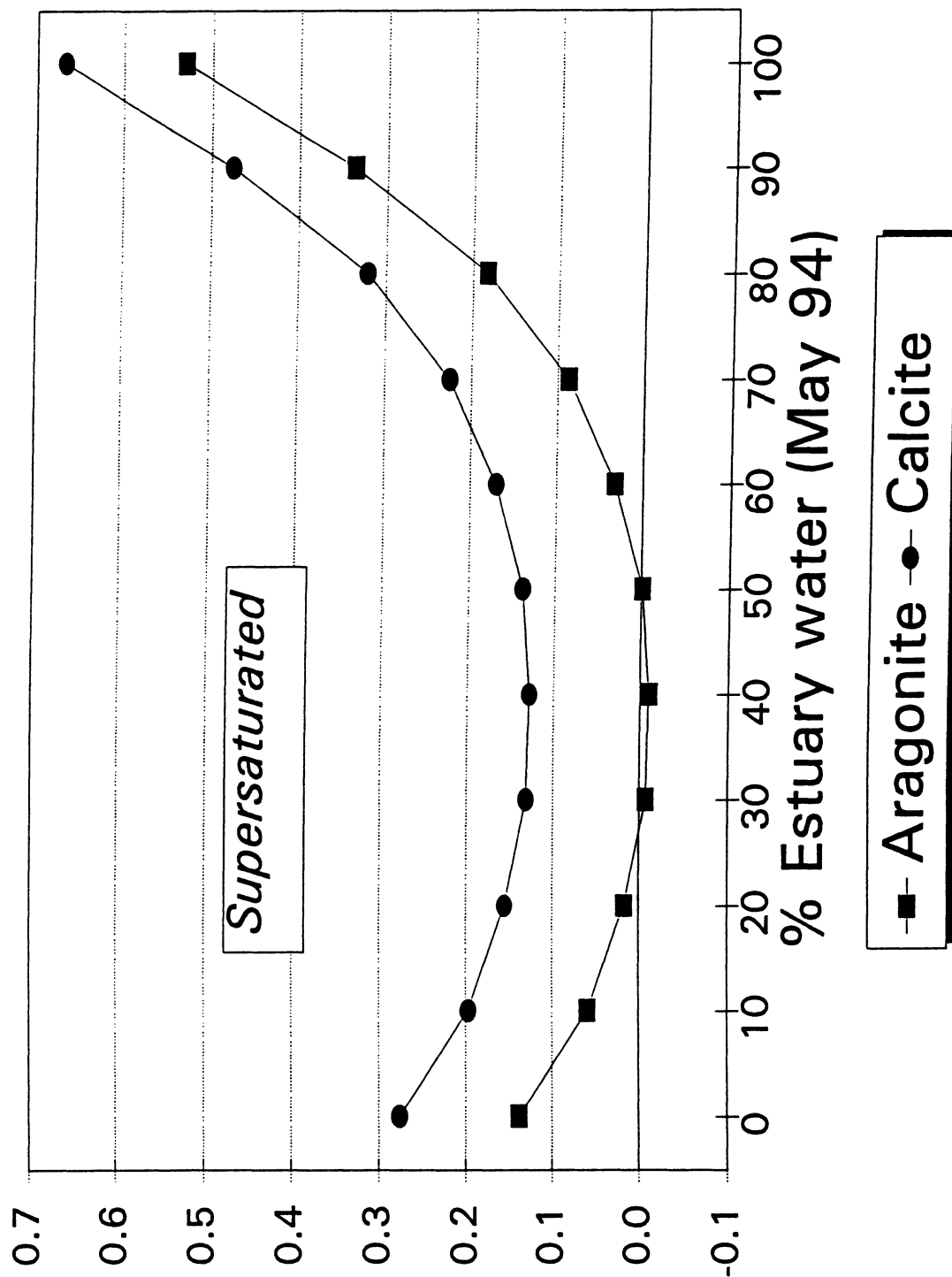


Figure 3. Calculated result of mixing surface water from Esterio Celestun with estuarine groundwater.

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1. Abstract

This work shows that the analysis of ^{222}Rn concentrations in a carbonate karstic and fissured aquifer containing variously distributed amounts of terra rossa, is a powerful tool for producing a better characterisation both of the superficial and of the subterranean hydrogeological environment. To this effect, concentration data must be surveyed following an areal distribution, as well as at various at the same location, and over time: the analysis will then provide a full range of additional information on the hydrodynamic characteristics of the aquifer and on groundwater hydrology, also in connection with the water supply and depletion processes.

The method was developed in the Apulian Cretaceous carbonatic environment which has been previously described in a number of detailed studies and is therefore well known. This work is also based on a large number of specially planned surveys carried out by conventional methods.

2. The Methodological Approach

As problems connected with subterranean waters are investigated to gain a better understanding of specific conditions and mechanisms that are often difficult to interpret, one must also try and work out new methodological approaches and elaborate further previously acquired information.

From this point of view, ^{222}Rn , a radioactive gas naturally present in groundwater, may yield valuable indications of the mechanisms affecting subterranean circulation of water in fissured karstic carbonate aquifers like the one known as the Apulian aquifer.

Radon belongs to the noble-gas group and has many radioactive isotopes, the longest half-life being 3.82 days for mass number 222, symbol ^{222}Rn : it is produced continuously by the alpha decay of ^{226}Ra in the ^{238}U decay series, occurring in varying amounts in rock formations.

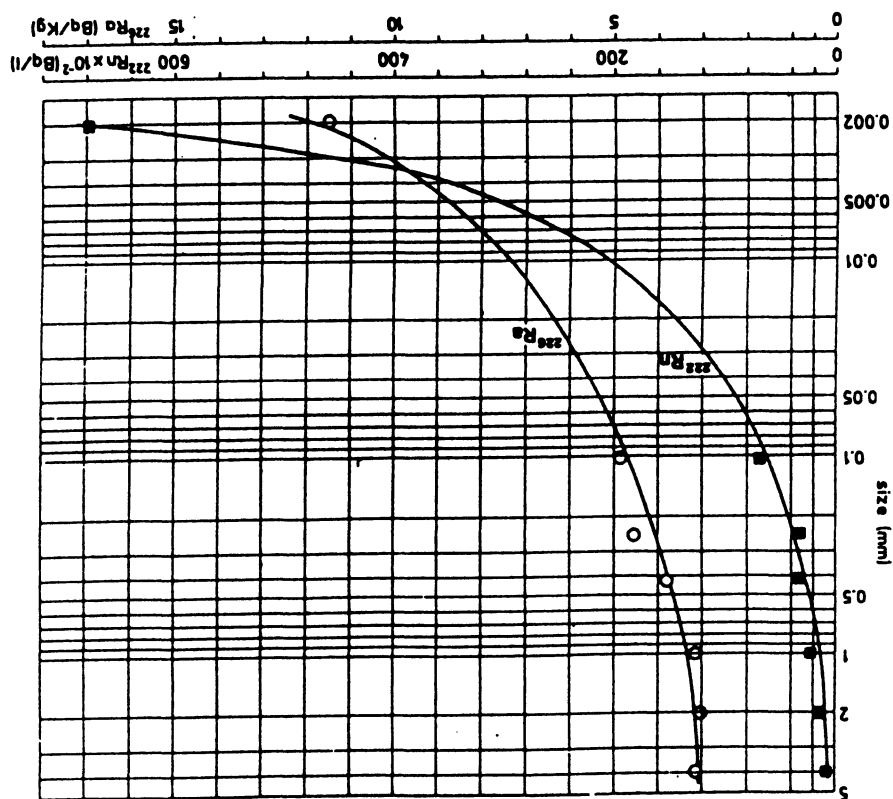


Figure 1. The dimensions of crushed calcareous material as related to ^{226}Ra concentrations in the rock and to ^{222}Rn in water, respectively.

It is a well-known fact that the kinetic energy of the ^{222}Rn fraction emitted by the crystal lattice of ^{226}Ra is rather low and is dissipated as the gas migrates through the intermolecular spaces; only the radon atoms produced on the marginal portion of the mineral's particle can escape and pass into solution in the waters permeating the rock (NWWA Conference, 1987; Tanner, 1980).

The amounts of ^{222}Rn that are so released (Figure 1) are closely related to particle size distribution, to the rock-water surface of contact, and to the time interval during which such contact occurs, whereas its diffusion in the groundwater depends mainly on the waters' hydrodynamic conditions (NWWA Conference, 1987; Tadolini and Spizzico, 1996). On the other hand, the intensity of radioactivity released from the Rn-emitting rocks depends on the rocks' thermal state because the solubility of ^{222}Rn increases when water temperature increases and decreases with increasing hydrostatic pressures.

Briefly, the Apulia geological environment is represented by a Mesozoic carbonate platform that is several thousand meters thick, well stratified and characterised by a monotonous succession of limestones and, subordinately, of dolomites. Geographically, its western portion is called Murgia, the eastern one is known as Salento. The main distinguishing features of the two areas are represented by their morphostructural set-up and geographic configuration.

Rock fracturing is often scanty and discontinuous; it may be quite intense locally, but varies greatly with depth. The karst process is fairly well developed both superficially and deep down, where tectonic fracturing has contributed to its genesis and evolution.

Water flowing inside the platform belongs to a single huge groundwater body: however, the two main morphostructural units described above differ essentially in terms of their hydrological features (Grassi and Tadolini, 1985). Having established the diffuse presence of ^{222}Rn in groundwater at concentration levels ranging from a few Bq/l to over 400 Bq/l, which are not comparable to those usually encountered in carbonate rocks, more had to be learned about the factors determining the observed high gas levels (Torgesen *et al.*, 1990).

Indeed, it would seem that still other phenomena should be triggered to make the water circulating in a fissured karst aquifer capable of maintaining a steady presence of the investigated gas at the observed concentration levels; nor could one believe that such concentrations are due to ^{226}Ra salts passing into solution in the groundwater through the rock's dissolution process.

^{226}Ra concentrations are relatively low in the calcareous-dolomitic rock both in the Murgia and in Salento. The order of magnitude (50-70 Bq/kg) is similar to those reported in the literature (Magnoni *et al.*, 1995); however, the Cretaceous carbonate formation contains, both superficially and inside karst fissures and cavities to considerable depths, large and variable amounts of "terra rossa" having a particularly high ^{226}Ra concentration of about 200 Bq/kg. Studies of the geochemistry and mineralo-genesis of the Apulian "terra rossa" (a reddish clay soil) in the investigated areas show that such soil results from the dissolution of limestones and dolomites and from subsequent re-working of non-carbonate residues (Dell'Anna, 1967; Moresi and Mongelli, 1988).

Laboratory findings show that the dissolution processes, whereby carbonate rocks eventually turn into karst forms, do not involve all of the radium salts contained in the rock; conversely, insofar as they reflect the rock's degree of dissolution, it is the residual products that present varying, though often high, concentrations of radium salts. When "terra rossa" is attacked chemically by H_2SO_4 and HCl , then a significant increase in ^{222}Rn concentration is observed in the water due to the resulting smaller particle size and also because a conspicuous amount of radium salts passes into solution.

In the light of the above statements, it appears that through the radioisotope characteristics of "terra rossa" we can gain a better understanding of the state of karstism in a carbonate environment and also derive indications about storage capacity and about natural or induced groundwater circulation.

Having said this, a particular isotopic cycle of water can now be define as follows: rainwater becomes enriched in radon as it flows away over soils that contain "terra rossa". When it starts replenishing the aquifer as supply water, it conveys ^{222}Rn down to considerable depths, just as it does transport "terra rossa" if this is made possible by favourable geo-environmental conditions. Inside the aquifer, then, groundwater flows into subterranean cracks and cavities and is thus further enriched in ^{222}Rn depending on the extent to which it has been in contact with the residual products of karstification and on the corresponding residence time (Tadolini *et al.*, 1996).

It goes without saying that the different radon concentrations observed are basically connected with the karst phenomenon, and thus with the presence of "terra rossa" that contains various amounts of ^{226}Ra and is more or less copiously distributed inside the aquifer. With a higher degree of karstification, hence in the presence of large karst conduits and extended cavities with "terra rossa" deposits, there are often correspondingly large amounts of water that are higher in ^{222}Rn concentrations.

In the Apulian groundwater body, ^{222}Rn concentrations differ greatly, both areally and, at one and the same spot, with depth; moreover, at any given sampling point (Figure 2), concentration generally changes with time over both short and long intervals (Cotecchia *et al.*, 1989; Tadolini *et al.*, 1994; Cotecchia, 1977).

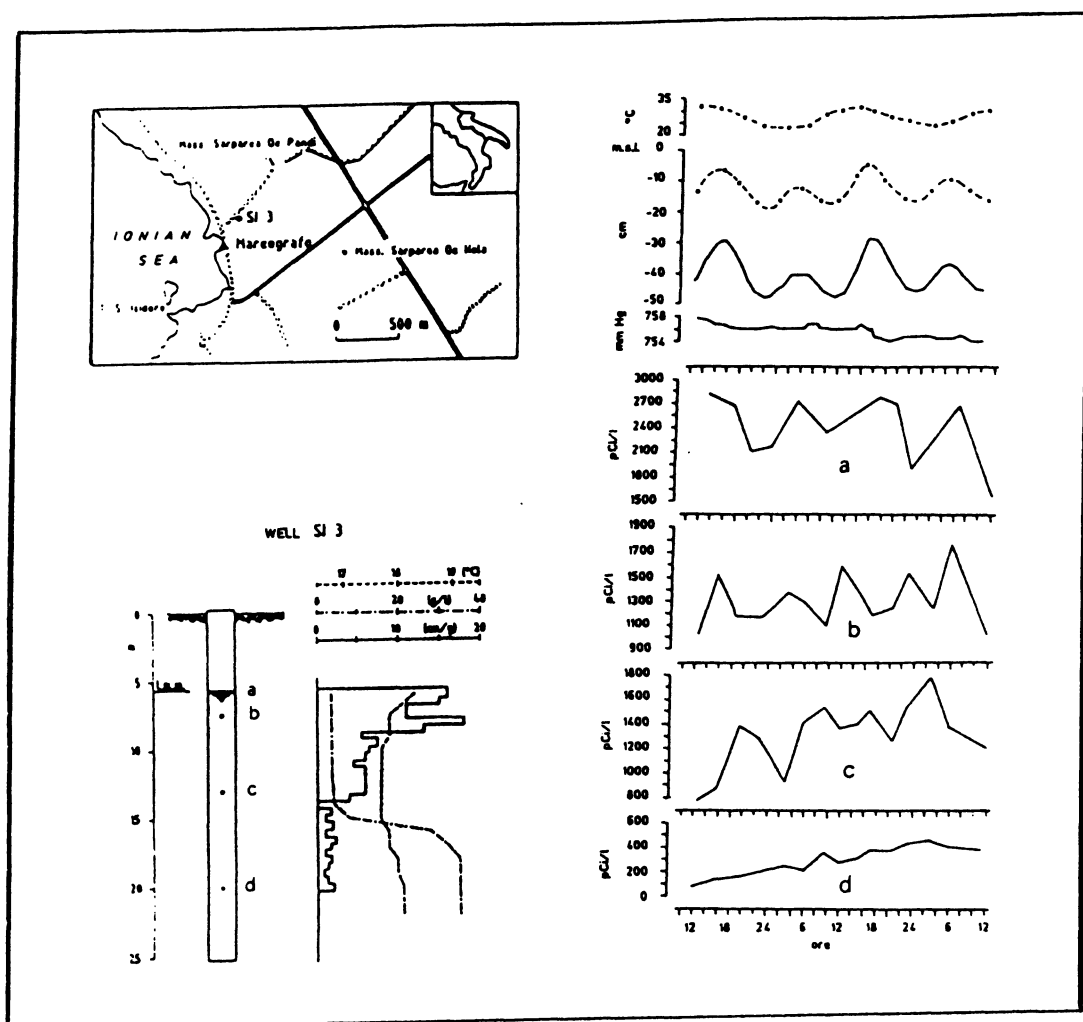


Figure 2. Time course of ^{222}Rn concentrations at different water levels selected on the basis of data obtained from temperature and salt logs and from the distribution of groundwater velocities as measured along the water column inside the borehole; trends of air temperature (T_a), depth of watertable (l.f.), sea level (l.m.) and atmospheric pressure (p.atm.) are also shown.

As a result of field surveys, water locations having Rn concentration levels of the same order of magnitude and, more generally, similar hydrodynamic characteristics over more or less extended areas, could be aggregated (Figure 3); such characteristics are well described by "specific yield", which is the most appropriate parameter for representing the permeability of a fissured karstic aquifer (Tadolini *et al.*, 1996). It was found that in those areas where waters are high in ^{222}Rn concentration, the karst system houses heavy amounts of terra rossa which means that permeability may be either high or low, depending on whether the water conduits are large enough to be practically open or are partly obstructed by the presence of terra rossa.

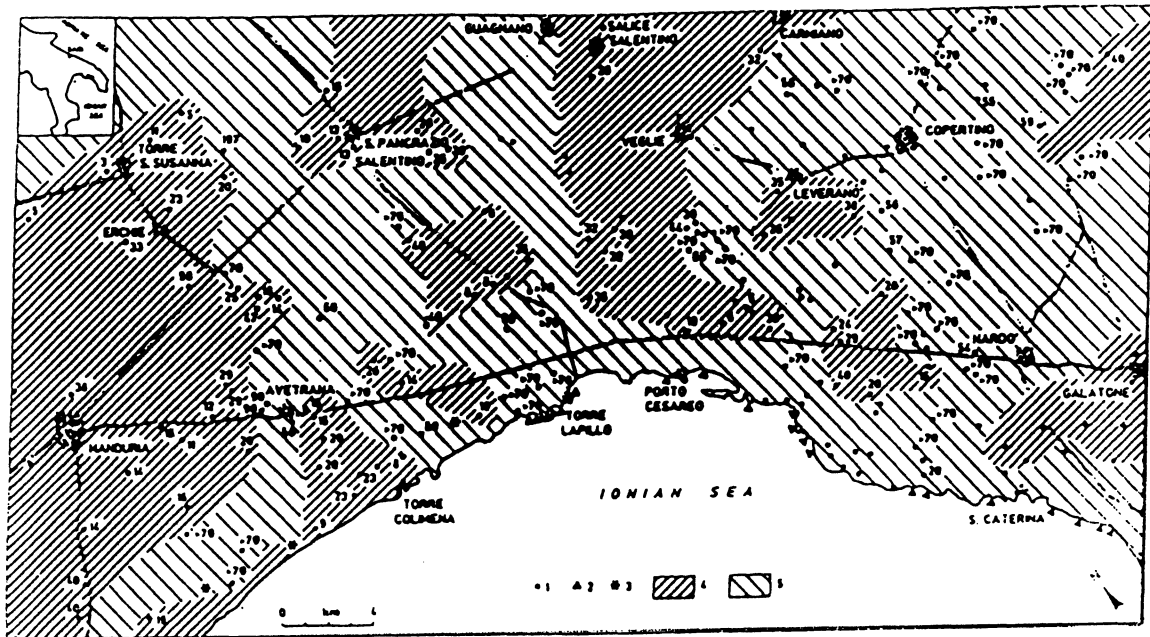


Figure 3a. Distribution of specific yield values (Q_{sp}) providing a good representation of permeability in the aquifer's investigated section (1. borehole; 2. coastal spring; 3. subaerial spring; 4. $Q_{sp} < 50$ l/s.m; 5. $Q_{sp} > 50$ l/s.m).

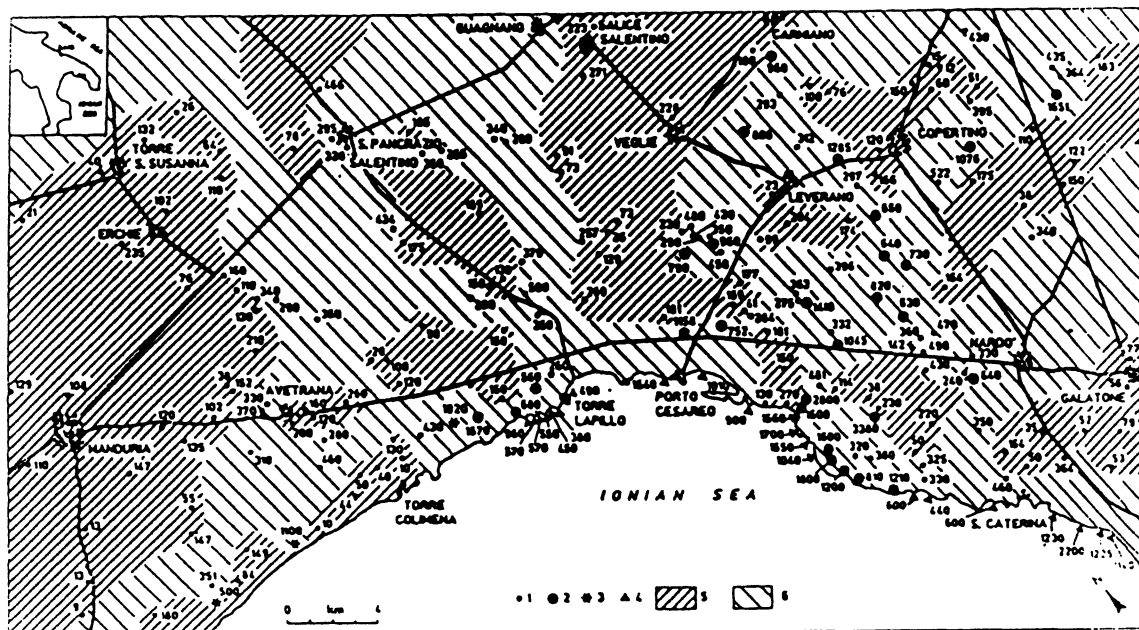


Figure 3b. Distribution of ^{222}Rn concentration levels in groundwater (1. borehole; 2. borehole with ^{222}Rn concentration levels > 600 pCi/l; 3. subaerial springs; 4. coastal springs; 5. areas characterised by the presence of ^{222}Rn at concentrations < 270 pCi/l; 6. areas with ^{222}Rn concentrations > 270 pCi/l).

Conversely, relatively low radon concentrations are indicative of a scanty presence of terra rossa and permeability may be either comparatively high or else quite low, according to whether the system is fully open or partially closed.

In both cases the hydrogeological system is defined by comparing the distribution of radon and of "specific yield".

Groundwater replenishment and depletion processes are also adequately reflected by the changing ^{222}Rn concentrations that can be observed over time when all the data collected for a whole water year at the same water sampling points and in a well defined portion of the aquifer are considered simultaneously (Tadolini *et al.*, 1994). By comparing the various concentrations, differences as high as 100% or more are observed and the following conditions are thereby highlighted: periods of low water withdrawals along with periods of low water supply; periods when groundwater is pumped under conditions of water stress and corresponding initial depletion phase; periods roughly coinciding with the termination of heavy water pumping and with the phase of groundwater depletion; no pumping phase and a corresponding water recharge phase. During the latter phase rainwater, being practically radon-free, causes the ^{222}Rn concentrations in the water inside the aquifer to be diluted (Figure 4).

Since, as stated earlier, the groundwater ^{222}Rn content closely depends on the presence, however varied and discontinuous, of terra rossa and on the length of time during which water becomes enriched in radon, it follows that water mobility plays a role of paramount importance upon the concentrations of this gas. Under conditions of normal flow, filtration rate is generally slow, about a few m/day at most; when the pumping season begins, groundwater velocity becomes remarkably faster and the directions of flow are quite varied both vertically and through inputs from portions of the aquifer adjoining the study area. This process may even cause the circulation of waters that, under normal groundwater flow conditions, are practically still. In addition to that, pumping also cause groundwater pressure to drop, favouring migration of gas bubbles.

In coastal areas, changes in the groundwater hydrodynamic distribution and in the position and thickness of the interface between fresh water and salt water are caused by sea level fluctuations; consequently, the differences in water heads between sea- and groundwater are yet another reason for the changes observed in filtration rate and for the reversed direction of flow, which favours seawater ingress into more inland districts.

Overall, these phenomena are well highlighted by ^{222}Rn (Figure 5). At first, the rising phase in seawater level is attended by increasing groundwater flow velocity, hence by a rising concentration of the radioactive gas; subsequently, due to the "buffer" effect brought by the sea upon water outflow, radon concentration decreases again because of the overall slowing down of water velocity and of the resulting marine intrusion that causes a mixture between groundwater and seawater, with the latter obviously being extremely low in radon concentrations.

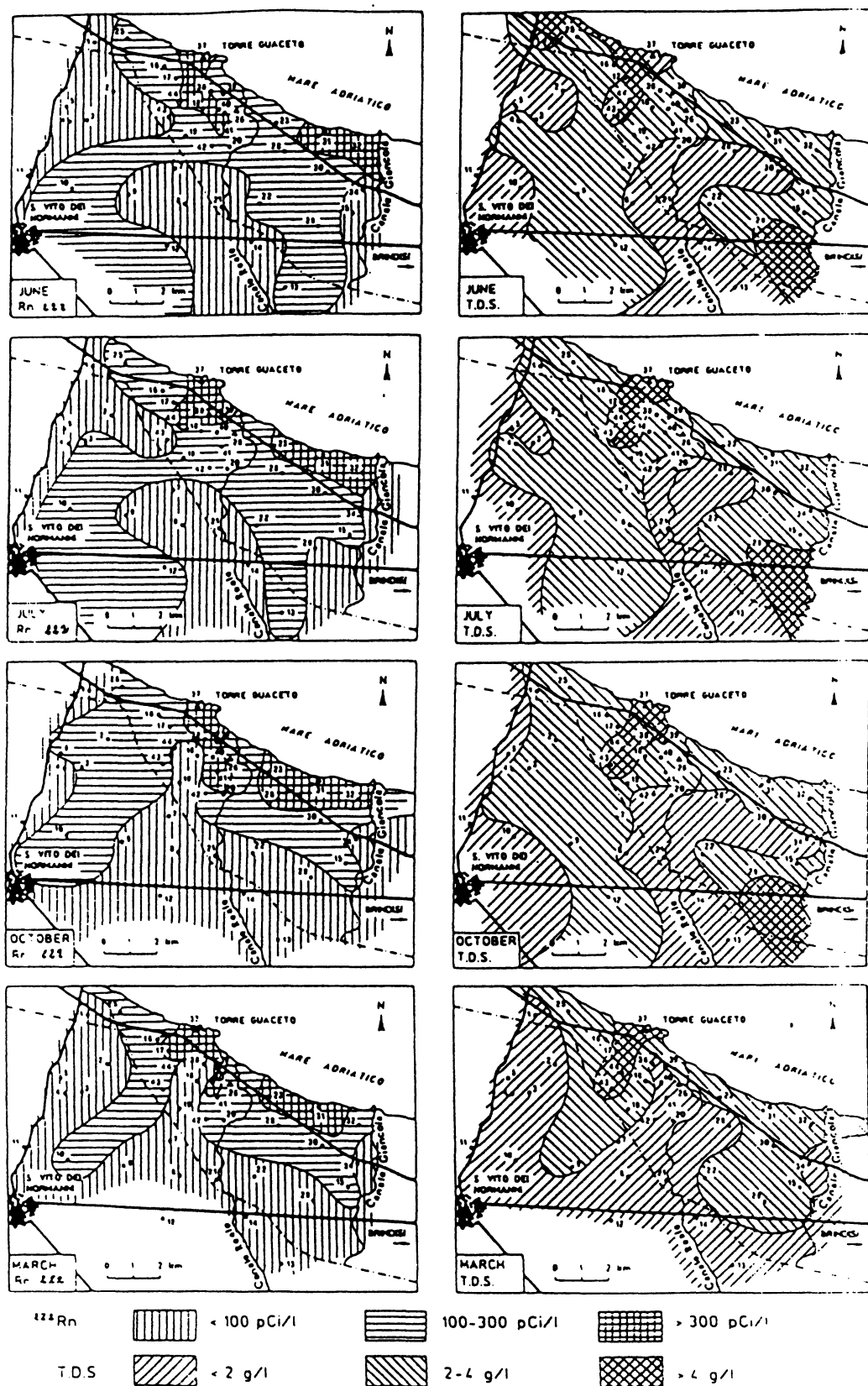


Figure 4. Different distributions of ^{222}Rn and T.D.S. concentrations in the karstic aquifer during the periods of observation, as follows:

- * a period of active water withdrawal and low supply from upstream reaches (June);
- * a period of peak pumping and of almost complete groundwater depletion (July);
- * period roughly coinciding with termination of the pumping season and with lowest level of groundwater depletion (October);
- * no pumping and groundwater recharge phase (March).

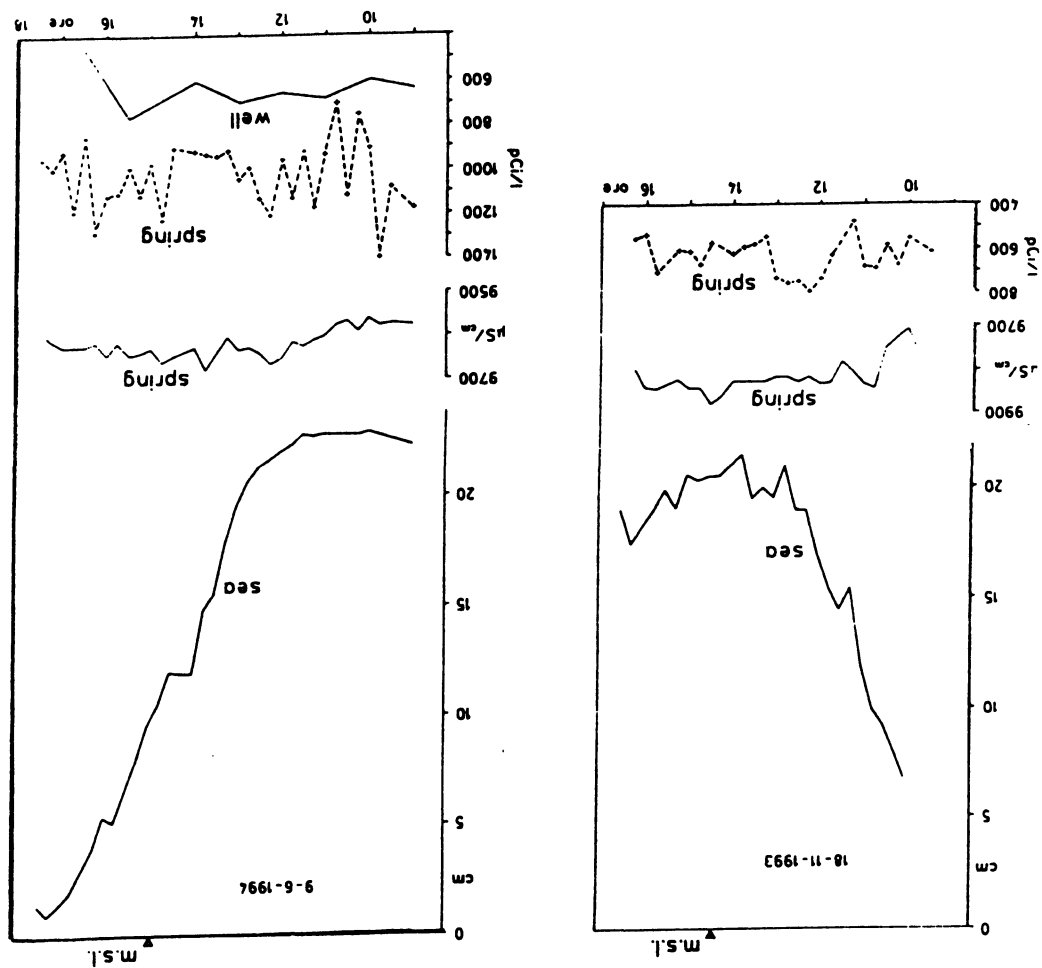


Figure 5. Changes in ^{222}Rn concentrations correlate with changes of sea level and of salt concentrations in the water flowing from a coastal spring and in that withdrawn from a well just inland from the shore. Subsequently lowering sea levels again mobilise the groundwater body resulting into increased radon concentration.

Furthermore, despite their cyclic variability, ^{222}Rn concentrations are an excellent indicator for characterising carbonate hydrogeological environments, no matter how complex and articulated (Tadolini *et al.*, 1995) by defining the degree of permeability and particularly by marking the main subterranean circuits followed by groundwater down to its outlet (Figure 6).

This is confirmed by detailed reconstructions from data obtained by conventional survey methods.

Note also that along coastal strips where groundwater drainage is quite effective, one often observes a highly developed form of karstism with larger amounts of terra rossa, and thus with higher concentrations of radium-emitting salts in the water (Figure 7).

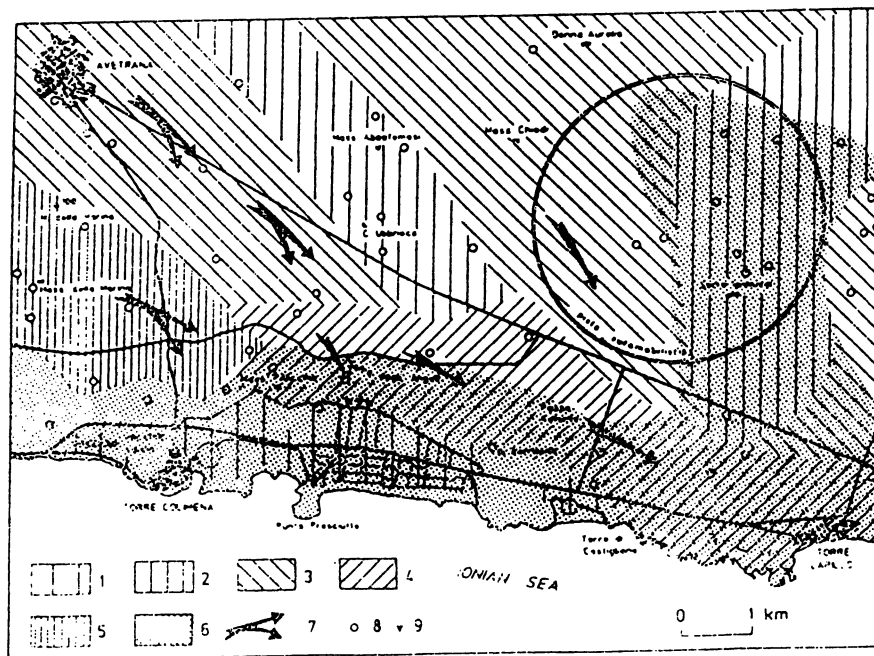


Figure 6a. Map of subterranean water circulation: 1. preferential flow areas essentially originating from direct groundwater supply; 2. preferential flow areas mainly developed along large and deep circuits strongly conditioned, among other elements, by the barrier to free seaward outflows imposed by Calabrian clays; 3. zone of confined groundwater flow where the impervious formation reaches very deep into the aquifer and where encroaching sea waters prevail; 4. zone where the ground waters just described flow together and are then actively mobilised by inland and coastal springs; 5. lowlands mostly controlled by drainage systems; 6. zone where fresh groundwater is mostly displaced by sea water ingressions from below; 7. main directions of flow; 8. wells; 9. springs.

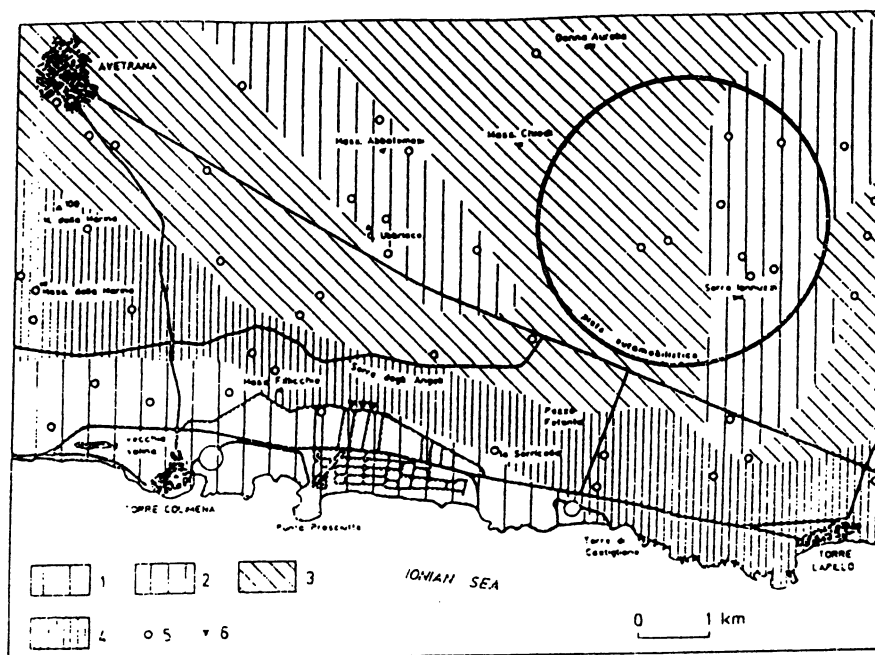


Figure 6b. Map of groundwater mobility as assessed by the radioisotope method. 1. Portion of aquifer where mobility ranges from zero to low owing to the obstruction to free seaward outflow imposed by the clay mass or else to the presence of scarcely permeable rocks (50-400 pCi/l); 2. Portion of aquifer with confined water flow in low permeability soils, locally reaching considerable depths (100 - 900 pCi/l); 3. aquifer housing water bodies coming from groundwater supply zones and flowing with fair mobility (800-1900 pCi/l); 4. Portion of aquifer containing groundwater from various circulation systems having good levels of permeability; its groundwaters shows a wide range of mobility, all the way from good to high (>2000 pCi/l); 5. wells; 6. springs.

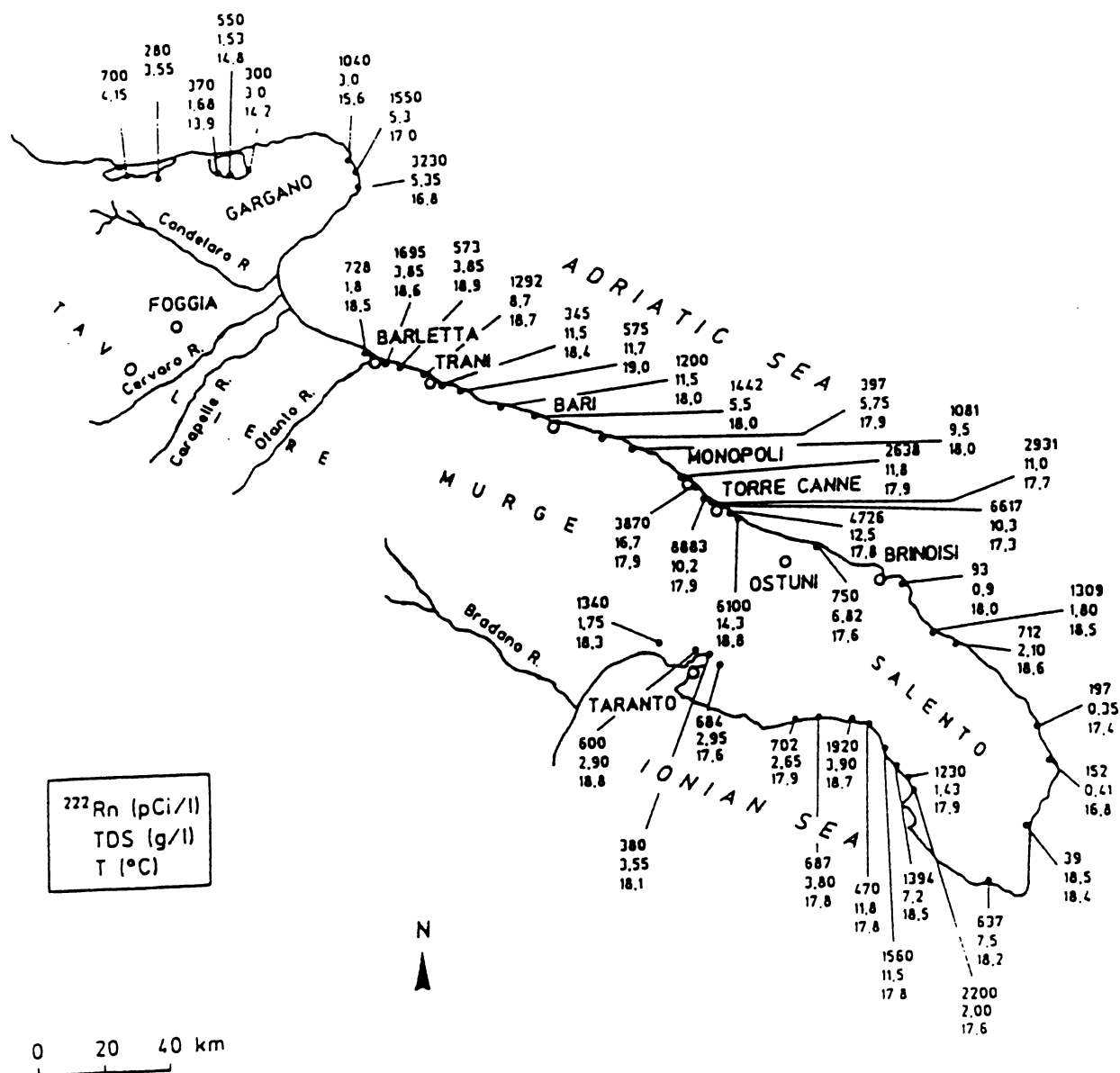


Figure 7. Mean value of ^{222}Rn concentrations in the waters of the main coastal springs fed by karstic groundwater; mean values of T.D.S. (g/l) and temperature ($^{\circ}\text{C}$) are also indicated.

Just like other parameters, radium too can be regarded as a good indicator of the phenomena governing the state of water in a carbonate karstic and fissured aquifer which is variously affected by the presence of terra rossa in its different portions. In particular, ^{222}Rn too has shown that the coastal groundwater body in the Apulian karstic aquifer is extremely sensitive to any condition of stress that may alter its hydrodynamic and chemico-physical state by affecting it directly as is the case with water supply, outflow, withdrawals, and other similar events, or as a consequence of changing boundary conditions such as, particularly, periodic or nonperiodic sea level fluctuations.

3. Acknowledgements

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NUTRIENT FLUX FROM AN ATOLL ISLAND COMPARED WITH NUTRIENT DELIVERED BY SEAWATER

TRIBBLE, Gordon W. and HUNT, C.D. Jr.

1. Introduction

In this report we present calculations of nutrient fluxes in groundwater discharged to nearshore waters along a segment of Kwajalein Island (Republic of the Marshall Islands, Figure 1), and compare these fluxes with estimates of nutrient delivery to the nearshore environment by surface seawater. The work is based on data collected from more than 100 monitoring wells on Kwajalein Island during a 1990-91 hydrologic study by the USGS (Hunt and others 1995a, 1995b, 1996, Tribble, unpublished data). Kwajalein Island (Republic of the Marshall Islands) has an area of 303 hectares, a population of about 3,000, and average annual rainfall of 2,570 mm.

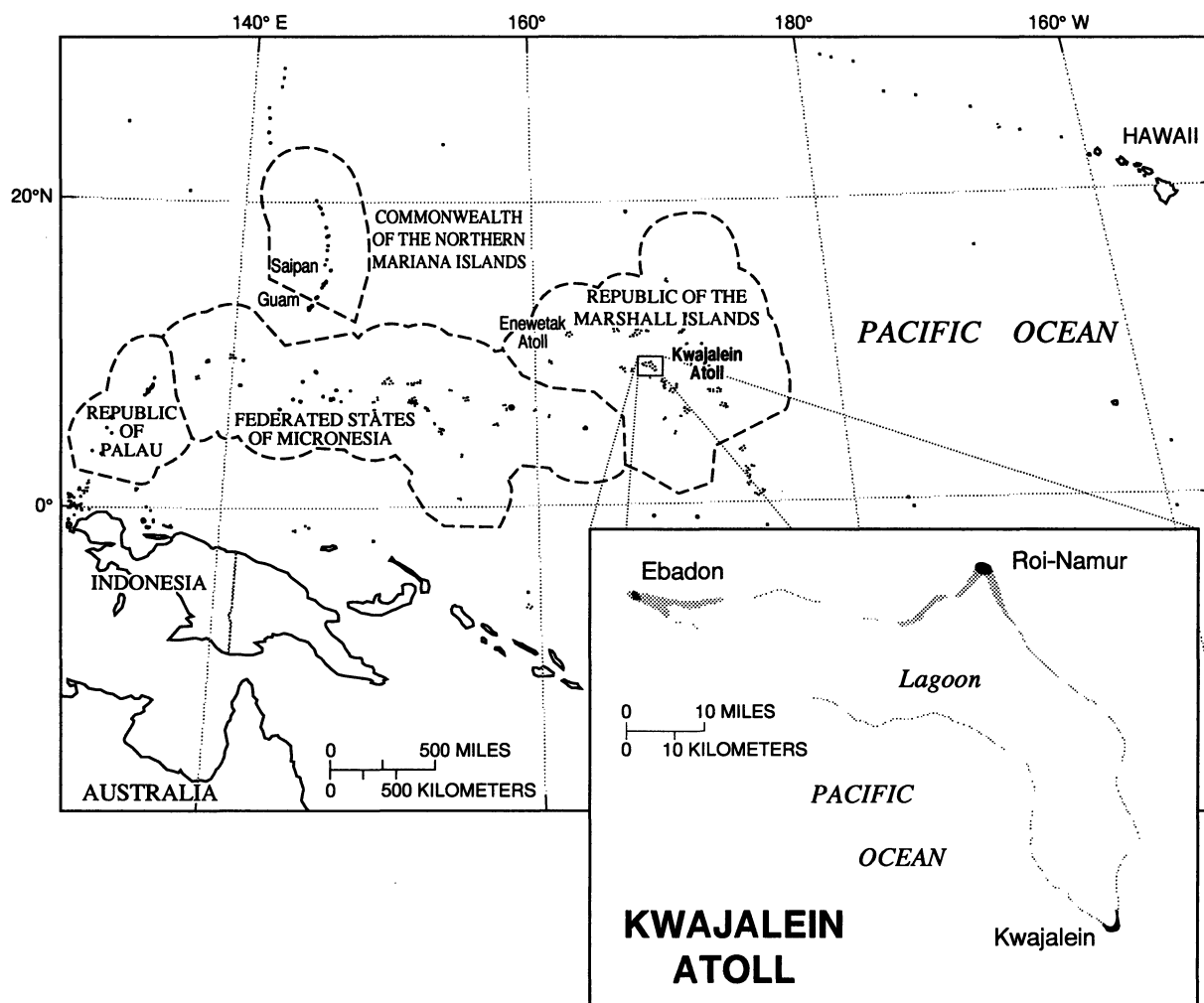


Figure 1. Location of Kwajalein Atoll and Kwajalein Island, Republic of the Marshall Islands.

2. Groundwater flux

Groundwater discharge from the area between two cross-island sections was calculated from a water budget that used climatic data to estimate groundwater recharge (1949-91). Mean groundwater discharge per meter of shoreline was $958 \text{ L d}^{-1} \text{ m}^{-1}$ on the ocean side of the island and $790 \text{ L d}^{-1} \text{ m}^{-1}$ on the lagoon side. Multi-depth wells along the transects defined cross-sections of salinity (Figure 2), dissolved inorganic nitrogen (DIN, Figure 3), and dissolved inorganic phosphorus (DIP, Figure 3). Mass fluxes of DIN and DIP were calculated as the volume of groundwater discharge multiplied by the nutrient concentration of the groundwater. Groundwater discharge was assumed to occur perpendicular to the shoreline.

DIN concentrations in groundwater were highest in freshwater ($\text{Cl}^- < 250 \text{ mg/L}$), with an average concentration of $37 \text{ } \mu\text{M}$, and decreased with increasing salinity. DIP concentrations averaged $0.35 \text{ } \mu\text{M}$ in freshwater and rose to $1.0\text{--}1.6 \text{ } \mu\text{M}$ in waters of intermediate salinity ($5,000\text{--}15,000 \text{ mg/L Cl}^-$). If groundwater discharging at the shoreline is assumed to be fresh, the fluxes of DIN and DIP are 4×10^4 and $3 \times 10^2 \text{ } \mu\text{mol d}^{-1} \text{ m}^{-1}$ on the ocean side of the island and 3×10^4 and $3 \times 10^2 \text{ } \mu\text{mol d}^{-1} \text{ m}^{-1}$ on the lagoon side of the island.

3. Seawater flux

The terrestrial fluxes are subject to dilution and flushing by marine currents having their own nutrient concentrations. On the ocean side, we envision rip currents perpendicular to shore that are driven by wave set-up on the ocean side. At Enewetak Atoll, ocean waves breaking on the reef create a raised sea surface (wave set-up) that drives $4.8 \times 10^7 \text{ L d}^{-1} \text{ m}^{-1}$ of reef across the reef flat (Atkinson and others 1981). We use this value for Kwajalein because the environments are similar. Average seawater DIN and DIP concentrations at Kwajalein were 0.45 and $0.10 \text{ } \mu\text{M}$. The wave set-up results in marine nutrient fluxes of 2×10^7 and $5 \times 10^6 \text{ } \mu\text{mol d}^{-1} \text{ m}^{-1}$ for DIN and DIP. The marine fluxes exceed the groundwater fluxes by 3 to 4 orders of magnitude on the ocean side (Table 1).

Table 1. Nutrient fluxes from groundwater discharge and seawater circulation on the ocean and lagoon sides of Kwajalein Island

Ocean side (in $\mu\text{m day}^{-1} \text{ m}^{-1}$ shoreline):		
	Groundwater	Seawater
DIN	4×10^4	2×10^7
DIP	3×10^2	5×10^6
Lagoon side (in $\mu\text{moles per day for the } 4500 \times 100 \times 2 \text{ m control volume}$):		
	Groundwater	Seawater
DIN	1×10^8	9×10^8
DIP	1×10^6	1×10^8

The mechanism of flushing along the lagoon shoreline is less clear. In the lagoon of Enewetak, surface currents are about 2% of the wind speed (Atkinson and others 1981). For Kwajalein, the prevailing NE trade winds average 21.4 km h^{-1} , and we assume a wind-driven longshore current of approximately 10.3 km d^{-1} parallel to the island. This longshore current flushes the 4.5-km long lagoon reef 2.3 times per day with a marine nutrient flux parallel to the shore. Because the fluxes are perpendicular to each other, they can be compared only by selecting a control volume where mixing occurs. From bathymetric data, we define a swath of reef extending 100 m from shore along the entire length of the island and having an average water depth of 2 m. The long-shore current should transport $2.1 \times 10^6 \text{ m}^3 \text{ d}^{-1}$ of seawater through the control volume, resulting in DIN and DIP fluxes of 9×10^8 and $1 \times 10^8 \text{ } \mu\text{mol d}^{-1}$. In contrast, the total groundwater input of $3.5 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ should result in DIN and DIP fluxes of 1×10^8 and $1 \times 10^6 \text{ } \mu\text{mol d}^{-1}$. Thus, for our assumed control volume, the marine fluxes exceed the groundwater fluxes by 1 to 2 orders of magnitude (Table 1).

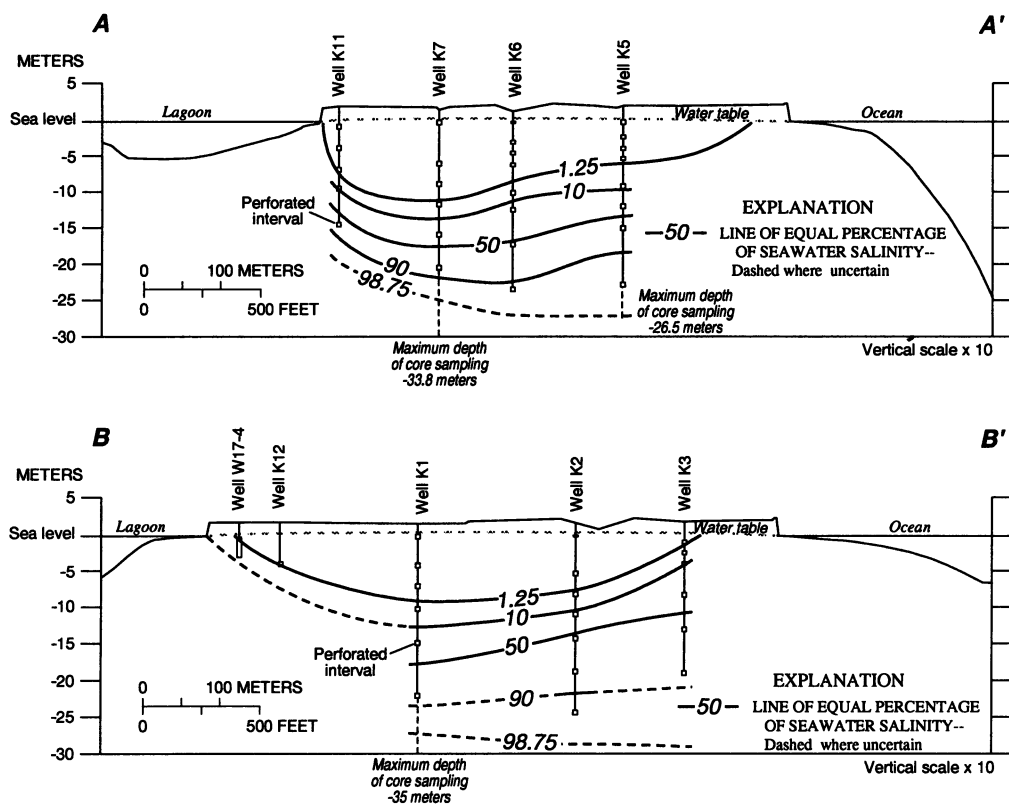
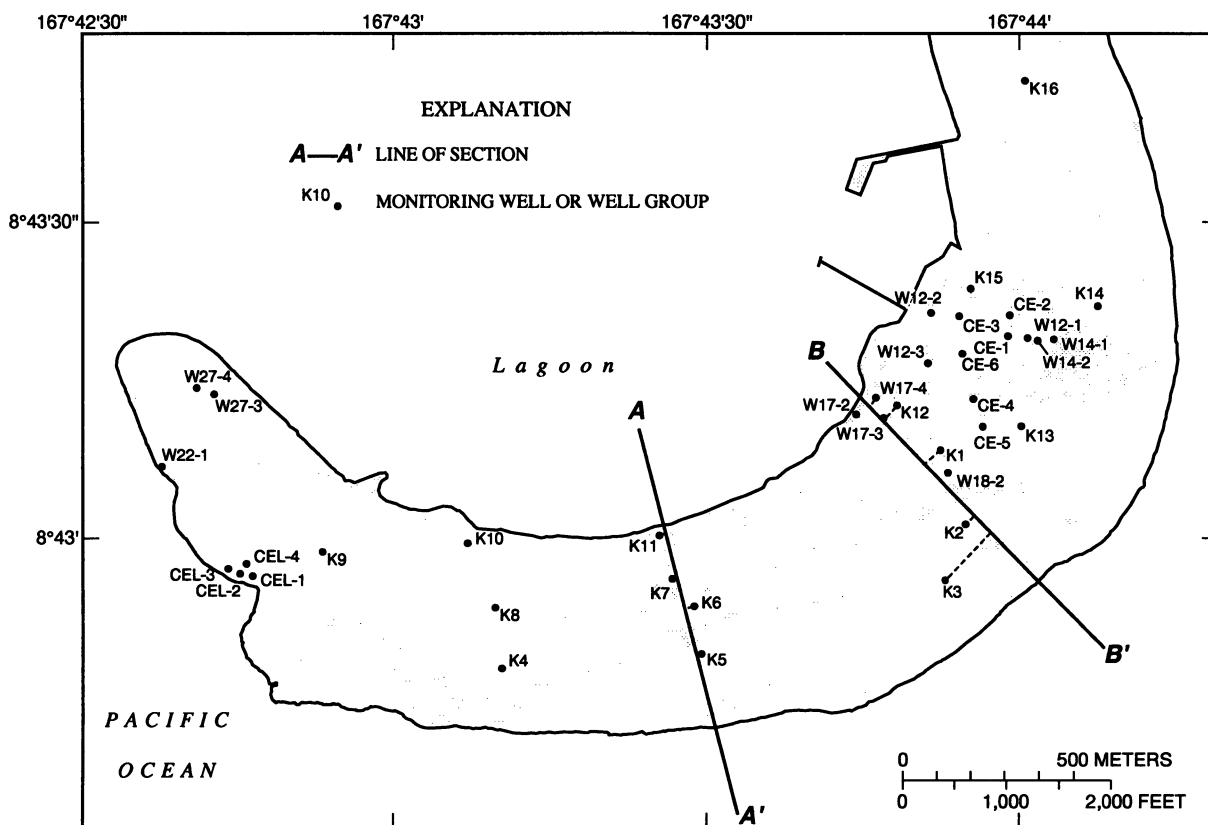


Figure 2. Location of monitoring wells and lines of section (top); and cross sections of chloride concentration as a percentage of seawater salinity (bottom).

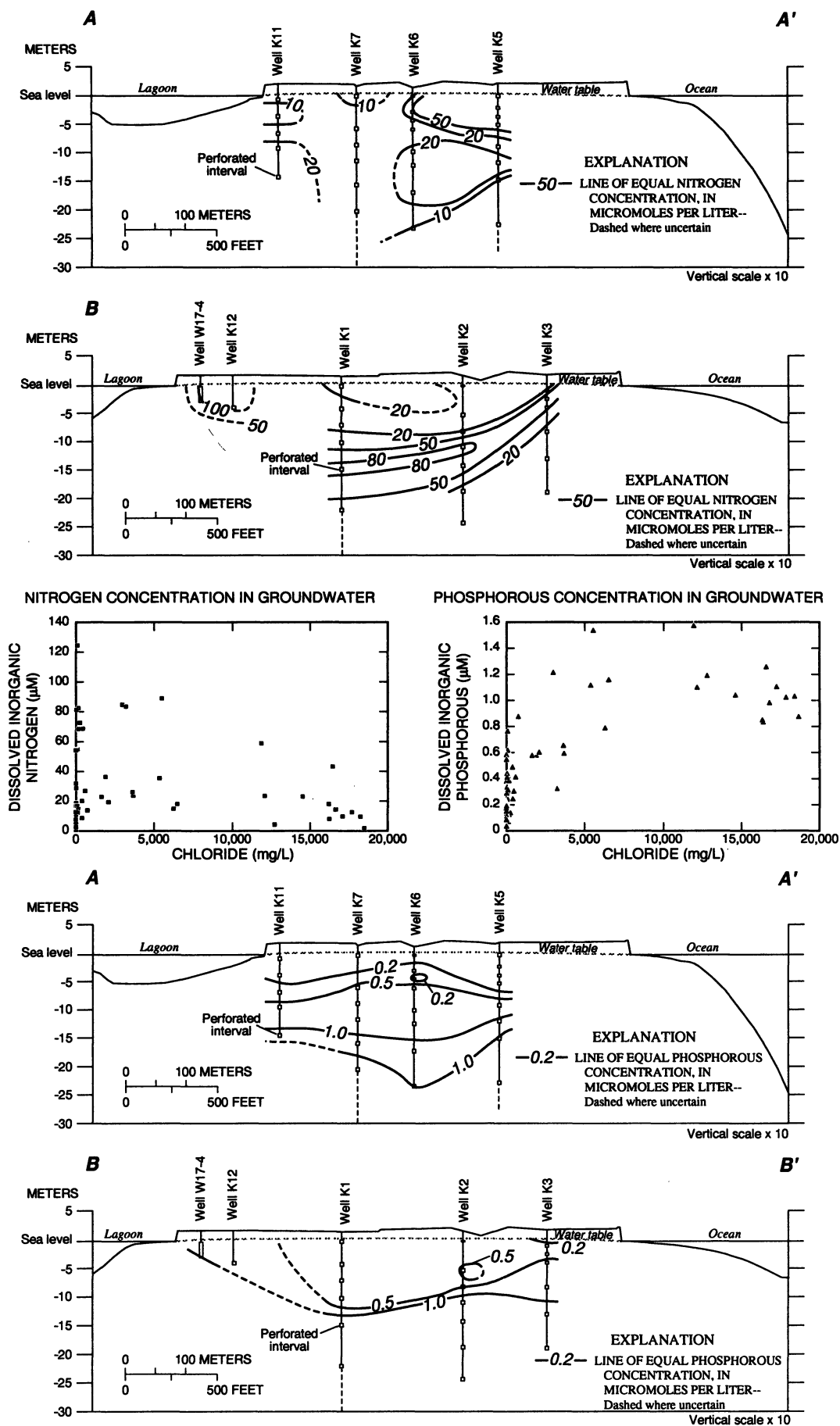


Figure 3. Cross sections of DIN (top) and DIP (bottom) concentration along lines of section A-A' and B-B', and graphs of DIN and DIP versus chloride concentration.

4. Summary

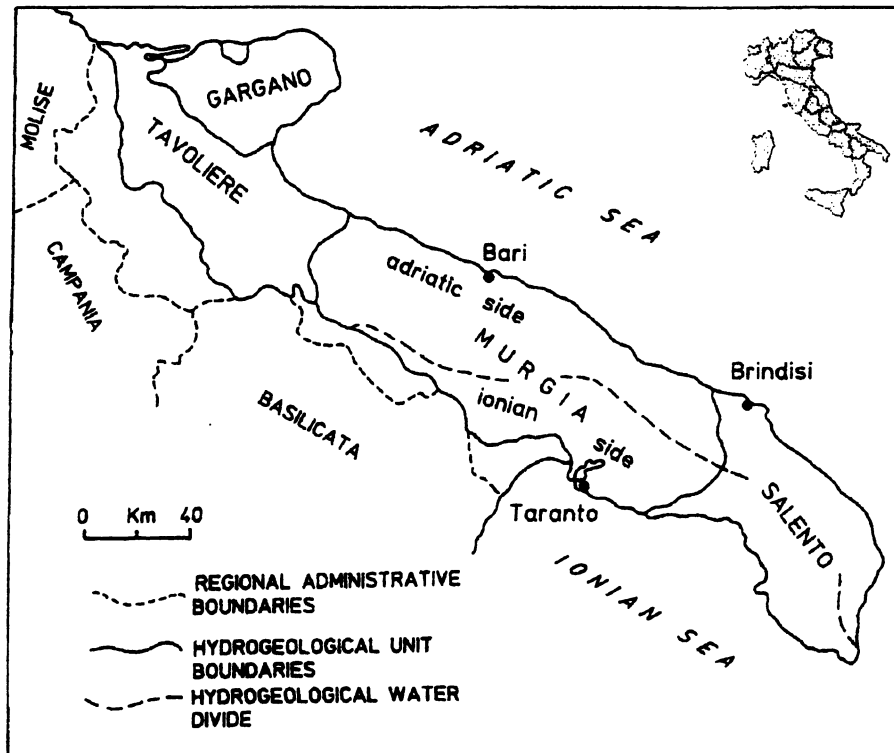
- This method of comparing terrestrial and oceanic fluxes provides a simple and effective first-order estimate of the contribution from land to nutrient reservoirs in coastal waters.
- The nutrient flux from seawater circulation is 10 to 10,000 times greater than the nutrient flux from the discharge of groundwater from an atoll island. On the ocean side, marine fluxes exceed the groundwater fluxes by 3 to 4 orders of magnitude. On the lagoon side, marine fluxes exceed the groundwater fluxes by 1 to 2 orders of magnitude.
- Groundwater discharge may influence near shore waters in areas with restricted circulation or during periods of calm weather, especially in the lagoon where the transport of seawater is less than that on the ocean side.
- It is unlikely that groundwater discharge plays a significant role in the overall biologic productivity or nutrient budget of atoll reefs.

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**MULTITRACING APPROACH FOR THE IDENTIFICATION OF MAIN HYDROGEOLOGICAL PATHWAYS
FEEDING COASTAL SPRINGS OF KARSTIC AQUIFER
TULIPANO, L. And M.D. Fidelibus**

FOREWORD



The Apulia region is composed of four aquifers: Gargano, Murgia and Salento are karstic coastal aquifers, while Tavoliere is a porous aquifer.

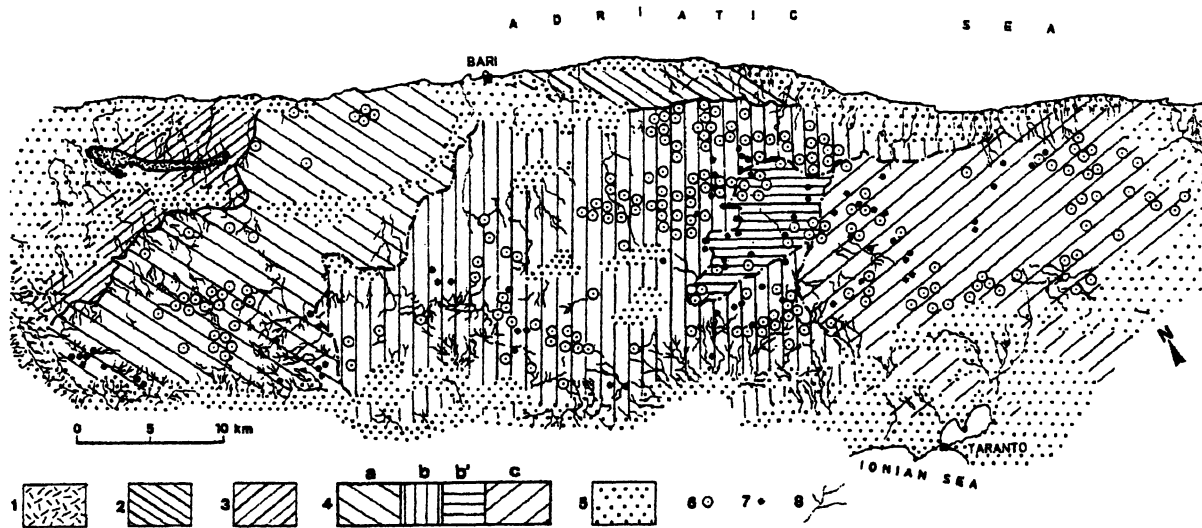
Murgia aquifer supplies most of the groundwater demand of the Apulia region. Groundwater discharges to the sea through coastal springs: composite fluxes of natural constituents and inland released pollutants are conveyed to the coasts.

Therefore, the safeguard of a karstic coastal environment depends both on knowledge about quality conditions of inland groundwaters and, above all, on the identification of the main hydrogeological pathways which allow the rapid and preferential propagation of pollution, reaching at the end the coast.

GEOLOGICAL AND HYDROGEOLOGICAL FEATURES

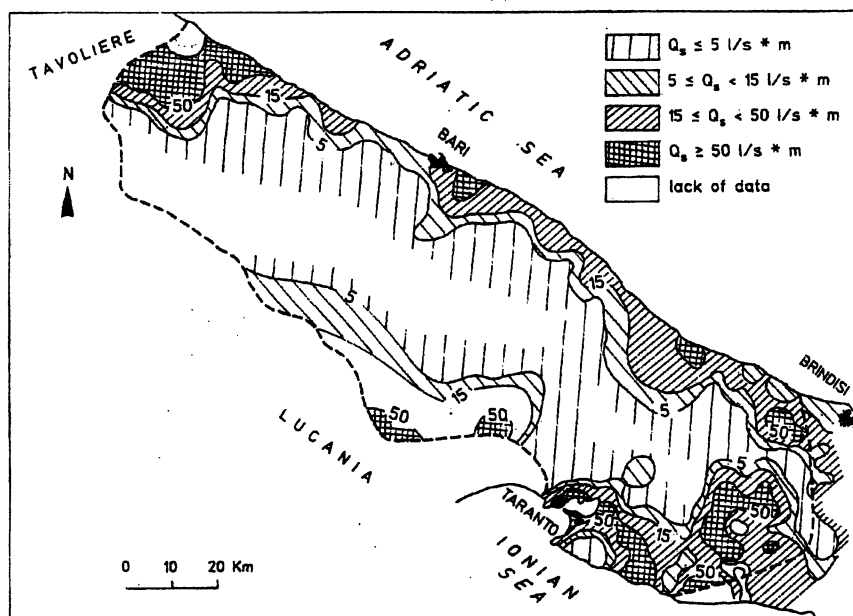
Geological characterisation of the aquifer represents the first step for the definition of the model of groundwater circulation.

Distribution of karst features depends mainly on the distribution of different carbonate lithofacies. Information about lithology allows the forecast of water-rock interaction processes potentially acting within the aquifer and the choice of chemical parameters able to trace the same processes.



Mesozoic lithofacies distribution: 1) dolomites and calcareous dolomites; 2) limestone and laminated dolomites; 3) limestone with pelitic intercalation; 4) micrite biostromal and calcarenite successions: a - prevalent interbedded biostromal limestone; b - both types present in regular alternation; b' - local concentration of rudistids; c - calcarenite intercalation; 5) post-Cretaceous formations; 6) doline; 7) hypogean karst form; 8) surface hydrography (from Zezza, 1975, simplified)

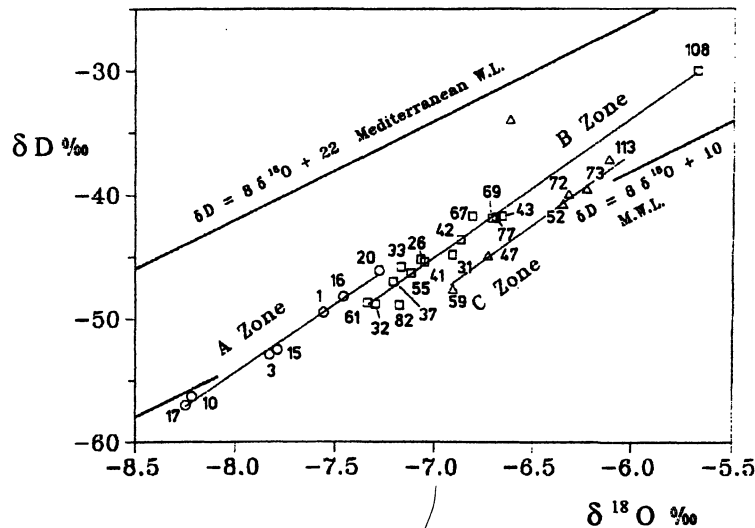
Karst solution is the main process leading to the development of conduits in the form of principal and secondary branches. Groundwater flows at the highest velocity along these branches (preferential pathways). Fissuring contributes to the overall permeability having also the hydraulic function of connecting the different preferential pathways, thus allowing the transmission of hydraulic pressures. Discharge tests on drilled wells allow the reconstruction of the areal distribution of the specific yield Q_s (Tulipano and Fidelibus, 1993). The areal trend of Q_s provides a rough evaluation of the permeability in the different parts of the aquifer.



Distribution of specific yield (Q_s): in a carbonate coastal aquifer the increase of permeability approaching the coast is mainly due to the re-activation of karst processes owing to mixing between fresh and salt waters.

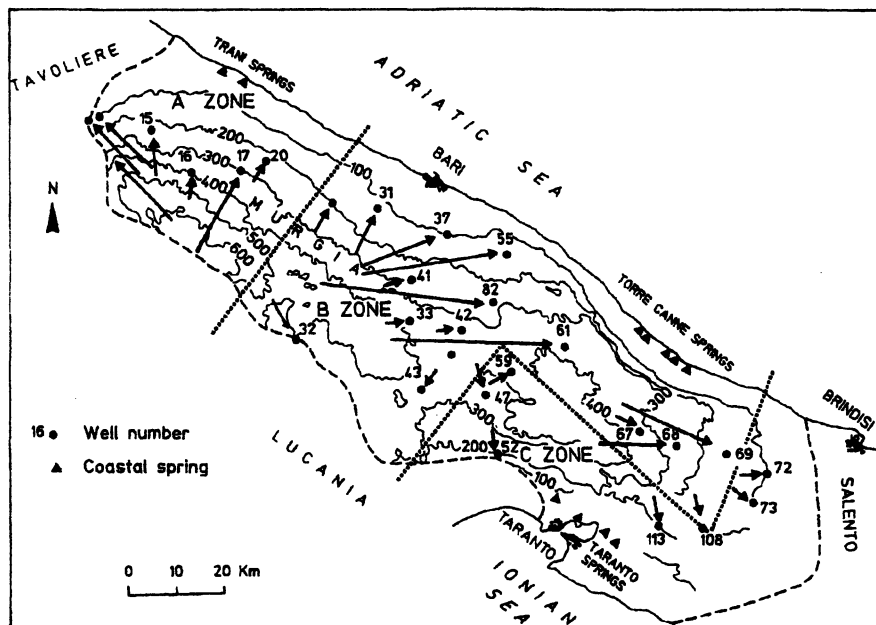
ENVIRONMENTAL TRACERS

Stable isotope data (δD ‰ and $\delta^{18}O$ ‰) of fresh groundwaters are used to establish their origin from feeding areas which are characterised by different elevations and climatic conditions.



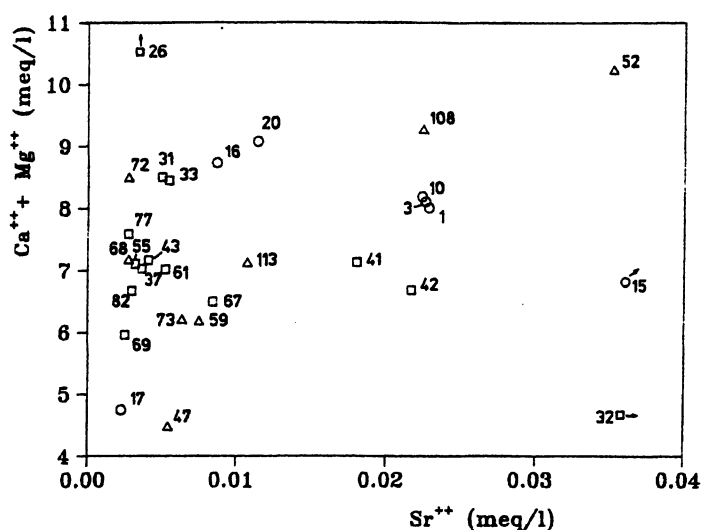
The distribution of the stable isotope data along three parallel lines is due to the climatic differentiation of the entire territory. For each climatic zone (A, B and C) the linear sample distribution is related to the change in altitude of the feeding area.

The stable isotopic composition of groundwaters allows to define the probable connections between each sampled point and the related recharge area. Within the same climatic zone the groundwaters having the most depleted isotopic contents have been supposed to origin from feeding areas located at the highest elevations present in the zone and viceversa.



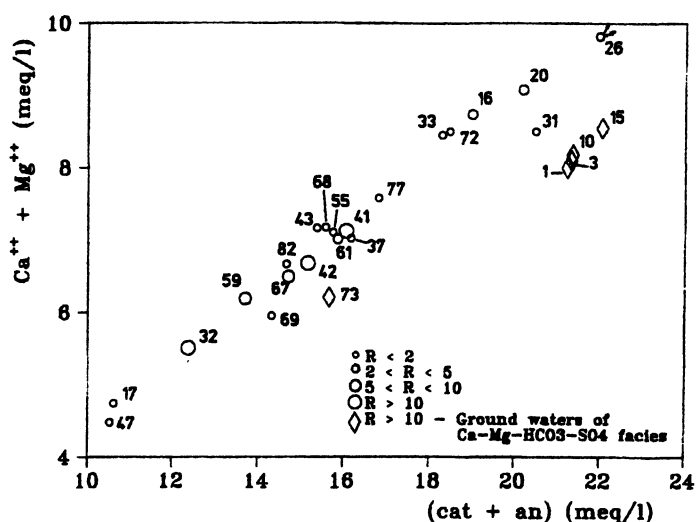
The arrows indicate the connections between each sampling point and the most probable recharge altitude: local characteristics of feeding water are likely to be preserved for long distances within the aquifer, as many of these groundwaters are restricted to preferential flow pathways. The notable differences among isotopic values from adjacent sampled points depend on the strong anisotropy of the aquifer.

The evolution of groundwaters flowing in the carbonate aquifer is the result of water-rock interaction. In particular, the succession of dissolution and precipitation steps causes continuous variation of Ca^{++} , Mg^{++} and Sr^{++} concentrations: these ions can be therefore used as tracers of groundwater evolution.



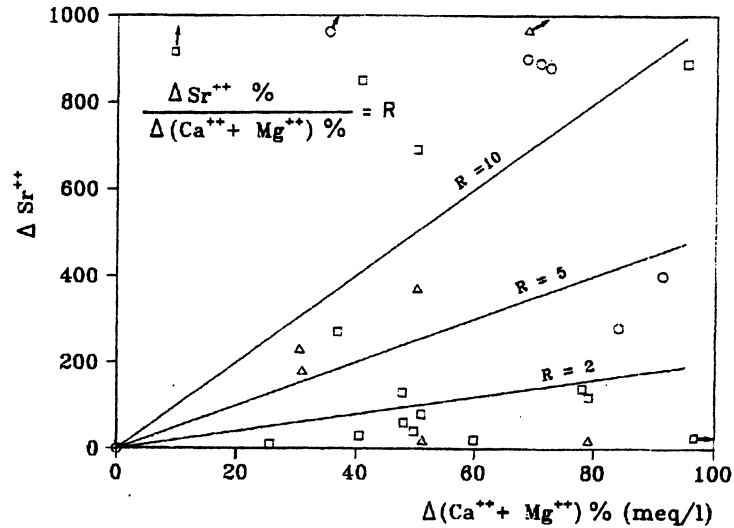
Due to incongruent dissolution of carbonate minerals, while Ca^{++} and Mg^{++} can be removed by precipitation, concentration of Sr^{++} tends always to raise: thus, the occurrence of numerous cycles of dissolution and re-precipitation can be recognised by high Sr^{++} concentrations. Among examined ground waters, sample no. 17 can be chosen as representative of the starting point of the chemical evolution which, as residence time in the aquifer increases, determines a progressive variation of chemical characteristics of ground waters.

For ground waters whose chemical evolution is dominated by dissolution ($R < 2$), the increase of total concentration of Ca^{++} and Mg^{++} provides an evaluation, in relative terms, of the residence time of the same ground waters.



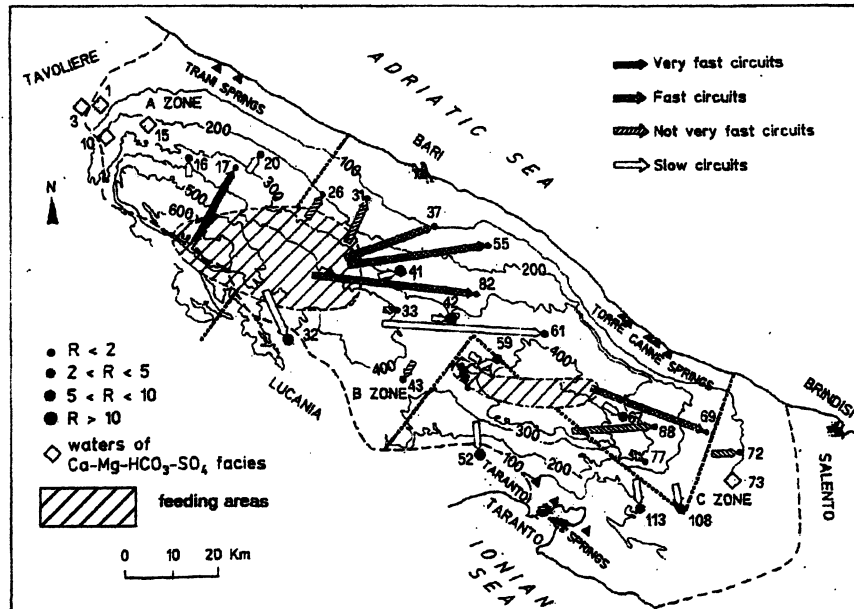
When water-carbonate rock interaction processes are the only processes determining the chemical evolution of ground waters, the increase of total salt content is linearly correlated to the growth of Ca^{++} and Mg^{++} : T.D.S. of samples out of the linear correlation is in fact influenced by evaporite solution. In particular, within the group of waters mostly occurring in a dissolution process ($R < 2$), highest ($\text{Ca}^{++} + \text{Mg}^{++}$) values can be linked to lowest velocities of flow.

For each water, increasing values of the ratio between the per cent increment of Sr^{++} and $(\text{Ca}^{++} + \text{Mg}^{++})$ sum, allow the identification of ground waters which have experienced increasing numbers of dissolution and re-precipitation cycles.



While lowest values of the ratio point out the development of prevailing dissolution (indicating a low maturity degree of groundwaters), higher ratios indicate the occurrence of precipitation processes as well (high maturity degree).

Information obtained from the interpretation of chemical data allow to differentiate the connections, established through the use of stable isotope data, according to a relative velocity.

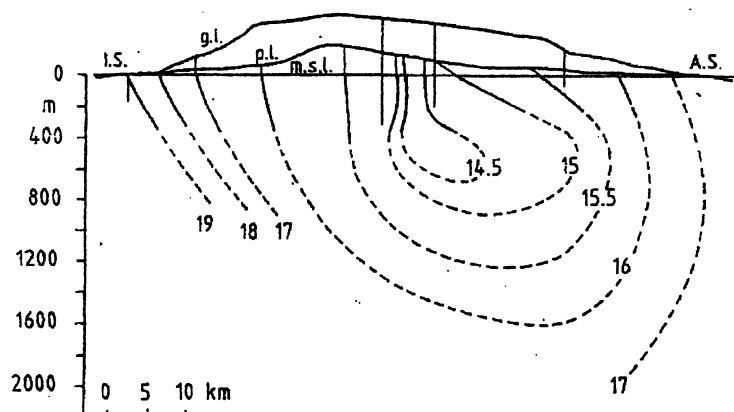
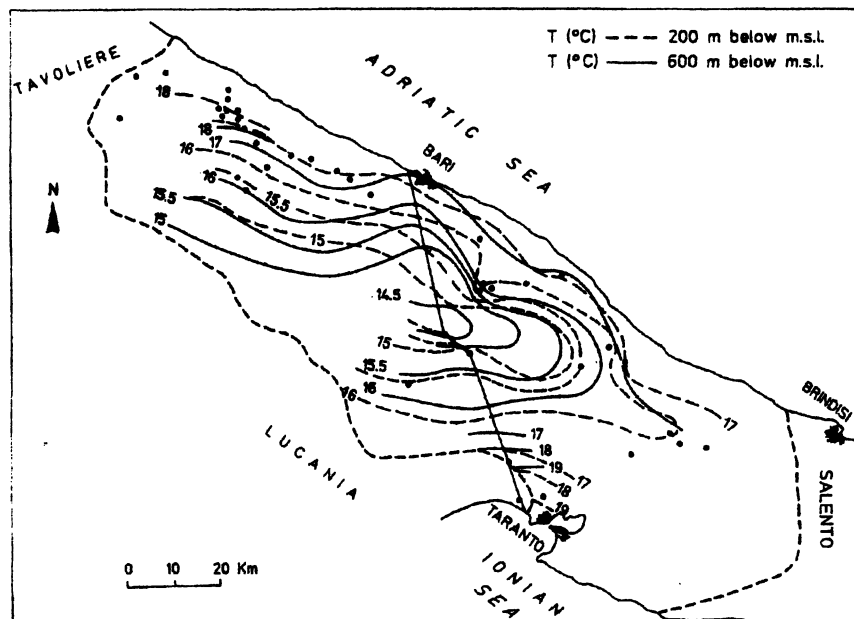


Groundwaters defined as having $R > 2$ (medium or high chemical maturity degree) belong to slow circuits; groundwaters with $R < 2$ (low maturity degree) pertain to fast circuits, distinguished in three levels of velocity. Most of the fast circuits originate from the two main feeding areas recognised in the region.

Groundwater temperature can be considered as a "mobility tracer": the longer the residence time of waters into the aquifer is, the higher is its temperature.

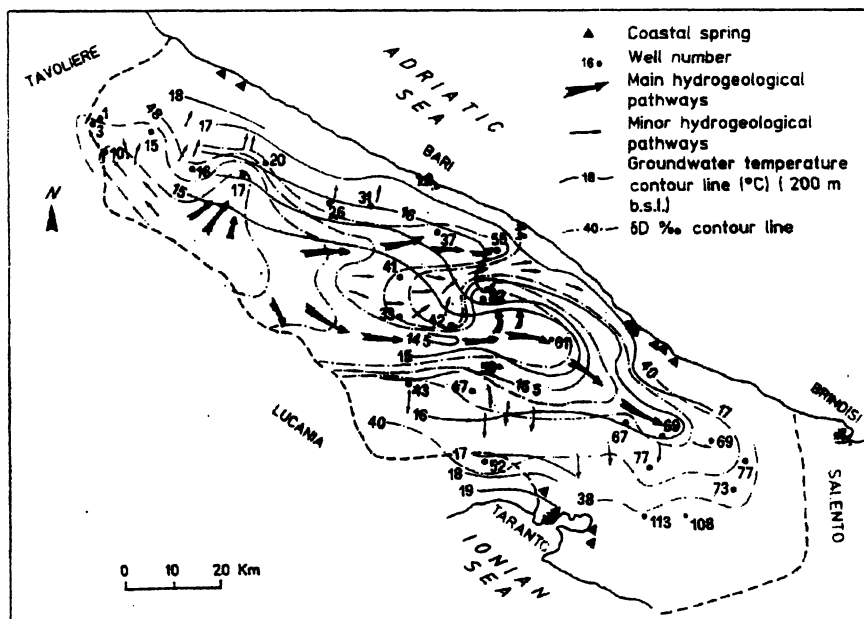
Temperature distribution within an aquifer is determined by the interference brought about by groundwater circulation on the geothermal gradient.

Particularly in an anisotropic aquifer, the reconstruction of iso-geothermal contours allows the main recharge areas and the preferential flow pathways to be recognised. The thermal gradient gives information on flow velocity and residence time of groundwaters: main discharge directions coincide with the directions of minimum thermal gradients.



The reconstruction of vertical sections of groundwater temperature, carried out through the interpolation of temperature logs of drilled wells, allow to outline horizontal sections at different depths. The different trends of horizontal reconstructions of the isotherms are in relation with the different directions of groundwater flow pathways at the various depths

The concurrent use of physical, chemical and isotopic tracers and the cross-verification of obtained information allow the compilation of a detailed hydrogeological framework (Tulipano *et al.*, 1990).



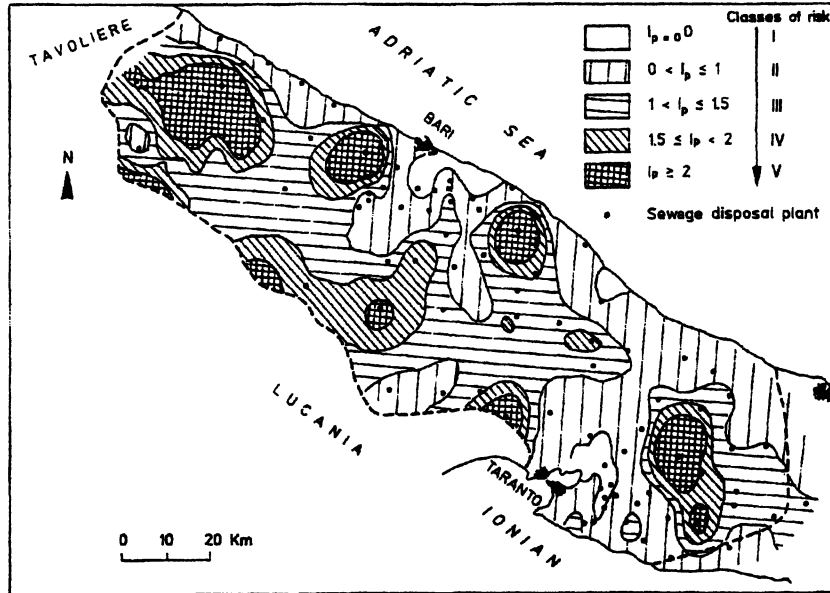
The trend of δD ‰ contour lines delineates flow directions smoother than the straight connections previously outlined between recharge areas and drainage zones. The trend of isotherms outlines the same directions for the preferential flow pathways, confirming the indications obtained by interpretation of whole data set.

Some conclusions regarding the groundwater circuits feeding the coastal springs can be drawn up.

- Main recharge areas are located along the ridge of Murgian hills.
- A rapid groundwater flow originates from the feeding area to the Northwest of the hydrogeological system. This groundwater flow steers toward the coast, following a preferential pathway which reaches a great depth and feeds the Trani springs.
- A second very slow flow originates from the same area and flows toward an adjacent hydrogeological unit.
- Two fast groundwater flows, separated by a slow flow of local origin, originate from the recharge area located in the central part of the region, at an altitude ranging from 400 to 500 m. Upon reaching the coast, southward flowing groundwater contributes directly to two large concentrated springs belonging to the Torre Canne group.
- The considerable contribution from the Murgia to the Salento hydrogeological unit to the southeast is illustrated by the rapid groundwater flow path which trends parallel to the coastline.
- Slow circulating groundwater generally flows to the Ionian Sea. The groundwater originates from a zone southeast of the Murgia, from an altitude below 400 metres. The presence of large concentrated coastal springs in the Gulf of Taranto leads to the hypothesis of a rapid hydrogeological circuit. However, no proof is available because of the lack of observation points upstream of this spring group.

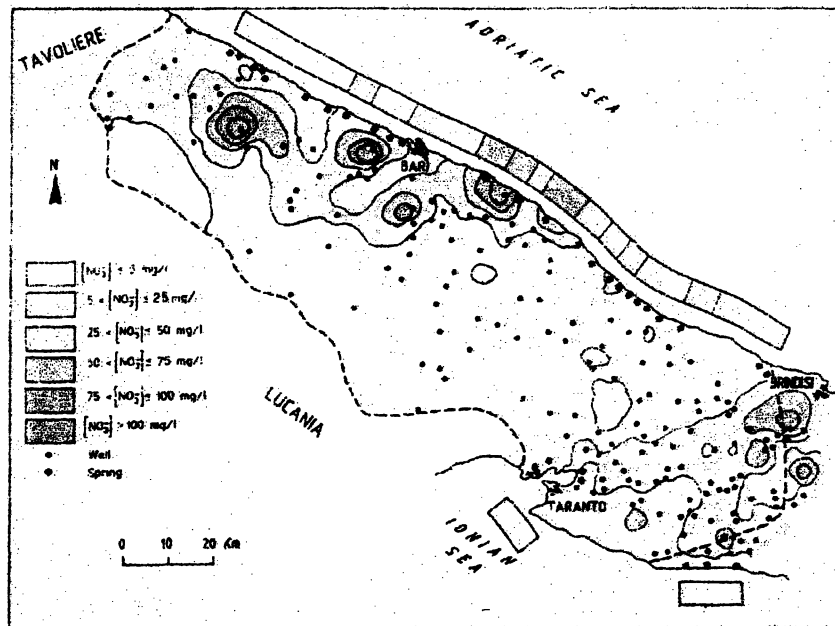
GROUNDWATER POLLUTION AND IMPACT ON COASTAL ENVIRONMENT

The main source of groundwater pollution in the Apulia region is the release of urban waste waters on the ground or underground (Tulipano and Fidelibus, 1993). To predict the impact of these polluted waters on groundwater, statistical methods can be used: the risk index represents a way to quantify the impact. The index is calculated, for each release point, as the ratio between the dilution flow rate (required to bring the NO_3^- concentration of sewage to the natural background of 5 mg/l) and the maximum natural groundwater flow rate, actually available in the same point for dilution.



The risk index distribution comes from both the local hydrogeological features and the distribution of urban areas in the region. Areas of high pollution risk mostly occur along the coastline, associated with highly populated areas.

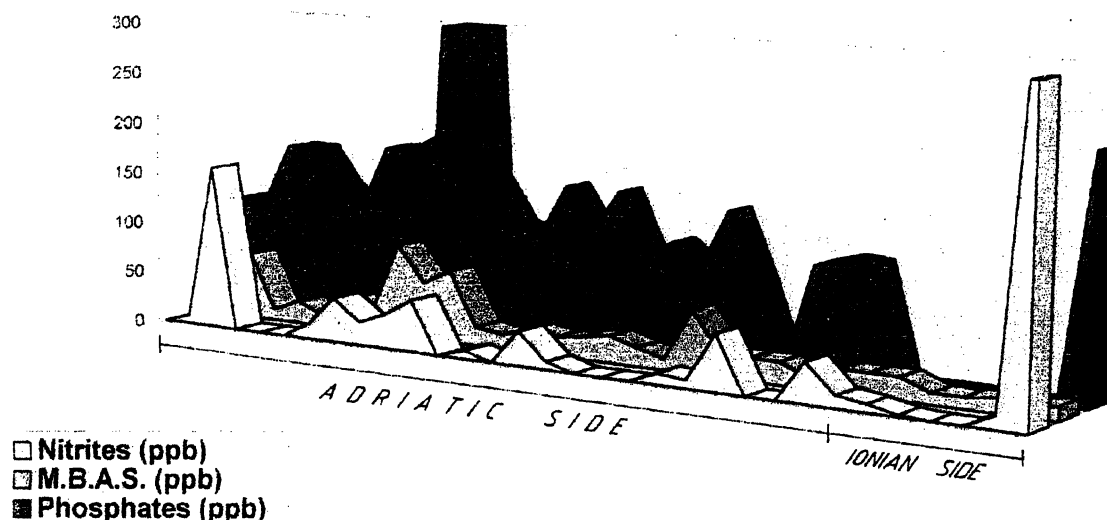
Actual distribution of NO_3^- concentration confirms that urban waste water release is the main factor affecting the quality of groundwaters in the region.



Pollution affects areas which are likely to be associated with Municipalities whose waste water release belongs to a higher risk class. The correlation between areas where NO_3^- presence is high and areas defined as belonging to a high risk class is evident. The strips parallel to the coastline show the nitrate concentration in coastal spring waters.

Values of NO_3^- concentration related to coastal spring waters are corrected for a dilution effect due to mixing with sea water, considered as having a zero value of NO_3^- concentration. NO_3^- presence in coastal spring waters is in fact mainly due to the freshwater component of discharge: the comparison between the nitrate concentrations in groundwaters sampled inland and those calculated for the coastal springs outlines that pollution transport occurs through the same flow pathways already outlined by multitracing.

As nitrates, all pollutants released inland have the possibility to reach the coastal environment.



In the waters of the coastal springs belonging to the Murgia aquifer, nitrites, detergents and phosphates have been detected (Tulipano and Fidelibus, 1991): considering the high values of the discharge rates of some of the coastal springs, the flux of pollutants to the sea may be locally considerable.

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*GROUNDWATER DISCHARGE INTO THE SEAS AND OCEANS : STATE OF THE ART

Zektser, I.S.

1. Abstract

Studies of groundwater discharge into seas and oceans is a part of a complex hydrological-hydrogeological problem of groundwater exchange between land and sea, that includes two oppositely directed, non-equivalent processes: groundwater runoff from land into sea and sea water intrusion into the coast.

The report is devoted to studying groundwater discharge into seas, that is, the portion of ground water, formed in the land and discharge directly into seas, bypassing river networks. Groundwater flux into seas is formed in the coastal water-saturated rocks under the draining impact of seas. It occurs actually everywhere and constantly with the exception of some areas in the Arctic and Antarctic covered with permafrost of great thickness.

Groundwater discharge is the most difficult to determine and insufficiently studied problem of modern and perspective water and salt balance of seas, however, specialists have to answer a variety of questions, concerning the amount of discharge, whether it considerably affects water and salt balance of water reservoir, and water and hydrochemical regime in the coastal zone, how will groundwater inflow change in future as influenced by possible climate changes and human activities intensification in the coastal zone, and to what extent groundwater constituent should be considered when studying salt and heat balance in a reservoir.

2. Introduction

Studies of groundwater discharge into the seas and oceans are a point of a complex hydrologic-hydrogeologic problem of underground water exchange between land and sea. Underground water exchange incorporates two opposite and non-equivalent processes: groundwater discharge into the sea and sea-water intrusion into the coast.

The article is devoted to groundwater discharge into the sea, i.e. that part of groundwater, that is being formed in the land, and discharged into the sea, passing the river network. Groundwater flux into the sea is formed in water saturated coastal rocks, affected by the sea drainage. It occurs actually constantly and everywhere, except some areas of the Arctic and particularly Antarctic, where thick strata of permafrost occur.

It should be emphasised, that the most significant studies of groundwater discharge to individual seas have been conducted by French, Italian, Yugoslavian, American and Russian specialists. For instance, according to data of Bodelle and Margat (1980), the submarine groundwater discharge from the area of France amounts to about 1 km³/yr. The computations of the groundwater balance, made by modelling, for the Aquitaine basin (in the region of Bordeaux) show, that the groundwater discharge to the ocean accounts for 10-15 % of the total outflow components of the Eocene-Paleogene aquifer balance. According to the data of American researchers, groundwater discharge is observed all over the coasts of the Atlantic Ocean and the Gulf of Mexico. Only in one of the areas of Long Island groundwater discharge to the ocean is estimated at 25 million m³ yr⁻¹. The results of estimating the groundwater discharge to the Caspian Sea, Aral Sea, Baltic Sea (from the area of the former USSR) as well as to some major lakes of the former USSR (Baikal and Balkhash) are presented in the book by Zektser *et al.* (1984) (Table 1).

Table 1. Direct groundwater and subsurface dissolved solids discharge to inland seas and major lakes of the former USSR.

Sea or lake	Groundwater discharge (km ³ /yr)	Subsurface dissolved solids discharge (tons/yr)
Baltic Sea (Adjacent to the former USSR area)	1.2	507
Caspian Sea	3.2	23.000
Aral Sea	0.18	6.570
Lake Baikal	1.1	-
Lake Balkhash	0.1	1.100

Studies of the interrelation of sea water and groundwater in coastal regions have been also performed for determining the optimal yield of wells withdrawing groundwater on coasts. Sea-water intrusion into aquifers is a severe danger for water supply wells in a number of coastal regions. Intensive groundwater development in these regions changes the water circulation in the sea water - groundwater system. An important task of the studies is determination of the interface between fresh groundwater and salt water and, consequently, prediction of the water quality in coastal groundwater development areas.

The main experience in theoretical and applied studies in this field has been gained in the USA, Japan, and the Netherlands. In the former USSR, sea water intrusion studies are urgent for some coastal areas of the Baltic Sea, Kamchatka Peninsula, and Caucasian coastal areas of the Black and Caspian seas, where the danger of salt sea water encroachment to coastal groundwater abstraction areas exists. For example, about $600\,000\text{ m}^3\text{ day}^{-1}$ of water is being withdrawn from confined aquifers for water supply at the coast of the Baltic Sea in the former USSR. This results in formation of deep (up to 40-50 m) cones of depression with a radius of up to 100 km and more. They occur not only in land areas of the Baltic Sea. Thus, hydrodynamic conditions for sea water encroachment to coasts have emerged here (Joudkazis and Mokrik, 1981).

Custodio (1982) points out, that in coastal regions the continuous replacement of fresh groundwater by brackish and saline water under the effect of groundwater development, particularly in the submarine portion of deep aquifers, is responsible for changes in the groundwater balance that is necessary to consider when estimating groundwater resources. An important aspect of the research is studying the processes of physico-chemical interaction appearing on mixing of groundwater and sea water of different compositions.

Groundwater discharge to seas is an essential indicator of groundwater resources. In coastal regions, water deficit and shortage of good-quality water in particular may be, in a number of cases, curtailed appreciably by use of ground water that "uselessly" flows to the sea.

Some countries have a positive experience in using water of large submarine springs discharging into the sea not far from the coast, as well as experience in groundwater development by wells drilled on the shelf and tapping fresh groundwater for water supply of seaside settlements.

The use of the groundwater of submarine springs for water supply is known from ancient times. Numerous cases where, using different implements, local population captured fresh groundwater of large submarine springs for water supply and for supplying ships with water have been described in literature (Glazovskii *et al.*, 1973; Dzhamalov *et al.*, 1977).

Quantification of submarine groundwater discharge allows us to find additional water for water supply. A spectacular example of practical use of the water of submarine springs is construction of dams in the sea near the southeastern coast of Greece, that made it possible to "fence" discharge sites of submarine springs and create a fresh-water lake within the sea. Here, the discharge of submarine springs is equal to about one million cubic meters per day and the water of this "lake" is used for irrigation of lands of the coastal area (Subsurface Springs from Freshwater Lake, 1973).

Great possibilities are opened up in development of submarine groundwater by offshore water intakes in connection with increasing drilling of deep wells on the oceans. A number of wells, which were drilled on the shelf of Australia, near the Atlantic coast of the USA, on the continental slope of the Gulf of Mexico and in other places, tapped weakly mineralised submarine water under substantial pressure. For example, in the course of drilling in the Atlantic Ocean near the Florida coast, fresh water was encountered at a distance of 43 km off the coast near Jacksonville. A vessel-mounted well tapped, at a depth of 250 m below the sea bottom, water with a TDS of 0.7 g/l, the head being 9 m above sea level (Kohout, 1966).

At present, in a number of countries, sophisticated procedures and means for capping water under water surface are being developed. In Japan, a patent was granted for a procedure of water withdrawal from a submarine spring, using a special cap equipped with water salinity transducers. If salinity values are in excess of the permissible level, water delivery to the consumer terminates until the water salinity and chemical content reach again the established values. Italian specialists proposed to cap a submarine spring with a bell sea floor. The bell is equipped with valves and transducers controlling the pressure, salinity, and composition of the water being withdrawn.

It should be borne in mind, however, that the problem of practical use of submarine water directly in sea is very complex. Above all, it depends on the possibility of capping submarine technological difficulties of drilling in sea. The conclusion as to the possibility of particle use of submarine water may be drawn only after assessment of the safe yield of this water and the technologic and economic substantiation of the advisability of its use.

Studies of the groundwater effect of generation of mineral deposits at sea bottom are at the initial of problem-formulation stage now. Important conclusions may be made of the origin of mineral deposits at the bottom of seas and oceans by studying the groundwater discharge to seas and processes of physico-chemical interaction of submarine groundwater, rocks and sea water. First, highly preliminary results of studies in this direction show, that in groundwater discharge areas at sea bottom sharp variations in redox situation lead, in a number of cases, to an appreciable increase in bottom sediments of the amount of modules of iron, manganese, lead, barium, nickel, chromium and other elements. Some researchers explain this phenomenon by processes of the interaction of discharging water with bottom sediments and groundwater (Brusilovskii, 1971; Baroyan and Brusilovskii, 1976; Brusilovskii and Glazovskii, 1983).

Sea water intrusion into the coasts in natural conditions are locally spread. However, this process is highly intensified under disturbed conditions. In many cases, a considerable groundwater withdrawal in the sea coast causes sea water inflowing (intrusion) into the coasts. Therefore, sea water intrusion into aquifers in some areas can be a serious threat to potable groundwater well fields. However, it should be noted, that this process in natural conditions is of a local character and calculation of groundwater well fields productivity, accounting the danger of sea water intrusion into the coasts, is an independent hydrogeological problem and is not considered in this article.

Submarine discharge into seas and oceans is the least studied element of the present and perspective water and salt balance of the seas. It is due to the fact, that groundwater inflow is the only water balance component, that cannot be measured and data, needed for a well-grounded calculation of a water balance underground component are often missing. Until recently there is no technique of such calculations. At the same time is impossible to have a general picture of the World Water Balance and water balance of the oceans without data on a groundwater discharge. It should be specially noted, that groundwater formed in the land and discharging in the coastal zone of seas and oceans, in many cases considerably affects hydrochemical, hydrobiological and temperature regime of sea water in the coastal zone and can affected the processes of sedimentation.

At a global scale, groundwater discharge investigations and its function in the water and salt balance of some seas and the World Ocean, were, on the whole, carried out in Russia in the latest years. As a result of these studies, both general and specific values were obtained of the groundwater discharge (l/sec per 1 sq. km and per 1 km of the coastal line) and salts flushing with the ground water (t/year per 1 sq. km and per 1 km of the coast). A considerable salts flushing into the World Ocean with the groundwater (52 % of the salts flushing with the rivers) radically changes an established idea, that primary bioproduction of the oceans and a scale of biogenic sedimentation are limited only with salts flushing with the river runoff.

The obtained data for water and iron groundwater discharge should be considered as greatly reference, characterising the phenomenon scale. However, they can serve a basis of ground and sea water interaction and, mainly, for predicting possible changes in groundwater discharge under a changing climate.

The main problems and aims in studying the ground and sea water interaction are the following:

- collecting and analysis of the available world data on the ground and sea water interaction in the coastal zones;
- working out the new and improving the available methods of quantitative estimation for groundwater discharge into the seas and oceans, including the sea, experimental and field observations;
- type-designing the coastal zones as to hydrogeological and hydrodynamic conditions of the ground and sea water interrelation;
- developing the mathematical models of the ground and sea water interaction under various geological-hydrogeological conditions of the coastal zones;
- working out a concept of a complex monitoring groundwater and sea water in the coastal zones;
- detailed investigations of the groundwater and sea water interaction in the key sections using remote sensing, test filtration, marine hydrogeological investigations on the ship board and other methods;
- working out methods of predicting the sea water intrusion into the aquifers under intensified withdrawal of the potable groundwater in the coastal well fields;
- working out predictions of groundwater discharge fluctuations into the seas and oceans under climate changes;
- revealing the regularities and peculiarities of the groundwater and sea water interaction under different geological-hydrogeological conditions in the coastal zones and the impact of the groundwater discharge on hydrochemical, hydrobiological and temperature regime of the sea water.

In this case, specialists have to answer a number of complex questions: what is the volume of this discharge; does it considerably affect salt and water balance of a reservoir, and water and hydrochemical the coastal regime of the coastal zone; in what way will groundwater inflow change in future under possible changes of climate and technological development in the coastal zone; to what degree should the underground component be considered under studying salt and heat balance in a reservoir.

Submarine groundwater discharge occurs in two ways: 1) in the form of submarine springs, usually confined to tectonic disturbances and to areas of fissured and karstified rocks development, and 2) due to the leakage through poorly permeable bed-load deposits. Submarine sources are widely spread in the Mediterranean Sea coastal zone, in the Atlantic coast of the USA, in the underwater slopes of large island systems and many other regions. However, submarine springs is the most visual but not the main way of groundwater discharge. Groundwater discharge via the leakage through poorly permeable bed-load deposits, that occurs mainly within the shelf and the adjoining part of a continental slope is the prevailing one.

When studying submarine groundwater, conditions of its formation and discharge into the seas, different geological, hydrogeological, geophysical, aerocosmic and isotopic methods, as well as methods specially worked out for studying the processes of ground- and sea water interaction, are used.

These methods should be subdivided into 2 groups: 1) methods based on a quantitative analysis of conditions for formation of groundwater flux into the sea within the catchment and, above all, the coastal areas of the lands and 2) methods of marine hydrogeological investigations, based on studying the sea aquatory.

Methods, based on studying the catchment area, adjoining the sea, include the analysis of hydrogeological conditions of the sea coastal zone, namely, a hydrodynamic methods for calculating the flow discharge (by the analytical way and simulating), a complex hydrologic-hydrogeologic method and a method of mean perennial water balance for the groundwater recharge areas. These methods and, above all, methods, based on studying the groundwater flow are the main for direct quantitative estimating the groundwater discharge into the sea within a geological profile with the available hydrogeological parameters.

The second group includes methods for prospecting and investigating different anomalies in the sea water and bed-load sediments, caused by submarine discharge (anomalies in temperature and sea water composition, bed-load sediments composition and properties, gas, chemical and isotopic composition of near-the-bottom layer of the water, etc.). These methods allow us to single out and give qualitative characteristics of groundwater submarine discharge areas and in some cases to make a reliable calculation of groundwater discharge, causing these anomalies.

A more detailed characteristic of the methods, used for studying groundwater discharge into the seas in the coastal zone is given in the article by R. Dzhamalov. It should be noted, that these methods are not competing but supplementing one another. The most reliable results are obtained under a complex use of these methods. Their right choice and grouping depends mainly on a concrete problem and the scale investigations, geologic-hydrogeologic conditions of the coastal zone and previous study.

It is essential to note that at present we may speak about the emergence of marine hydrogeology, a new branch of knowledge in the field of the earth sciences, at the junction of a number of neighbouring sciences, above all, hydrogeology, hydrology, marine geology, and oceanology. Marine hydrogeology has its own goal of research - studying subsurface water exchange between land and sea and processes of the interrelation of groundwater and sea water, its own object of studies - submarine groundwater, as has a number of independent methods of research.

Investigations of groundwater discharge into the seas and large lakes are carried out in different countries with different aims and at different scales. Thus, detailed enough studies of groundwater submarine discharge have been made for the Mediterranean Sea by French, Italian, Greek and Spanish specialists, for the Black Sea - by Georgian, Ukrainian and Russian specialists, for the Caspian Sea - by specialists of some former USSR countries, for the US Atlantic coast - by American specialists. There are a lot of these detailed studies examples for separate areas.

3. Acknowledgement

This article has been written on the basis of studies, carried out with a financial support of the Russian Foundation for Fundamental Investigations.

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3.2 Extended Abstracts (see Annex 2 for primary author address and affiliations)

COASTAL FUEL HYDROCARBON CONTAMINATION IMPACTS ON GROUNDWATER DISCHARGE CHEMISTRY AND COASTAL PRODUCTIVITY

EVERETT, L.G.

In the United States and most developed countries, the largest source of industrial contamination which affects coastal groundwater chemistry and productivity is petroleum hydrocarbon and its decomposition products and effects. The sources of petroleum hydrocarbon are related to fueling locations associated with commercial fishing and cargo operations, private boating interests, national Navy facilities, and the presence of coastal communities which rely on gas stations to support everyday automobile and truck commuting. The majority of these hydrocarbons sites are located directly adjacent to coastal subsurface discharge and tidal influence areas.

The United States Navy National Test Site Program, has the responsibility of characterizing and remediating coastal petroleum hydrocarbons. The characterization program covers impacts on dissolved oxygen and carbon dioxide ratios, contributions of carbon to the system, and impacts on high TDS water. If the system is driven to anaerobic conditions, alternative electron receptors other than oxygen result in substantial changes to the nutrient levels in coastal areas. Preferred electron receptors under anaerobic conditions include, manganese, nitrate, sulfate, iron, and lastly carbon dioxide. As a result, the anaerobic degradation of petroleum hydrocarbons substantially affects the nutrient balance and primary productivity associated with coastal areas.

The United States Naval Facility's Engineering Service Center at Port Hueneme has embarked upon a number of projects related to remediation of hydrocarbons in coastal areas. In particular, projects related to surfactant enhanced bio-pile remediation, insitu anaerobic degradation, intrinsic bioremediation of diesel, bio-pile remediation of low permeability soils, ex-situ bioremediation in cold regions, windrow composting, bio-venting, bioremediation of fuel contaminated sediments, risk assessment evaluations, and a fully optimized hot-air vapor extraction (HAVE demonstration). Of particular importance is to recognize that the Navy has identified bioremediation strategies as the primary focus of its petroleum hydrocarbon degradation program. Soils contaminated with heavier hydrocarbons beyond the diesel range, however, lend themselves more to hot air vapor extraction technologies.

As a coastal hydrogeologic characterization tool, the Navy has spent considerable funds in developing a cone penetrometer system. This system has fundamental capabilities related to describing lithologic profiles. Further research in developing the probe has resulted in the development of a pore pressure sensor, which allows the operator to determine if the groundwater is upwelling or not. The cone penetrometer probe is fitted with a sapphire window which allows vertical soil chemical identification of petroleum hydrocarbons. Improvements associated with the rapid optical scanning technology (ROST) results in the vertical characterization of chlorinated hydrocarbons as well. Additional parameters such as time domain reflectometry on the cone penetrometer now allows for an understanding of the vertical profile of soil moisture, and as a result, can be used to determine contributions of fluids from the unsaturated zone. The cone penetrometer also has a window in the probe and a miniature camera which allows a grain size distribution count to be determined. From this data, a measure of saturated hydraulic conductivity can be obtained.

Technologies related to the unsaturated component of beach discharge, can be measured using new breakthrough technologies. These technologies include, time domain reflectometry and frequency domain capacitance probes. These probes can now be used to calibrate neutron probes or used in lieu of the use of neutron moderation. Both the TDR probes and the capacitance probes are capable of measuring water content at an accuracy of plus or minus one percent in real time. The time domain reflectometry system has the added capability of operating in highly conductive soils associated with coastal areas. The dielectric constant frequency domain probe, however, is not as effective as the beach soil salinity increases.

The use of neutron probes to determine the vertical profile of hydrocarbons and contaminated soil moisture in the vadose zone has been the standard technology to determine unsaturated flow. By perforating the neutron probe access casing, one is able to obtain soil gas samples at discrete depths. The combination of thermalized neutron counts to determine whether unsaturated flow is taking place and the comparative DO/CO₂ ratios, can result in an understanding of whether flow is taking place and whether natural bioremediation is occurring. At a contaminated site, thermalized neutron counts can range between six and eight thousand as compared to background conditions which may be in

the range of 3-4 thousand thermalized neutron counts. The vadose zone gases can flip flop. For example, oxygen levels in atmospheric conditions typically run about 21% whereas in the subsurface in a contaminated area, they can be reduced to anaerobic conditions or to very low levels of 1-3 percent. The carbon dioxide levels, however, at the surface typically are less than one percent, however, they can range as high as 15-17 percent in contaminated soils.

Techniques are required to obtain groundwater samples on shore and off shore in a screening mode. The BAT system has been used in a penetrometer mode to obtain groundwater samples at discrete depths over a vertical profile. The BAT system utilizes a pre-evacuated sampling container, and as such, does not allow for any loss of gases, no cross contamination, and no pumping requirements. In addition, the BAT system is depth independent. The BAT groundwater collection system allows for understanding the vertical profiling of hydrocarbon degradation products and the resultant changes in nutrient levels. The effect on oxygen levels is obvious, however, when the system goes anaerobic, electron receptors such as nitrate, and sulfates are highly influenced.

One of the new technologies showing considerable promise in characterizing coastal areas is sonic drilling. Sonic drilling uses vibrations to move a drill casing deep into the subsurface. The technology does not use air or water to support the drilling process. In addition, the technique results in a continuous undisturbed core. Further advantages of the sonic drilling technique include the installation of neutron probe access hole casing using the sonic technology. In this kind of application, the sonic rig actually drives the neutron probe access casing into the subsurface. As a result, one can get both continuous core and a vertical distribution of soil moisture.

This paper attempts to introduce exemplary technologies related to direct measurement in the coastal arena. Each of the technologies presented can be used in a survey mode and therefore can be used to characterize broad coastal areas. Fundamental to understanding groundwater discharge in coastal areas, is an understanding of the various hydrogeologic investigation tools which should be presented to the oceanographic community. This paper has focused on sonic drilling as a technology to get a continuous vertical profile of the lithology in a coastal area. In addition, techniques related to determining whether one has an upward gradient from the groundwater discharge is outlined. Techniques for measuring unsaturated flow and for characterizing the vadose zone have been identified. Groundwater collection systems for vertical profiling in the subsurface are identified. Examples of the impact of hydrocarbon degradation, oxygen level variation, carbon dioxide level increases, and the effects on nutrient balances such as nitrate and sulfate reduction under anaerobic conditions. While this paper identifies characterization technologies associated with hydrocarbon contamination discharges in coastal areas, the techniques presented represent a first cut at the hydrogeologic testing techniques that oceanographers may rely upon to obtain direct measurement of groundwater discharge chemistry in coastal areas.

Sophisticated remediation technologies are in development which focus on maintaining the chemistry of the groundwater discharge areas to support primary productivity. Coastal zone remediation strategies related to aerobic and anaerobic degradation of fuel hydrocarbons to conserve the coastal groundwater chemistry are presented. Techniques such as the UVB system which controls TPH, DO, and nutrient levels in recirculating coastal groundwater discharge areas are in the demonstration phase.

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