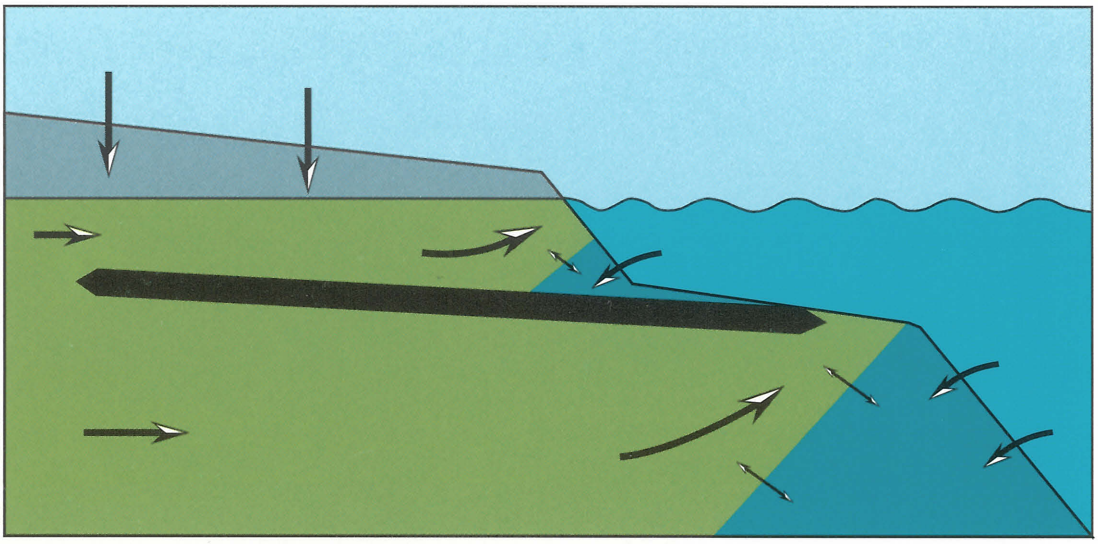
LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE (LOICZ)

Core Project of the
International Geosphere-Biosphere Programme: A Study Of Global Change (IGBP)
of the International Council of Scientific Unions (ICSU)

GROUNDWATER DISCHARGE



IN THE COASTAL ZONE

PROCEEDINGS OF AN INTERNATIONAL SYMPOSIUM

Held at the **Russian Academy of Sciences, Moscow, Russia, 6 - 10th July 1996**

LOICZ
IGBP

**Russian
Academy
of
Sciences**

compiled and edited by

R.W. Buddemeier

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GROUNDWATER DISCHARGE IN THE COASTAL ZONE: Proceedings of an International Symposium

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Cover: Stylised vertical cross-section of coastal groundwater fluxes.

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TABLE OF CONTENTS

3.2 Extended Abstracts

3.3 Original Program Abstracts-presentations not represented by a full paper or extended abstract

1. BACKGROUND AND INTRODUCTION

1.1 Background and Organisation

The International Symposium on Groundwater Discharge in the Coastal Zone was jointly sponsored and organised by the Russian Academy of Sciences (RAS) and the Land-Ocean Interactions in the Coastal Zone (LOICZ) Core Project of the International Geosphere-Biosphere Programme (IGBP). The initial impetus stemmed from the recognition that an understanding of the biogeochemical dynamics of the coastal zone (a primary LOICZ objective) requires knowledge of all inputs, and that in some locations the contribution of groundwater discharge, although not as easily recognised as oceanic exchange or surface flow, could be important.

An initial rationale for the meeting was developed at the Second LOICZ Open Science Meeting (see LOICZ Meeting Report No. 9: The Dynamics of Global Change and the Coastal Zone). Subsequently, a Scientific Organising committee was formed and a planning meeting was held at which meeting structures, objective, and organisational responsibilities were determined (see LOICZ Meeting Report No. 13). Members of the Scientific Organising Committee were:
Prof I.S. Zektser - Chairman, Water Problems Institute, Russia
Dr A. Aureli - University of Catania, Italy
Dr R.W. Buddemeier - Kansas Geological Survey, United States
Dr R.G. Dzhamalov - Water Problems Institute, Russia
Dr Fei Jin - Institute of Hydrogeology and Engineering Geology, P.R. of China
Dr V.V. Gordeev - P.P. Shirshov Institute of Oceanology, Russia
Dr H. Loaiciga - University of California, United States
Dr J.C. Pernetta - LOICZ Core Project Office, The Netherlands
Shortly before the Symposium was held, Dr. Pernetta left the LOICZ CPO, and was replaced on the organising committee by Mr. Paul Boudreau, LOICZ CPO.

It was agreed at the organisational meeting that the Symposium should focus on the following key Issues with respect to groundwater fluxes in the coastal zone:

- classification of regions, types, and influences on groundwater discharge;
- methods of analysis and presentation of data relating to groundwater discharge;
- the location and need for further development of data sets; and,
- co-ordination of data and information exchange.

1.2 Conduct of the Symposium

The Symposium was attended by over 50 invited participants representing 16 countries (Annex 2 is a directory that includes all participants, as well as others who have expressed interest in the topic), and was held at the Hotel "Uzkoe," Moscow, July 6-10, 1996. The scientific presentations were divided into five Themes:
Theme 1: "Main Problems of Studying the Interaction between Ground and Sea Water"
Theme 2: "Methods and Approaches to the Groundwater Discharge Assessment in the Coastal Zone"
Theme 3: "Classification of the Coastal Zones According to the Types of Groundwater Discharge, Climatic and Hydrogeological Conditions"
Theme 4: "The Main Directions of the Further Investigations Concerning Groundwater Discharge"
Theme 5: "Methods and Recommendation Concerning Data Collection and Processing"

Theme session 1 consisted of keynote presentations designed to identify the context for the more focused sessions. Each of the subsequent theme sessions consisted of a keynote presentation, brief introductions to the posters, a period for poster viewing and discussion, and a summary session for general discussion and recommendations. Session rapporteurs provided written reports of theme discussions. During the course of discussions it became clear that some issues required more detailed review than would be possible in plenary discussions, and a total of seven Ad Hoc Working Groups were formed. Following meetings and informal discussions throughout the Symposium, Working Group reports were presented in plenary on the final day. All discussion and Working Group reports are contained in LOICZ Meeting Report No. 17, as are the annotated program, participant list, abstracts, and conclusions and recommendations (which are also contained in Annex 1 of this Proceedings volume).

1.3 Preparation of this Proceedings

In view of the perceived importance of building upon the success of the Symposium in establishing links among the diverse topics and researchers with relevance to coastal groundwater discharge, the LOICZ CPO agreed at the post-Symposium meeting of the Organising committee (LOICZ Meeting Report No. 17) to undertake publication of a Proceedings volume. Because of time and budget limitations associated with the duration of the Editor's presence at the CPO, it was necessary to have the volume finalised prior to mid-December, 1996. Accordingly, all participants were invited to submit camera-ready and/or electronic versions of papers or extended abstracts derived from their Symposium presentations, with a nominal deadline of 1 November, 1996. The response was gratifyingly strong, especially in view of the short time available.

The submissions were classified by the Editor as papers (section 3.1 of this volume) or extended abstracts (section 3.2), and in some cases were edited for clarity or format. It should be noted that because of time constraints, neither the classifications nor the editorial changes have been submitted to the authors for their approval. The Editor accepts responsibility and apologises for any errors that may have been introduced in this way, in hopes that the overall process has resulted in a generally improved publication.

In the interests of inclusivity and integration of this fragmented technical field, it was decided to include the original program abstracts from the Symposium for those participants who were unable to submit a paper or extended abstract. These original abstracts are reproduced in section 3.3. For similar reasons, the directory of scientists in Annex 2 includes not only the symposium participants, but also others who have expressed interest or are known to be active in the field.

This report is being distributed to all individuals in the directory as well as to standard LOICZ and IGBP distribution lists; additional copies may be obtained on request from the LOICZ CPO at the address indicated in this report.

1.4 Acknowledgements

These scientific developments owe much to the insight of J. C. Pernetta, first LOICZ Core Project Director, and V. V. Gordeev, LOICZ SSC member, who recognised the relevance of groundwater flux to LOICZ objectives and the long-standing interests in this area of scientists at the Russian Academy of Sciences. For the success of the Symposium, thanks are due to the members of the International Organising Committee, but most especially to the Local Organising Committee and to all who worked tirelessly to provide the participants with guides, translators, transportation and supplies, often under challenging circumstances. Paul Boudreau of the LOICZ CPO provided organisational support throughout the process and played a major role in the meeting Secretariat; Cynthia Pattiruhu, Mildred Jourdan and Annaig Renault made important contributions to the meeting organisation and preparation of the Proceedings. Finally, particular thanks are due to the participating scientists who took it upon themselves to make the effort of meeting deadlines and communicating across both disciplinary and linguistic barriers in order to realise the combined potential of their individual efforts and interests.

Robert W. Buddemeier, Editor
28 November 1996

2. COASTAL GROUNDWATER FLUX ISSUES -- AN OVERVIEW

R. W. Buddemeier

2.1 Introduction

In 1980, Johannes published what was probably the first general review of the ecological significance of groundwater flux to the coastal zone (Johannes, 1980). The first sentences of that review were: "The literature on submarine groundwater discharge (SGD) is scattered and fragmentary. Collectively, however, it suggests that SGD deserves more attention than it has received from marine ecologists." There is little to suggest that progress has been made in the intervening 16 years, except for the fact that we should add to Johannes' category of "marine ecologists" other groups such as coastal oceanographers, marine and terrestrial geochemists, hydrologists and geohydrologists, resource managers, conservationists, and others.

What follows is a highly personal attempt to combine the traditional proceedings overview (highlighting and connecting the themes and issues developed by the individual contributions) with some analysis of why the scientific field of SGD-related studies has remained so fragmented, and what may be done to rectify that. If justification for this approach is needed, I present it in the form of the following anecdote.

When it became clear, in the latter part of 1995, that the conjunction of interests in SGD by the Russian Academy of Sciences (RAS) and the Land-Ocean Interactions in the Coastal Zone (LOICZ) Core Project of the IGBP would result in a small symposium on the subject, the question of suitable participants arose. I sent e-mail messages to a dozen or so colleagues whom I judged to be interested in or knowledgeable about the subject. Almost all responded -- some with statements of personal interest, but most with suggestions of others to contact. I followed up on these suggestions, receiving in turn still more names of researchers, whom I also contacted. Even in the responses of this "third generation" of network contacts there was no cross-linking -- people on any one branch of the "contact tree" seemed unaware of the other branches. This was all the more remarkable and distressing because of the limited nature of the selection -- all based on the initial contacts of one person, and almost all developed-country, mostly English-speaking scientists. I decided that if the enthusiasm were that great and the connections that poor, the Symposium would be justified as a communication exercise if nothing else.

This judgement was confirmed when, at the end of the Symposium, I asked several participants if they thought it had been worthwhile. One replied "It has been great -- for the first time I don't feel like my students and I are working all alone." In an absolute sense, of course, they were not "alone," but they clearly were isolated from the others with common interests -- and this in spite of the fact that they work at an institution with stable funding, good access to the scientific literature and to communication media, etc. Why? One cannot blame just the individuals -- it is the scientific system that has failed, or at least has not been adequately developed.

2.2 The Symposium

Given the limitations imposed by available funding, the short organisational lead time, and the specific goals and interests of the sponsoring institutions, participation could not be expected to be completely balanced or representative. Workers in the field of global geochemical cycles were not heavily represented -- to a significant degree because their interests are well-defined and they already represent a cohesive group. There was a definite effort to recruit participants and to suggest topics of discussion that would address LOICZ programmatic concerns (Gordon *et al.*, 1995; Pernetta and Milliman, 1995; see also Section 1: Introduction and Background, and Buddemeier, this symposium). This effort was far from completely successful, perhaps fortunately, and there was a wide diversity of disciplines, environments, countries and scientific issues represented, which made their enthusiasm and agreement all the more significant (see Annex 1 of this proceedings, and Buddemeier (1996).

The scientists of the former Soviet Union and allied countries have had a long tradition of research into general issues of SGD, especially at regional and global scales but also with reference to specific local and regional issues. The work of the Water Problems Institute of the RAS is reflected in the results summarised by Zektser and by Safronova, and in the methods description of Dzhamalov. This is almost certainly the largest group and the most long-term effort devoted to the estimation of regional SGD. It is unfortunate that the detailed primary literature for these studies is available only in Russian. Lack of access to and review of the primary data and methods used has almost certainly limited application of these of these interesting results by other scientists.

The results of these studies that are currently available lack the spatial and temporal resolution required for most LOICZ biogeochemical modelling (Buddemeier; see also discussion of discharge zonation by Koldysheva). However, the regional groundwater budget developed for part of the Sea of Japan by Boldovski exemplifies not only the problems and uncertainties in the process, but also the kind of systematic assessment of fluxes and their spatial distribution that will be useful in interpreting and predicting the results of marine biogeochemical studies.

Khublyaran addressed the "inverse SGD" problem – saline water intrusion into coastal aquifers. His approach, from a theoretical and methodological standpoint, was complemented by the mechanistic descriptions of seawater entry into karst aquifers by Drogue and by Mijatović, and also by the impact studies discussed by Li and Zhao, and by Lin and Liao. As a consequence of the absence or reduction of SGD, saline water intrusion provides an excellent example of the importance of groundwater flux in determining the characteristics of the terrestrial side of the coastal system.

Saline water intrusion is only one concern of water resource management, and a special case in the spectrum of subsurface coastal fluxes. The broader, integrated issues of regional water management were emphasised by the contributions concerning China (Lin and Liao, Li and Zhao). A prerequisite for management is understanding of the hydrologic system; the papers by Tulipano and Fidelibus, Perry and Velazquesz-Oleman, and Tadolini and Spizzico all discussed techniques and presented results of combined isotopic, geochemical, and hydrologic investigation of complex aquifer systems. Such geochemical studies can provide integrated signals that may better reflect system behaviour than individual sampling points, especially in heterogeneous formations. Jacobson and Graham present an unusual study combining hydrogeologic assessment in connection with management of a human health problem -- mosquito breeding grounds. A generalizable methodological contribution was presented by Ganoulis in the form of a novel and potentially powerful approach -- the use of arithmetic based on fuzzy logic theory -- to the vexing problem of recharge.

The hydrology and geochemistry of coastal systems are clearly of interest to the LOICZ project from the standpoint of natural functioning, but water resources and their exploitation by human populations are key elements in coastal population and economic development -- which are major drivers of global change. The relationships among hydrologic systems, water resource development, and human activity is thus very relevant to the socio-economic component of LOICZ research and integration.

Although pollution is not by itself a priority issue for LOICZ, it is a major motivation for groundwater and coastal research. Voronov, Kuzmitskaya and Shvartz reported on one proposed study of groundwater transport of pollutants to part of the Baltic Sea, and Souveri discussed another co-operative effort with similar goals. Everett discussed assessment of the effects of hydrocarbon pollution, and Kim and Rhie provided an overview of groundwater contamination problems and sources in Korea.

Two of the primary focal issues for LOICZ are global change – including climate change – and the relationship of the coastal zone carbon cycle to the biogeochemical functioning of coastal ecosystems. The former topic is represented by two papers addressing very different scales. Loaiciga develops a general approach for estimating the effects of climate change on groundwater flux and salt transport to the oceans on a global or large regional scale, while Oberdorfer uses model simulations to study the effects of sea-level rise on the groundwater discharge of a coastal river basin.

In the field of marine biogeochemistry and its relationship to SGD, Burnett *et al.* and Moore both report on the use of isotopic tracers to probe the extent of groundwater discharge and sediment interactions in ways very similar to the study of Tadolini and Spizzico in a terrestrial aquifer. Chanton *et al.* use in methane in a similar fashion; although it is a non-conservative tracer, it has the advantage of being a sensitive product of sedimentary carbon metabolism. Tribble and Hunt directly address the question of the influence of island-derived nutrients on the metabolism of the nearshore zone -- an issue that is of growing interest in view of the recognition of widespread nutrient contamination of coastal groundwaters. Such studies provide direct links with the LOICZ biogeochemical model approach (Gordon *et al.,* 1995).

One of the outcomes of considering the marine studies in conjunction with terrestrial investigations was the recognition of basic differences in concepts and terminology between the fields. In marine studies, sedimentary porewater is the functional equivalent of groundwater or soil moisture on land. It is also the "compartment" through which the submarine discharge of groundwater occurs. However, there are active fluxes and reactions between sediments, porewater, and the overlying marine water that have little or nothing to do with the transport or reaction of groundwater of terrestrial origin. The exchange of solutes between sediments and overlying water can be enhanced by a factor of 3 to 5 above molecular diffusion rates by macrobenthic activity (Aller, 1992), and by two orders of magnitude as a result of physical forcing (wave action and sediment percolation) (Lohse *et al.,* in press). Clear definitions of what parameters are measured, and of what is meant by the terms used, are both important and challenging as the scientists approach the same subject from different sides of the intertidal zone.

There are, of course, many ways to divide or classify the various studies reported. In addition to topic, method, region or environment, and especially the scale of study are all relevant.

In terms of specific environments studied, it is instructive to look at the contributions with some bearing on karst formations. Specific karst studies are reported from the Mediterranean (Mijatović, Drogue, Tadolini and Spizzico, Tulipano and Fidelibus), but the Yucatan peninsula investigation of Perry and Velazquesz-Oleman also addresses karst phenomena. Moreover, karst-like formations and behaviour are important to the carbonate platform and island studies reported by Burnett *et al.*, Chanton *et al.*, and Tribble and Hunt. Further, the role of karst in specific problems is mentioned by Voronov *et al.* (groundwater pollution discharge) and by Lin and Liao (land collapse). In spite of the common hydrogeologic environments and similar methodologies in several cases, the reference lists for these papers have almost no citations in common except in the case of co-operative and coincident studies.

This lack of common references or cross-citation is a general phenomenon throughout the papers, but is particularly noticeable when the topics are closely related. Much of this is no doubt due to the differences in study locations and to the somewhat informal nature of publications in proceedings volumes; it is also a logical consequence of the anecdote about the non-intersecting network with which I started this summary. However, it definitely leaves the impression that researchers in the field do not regard themselves as a interactive body of scientists building on developments of common interest. Are they the victims of this viewpoint, the perpetrators, or both?

2.3 The Relative Merits of Problems and Solutions -- An Editorial

In looking for reasons for the fragmentation of the fields of study related to SGD, and for means of integration, there is one problem that can be attributed to the combination of researchers and funding agencies. I term it the "Necessity of Uniqueness" problem, and it is one that affects coastal zone research (and indeed, much environmental research) in general. Nobody wants to pay to duplicate research that has already been done. In order to justify proposed research, an investigator will therefore explain that the reason for carrying out work very similar to what has already done in a similar setting is that the proposed new research site is unique, and that the answers obtained elsewhere cannot be applied to the different and important problems faced here and now. From saying that to believing it is a short step, often promptly followed by completely forgetting about the existence of the other (by definition not relevant) research. We must remember that the enterprise of science is based on a community process of review, validation, interpretation, and extension of results, not the random collection of similar facts and observations.

However, I retain sufficient optimism and faith in my profession to believe that there is a genuine desire to make connections and that there are structural and cultural problems that interfere with a more cohesive approach to the subject of SGD. To understand these, it is useful to focus attention on differences among the practitioners, and how these may contribute to the divisions.

One obvious difference is between the terrestrial and the marine scientists. These two groups generally join different societies, attend different meetings, and publish in different journals. Perhaps more seriously, they may lack experience with gaining access to relevant literature in the other disciplines, and may not know how to select (or search for) titles or keywords that would make publications more widely accessible to interested colleagues. However, the solution to these difficulties is to some degree already available. There are in existence a number of journals, newsletters and societies dealing with various aspects of coastal, estuarine, or continental shelf research, and there is corresponding experience with relating terrestrial and marine interests and approaches. Operationally, it seems clear that none of these have done a completely adequate job of addressing the range of issues relating to SGD, but it also seems clear that this is an interdisciplinary area where existing entities could meet much of the need with relatively minor modifications of direction and expansion of activities.

Similar arguments could be made for any other mix of specialities -- engineers, chemists, geologists, resource managers, and others all have less-than-perfect communications between groups. However, at each of the boundaries there can be found organisations, individuals, or institutions with a commitment to improving interactions. The challenge is not so much in creating new organisations as it is in identifying the existing ones that can do the job, convincing them to make the effort, and educating the interested scientists about where to seek information and assistance.

However, the issues discussed above -- the problems of interdisciplinary communication -- are well-recognised residuals of the developmental pathways of Western science, and there are at least some means of addressing them. Two other sets of distinctions which also have historical roots are less tractable. One of these is the distinction between fundamental and applied research.

A significant feature of the mix of contributions to this Symposium is the division between the work that has a general descriptive or fundamental component (although perhaps with obvious applications), and those that might best be described as primarily applied -- problem- or management-oriented. Although the two types of studies may address essentially the same processes, issues, and environments, they appear to draw upon each other's results only in a rather limited and perfunctory way, if at all. This does not necessarily reflect lack of mutual interest; indeed, when brought together in person, the two sets of researchers interacted with interest and enthusiasm.

Unfortunately, there are clearly some institutional barriers to strengthening this sort of interaction through traditional means of scientific communication. One is a system of status and rewards, at least in some societies, that treats applied research as less desirable than fundamental research -- and that tends to enforce separations of funding, literature, and effort. This inhibits outreach from the "basic science" side; on the "applied" side, researchers are often under time and resource pressures that make it difficult to develop and publish their findings, much less derive larger applications or significance from them (most of us have had experience with program managers who tolerate shortfalls, but feel cheated or betrayed if the researcher manages to produce more than was contracted for, or is willing to take scientifically defensible risks in extrapolating information to apply to practical scenarios).

In my opinion, existing institutions offer little hope for solving these problems in a useful period of time, in spite of the fact that many developed countries are busily dismantling their fundamental research programs. Fortunately, however, technology has developed a way around the problem. Modern electronic communications, database capabilities, and "search engines" offer a means to connect individuals with common interests to each other, or to sources of literature or data that are not reliably accessible through the traditional abstracting or citation search services. For this approach to be effective, some institution or organisation would have to serve as the "metadata" Center, maintaining and transmitting the information on individuals, studies, and publications. However, this is not an excessively difficult task, and can have substantial rewards if access to information or individuals is important to the organiser. The directory of researchers presented in Annex 2 of this proceedings is printed from the LOICZ (MS Access) contact database; it is available as a starting point, as is a preliminary compilation of references (available as a text file or EndNote library).

The third distinction, between developed and developing country science, cuts across the first two in rather different ways. On the one hand, it can be argued that many developing countries are relatively free of the disciplinary and fundamental vs. applied tensions, since they have not had the "luxury" of following the Western trajectory of developing their science establishments. It has even been suggested that developing country scientists may be intrinsically better adapted to interdisciplinary problem solving than many developed-country researchers because of the variety and urgency of the problems faced in developing countries (J. C. Pernetta, pers. comm.); the fact that many of such issues are economically-driven lends urgency to the LOICZ approach to integrating natural and socio-economic assessments.

However, if these problems are less in developing countries, the problems of communication and information dissemination are substantially greater. Time and resource constraints on publication are compounded by language problems, difficulty of access to the international literature (much less that of other individual countries) and research community, and in some cases, by culturally-determined approaches to scientific communication that are at odds with the Western scientific traditions.

These problems can also be addressed through informal incorporation into a "metadata" network, but significantly more effort will be required than the basic effort described above. Regional or national contact points or repositories will be needed in situations where individual researchers do not have the facilities to go "on line" regularly, and multilingual translators or facilitators will be needed to establish contacts and information transfers once mutual interests are identified. To some extent the type of organisation described in the LOICZ Implementation Plan (Pernetta and Milliman, 1995) -- with regional and research nodes, national contact and committees, etc., could provide a model. However, LOICZ depends on volunteer efforts by interested organisations for its own implementation plan, and lacks resources to do more than facilitate groundwater-related exchanges as one component of its own development.

Given this scenario, it will be extremely interesting to look back in another ten to twenty years and see whether there has yet been any change in the situation originally described by Johannes (1980).

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3.1 Symposium Papers (see Annex 2 for primary author addresses and affiliations)

GROUNDWATER FLOW IN THE COASTAL ZONE OF THE EAST SIKHOTE-ALIN' VOLCANOGENIC BELT

BOLDOVSKI, Nikolai V.

1. Abstract

The East Sikhote-Alin' marginal-continental volcanogenic belt is situated in the south of the Far East of Russia. This belt is spreading along the north-western shore of the Japan Sea. Part of this belt extends under the water of the Japan Sea. The total area of the belt (subaerial and subaqueous parts) is about of 130000 km^2. The estimation of groundwater flow in the coastal zone of the East Sikhote-Alin' volcanogenic belt was carried out using four components: baseflow, stream underflow, spring flow and subaqueous ground-water discharge. As a result of investigations, it has been found that the basic groundwater flow is concentrated in the baseflow component and is equal approximately to 2.9 L/s-km^2.

2. Introduction

The development of the marginal-continental volcanogenic belts is a unique feature of the Pacific Rim. Extending along the Asian, Australian and American coasts these belts form a system of massive volcanogenic belts. The Cordillera-Andean volcanogenic belt consists of a series of volcanic arcs which frame the eastern side of the ocean from Alaska to southern Chile. On the western side of the Pacific the East-Asian (Itzikson and Krasnyy, 1959) or Chukotsko-Katasian (Tectonics of Eurasia, 1966) volcanogenic belt extends from the Chukotski Peninsula on the north to the Indochina Peninsula (Vietnam) on the south. There are fragments of marginal-continental volcanogenic belt along the Pacific coast of Australia and in Tasmania. These marginal-continental volcanogenic structures were formed during the Mesozoic and Cenozoic eras. A system of faults, which served as conductors for the eruption of magma is largely responsible for the formation of the belts. The East-Asian volcanogenic belt is broken down into several small belts among which is the East Sikhote-Alin' volcanogenic belt (ESAVB). In this paper the ESAVB "is defined as a continuous linear arrangement of volcanic formations, deposited on the folded basement" (Sinyukov, 1986) on the continental shore of the south of the Far East and adjacent marine environment of the Japan Sea (Figure 1). The ESAVB is an overlapped structure of the Sikhote-Alin' geosynclinal folded system. Late Precambrian metamorphic rocks, Palaeozoic terrigenous-siliceous, volcanogenic-sedimentary rocks and Mesozoic marine, coastal-marine and continental geosynclinal deposits underlie the volcanic belt. This basement is overlain by Upper Cretaceous, Palaeocene, Neogene and Early Quaternary volcanogenic rocks of various composition and volcanogenic-sedimentary deposits. Intrusive rocks are wide-spread and represented by Precambrian, Palaeozoic, Mesozoic and Cenozoic intrusives from acid to ultrabasic composition.

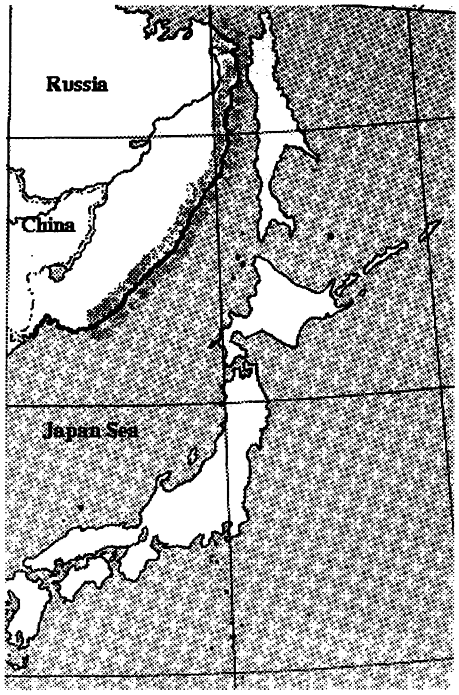

Figure 1. Location of the East Sikhote-Alin' volcanogenic belt (subaerial and subaqueous parts).

Geological analysis of various parameters allows an interpretation of the hydrogeological conditions and groundwater flow in the coastal zone. Based upon groundwater flow characteristics two large-scale hydrostratigraphic systems can be identified: volcanogenic hydrogeological basins and volcanogenic hydrogeological adbasins. Both hydrogeological systems extend into adjacent water areas.

Volcanogenic hydrogeological basins are composed of relatively undeformed stratified Paleogene, Paleogene-Neogene, Neogene and Early Quaternary flows and tuffs of basic to intermediate composition with interbedded clastic sediments. These rocks have high primary cavern porosity and are moderately fractured. Stratal groundwater flow is mainly typical for the volcanogenic hydrogeological basin.

Volcanogenic hydrogeological adbasins are composed of intermediate to acidic rocks that are often deformed. Primary cavern porosity is low and groundwater occurs predominantly in fracture zones. Volcanogenic hydrogeological adbasins are mainly characterised by fracture types of groundwater flow.

This paper details the methods for the estimation of groundwater flow in the coastal zone of the ESAVB using four components: baseflow, stream underflow, spring flow and subaqueous groundwater discharge.

3. Baseflow

The magnitude of baseflow to streams can be obtained by the direct estimation method of mean long-term river discharge for 5 winter months (November, December, January, February, March) of low-water flow regime. Information of stream discharge is available at 32 stations on the 24 rivers, and the period of record ranges from 4 to 42 years (Table 1).

In addition, we also used the hydrograph separation method as one of the variants of baseflow estimation. This method involves a direct line connection of the points of minimum discharge of river runoff at the beginning of spring and at the end of autumn. Such hydrograph separation permits an estimation of the mean annual baseflow. 12 hydrographs for the years of dry, wet and normal total discharges were constructed for 4 stations. The lowest discharges are in March and February. Findings of mean annual baseflow for the dry years are 0.5-1.5 L/s-km^2, for the normal years - 1.8-4.0 L/s-km^2 and for the wet years - 2.0-6.5 L/s-km^2 (Tables 2-5).

Here one should compare the mean annual baseflow (Tables 2-5) with baseflow determined by calculation for the winter period (Table 1). Thus, the mean annual baseflow of the Tumnin station on the Tumnin River by the hydrograph separation is 2.1 L/s-km^2 and mean long-term baseflow for winter period is 2.0 L/s-km^2. The mean annual baseflow of the Tuluchi station on the Tumnin River by the hydrograph separation is equal to 1.8 L/s-km^2, and mean long-term baseflow for the winter period equals 1.73 L/s-km^2. The mean annual baseflows of the Unty station on the Samarga River and Artemovo station on the Serebryanka River by the hydrograph separation are 4.0 and 3.3 L/s-km^2, respectively, and mean long-term baseflow for winter period are 2.8 and 3.0 L/s-km^2, respectively. The analysis of all data shows that the largest part (60% of the subaerial portion of the ESAVB) is characterised by values of baseflow from 2-3 L/s-km^2.

Table 1. Baseflow characteristics of the East Sikhote-Alin' volcanogenic belt at hydrological stations.

Station # and name; mean elevation of the drainage basin, m	Mean winter baseflow for a given period, l/s-km^2	Area drainage basin, km^2	Years of record
1. Tuluchi (Tumnin River); 589	1.73	11300	13
2. Tumnin (Tumnin River); 586	2.00	13900	18
3. Vysokogornyy (Muli River); 742	2.52	154	6
4. Dzhigdasi (Muli River); 648	2.03	1410	28
5. Khutu-Datta (Khuttu River); 659	2.37	6590	8
6. Tumnin (Buya River); 363	1.69	31	17
7. Grossevichi (Botchi River); 523	5.02	2810	5
8. Unty (Samarga River); 719	2.79	7280	21
9. Peretychikha (Edinka River); 655	3.78	2100	13
10. Nakhtakhe (Kaban'ya River); 637	6.15	1060	10
11. Kuznetsovo (Kuznetsova River); 678	3.82	393	4

Station # and name; mean elevation of the drainage basin, m	Mean winter baseflow for a given period, l/s-km^2	Area drainage basin, km^2	Years of record
12. Maksimovka (Maksimovka River); 603	2.99	2160	23
13. Amgu (Amgu River); 377	4.87	489	15
14. Belembe (Taezhnaya River); 497	2.72	678	5
15. Artemovo (Serebryanka River); 500	2.96	2070	6
16. Cheremshany (Cheremukhovaya River); 578	2.88	81.6	28
17. Krasnorechensky (Rudnaya River); 808	3.54	42.4	10
18. Dal'negorsk (Rudnaya River), 584	2.87	293	33
19. Brinerovka (Rudnaya River); 518	2.46	545	7
20. Gorbusha (Gorbusha River); 484	4.06	83.1	14
21. Kavalerovo (Zerkal'naya River); 492	2.14	280	19
22. Bogopol' (Zerkal'naya River); 436	2.60	1510	29
23. Gornorechensky (Vysokogorskaya River);570	1.49	518	6
24. Mikhaylovka (Avvakumovka River); 554	2.13	625	5
25. Moldovanovka (Avvakumovka River); 513	2.25	909	15
26. Vetka (Avvakumovka River); 433	2.57	1740	42
27. Permskoe (Avvakumovka River); 302	2.85	644	6
28. Shcherbakovka (Margaritovka River); 582	3.35	447	22
29. Margaritovo (Margaritovka River); 468	2.80	763	29
30. Milogradovo (Milogradovka River); 480	3.19	770	15
31. Chernoruch'e (Chernaya River); 383	3.59	475	21
32. Zvezdochka (Kievka River); 546	4.37	2270	5

Table 2. Baseflow of the Tumnin River (station Tumnin).

Months of record	Normal year (1952)		Dry year (1954)		Wet year (1957)	
	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2
October	37.5	2.7	8.0	0.6	45.0	3.2
November	40.0	2.9	8.0	0.6	40.0	2.9
December	21.1	1.5	20.9	1.5	24.5	1.8
January	21.8	1.6	6.1	0.4	43.3	3.1
February	17.1	1.2	1.9	0.1	26.9	1.9
March	15.5	1.1	1.4	0.1	23.4	1.7
April	27.5	2.0	3.0	0.2	25.0	1.8
May	32.5	2.3	4.0	0.3	30.0	2.2
June	32.5	2.3	5.0	0.4	35.0	2.5
July	35.0	2.5	6.0	0.4	40.0	2.9
August	35.0	2.5	7.0	0.5	40.0	2.9
September	37.5	2.7	8.0	0.6	45.0	3.2
Mean annual baseflow, l/s-km^2		2.1		0.5		2.5

Table 3. Baseflow of the Tumnin River (station Tuluchi).

Months of record	Normal year (1973)		Dry year (1974)		Wet year (1981)	
	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2
October	35.0	3.1	10.0	0.9	15.0	1.3
November	40.0	3.5	15.0	1.3	10.0	0.9
December	18.1	1.6	14.9	1.3	8.9	0.7
January	14.1	1.2	13.9	1.2	21.7	1.9
February	8.0	0.7	12.7	1.1	9.0	0.8
March	4.1	0.4	11.4	1.0	7.7	0.7
April	5.0	0.4	20.0	1.8	40.0	3.5
May	10.0	0.9	25.0	2.2	40.0	3.5
June	20.0	1.8	22.5	2.0	40.0	3.5
July	25.0	2.2	20.0	1.8	30.0	2.6
August	30.0	2.6	17.5	1.5	30.0	2.6
September	35.0	3.1	15.0	1.3	20.0	1.8
Mean annual baseflow, l/s-km^2		1.8		1.4		2.0

Table 4. Baseflow of the Samarga River (station Unty).

Months of record	Normal year (1964)		Dry year (1976)		Wet year (1981)	
	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2	Mean monthly discharge, m^3/s	Mean monthly baseflow, l/s-km^2
October	50.0	6.9	18.0	2.5	105.0	14.4
November	56.0	7.7	20.0	2.7	95.0	13.0
December	16.7	2.3	14.3	2.0	47.0	6.5
January	12.9	1.8	7.8	1.1	7.8	1.1
February	8.8	1.2	3.9	0.5	5.9	0.8
March	13.2	1.8	3.5	0.5	5.2	0.8
April	18.0	2.5	4.0	0.6	10.0	1.4
May	24.0	3.3	7.0	1.0	25.0	3.4
June	29.0	4.0	10.0	1.4	42.5	5.8
July	34.0	4.7	12.0	1.6	57.5	7.9
August	40.0	5.5	15.0	2.1	75.0	10.3
September	45.0	6.2	17.0	2.3	90.0	12.4
Mean annual baseflow, l/s-km^2		4.0		1.5		6.5

Table 5. Baseflow of the Serebryanka River (station Artemovo).

Months of record	Normal year (1981)		Dry year (1978)		Wet year (1984)	
	Mean monthly discharge, m^3/s	Mean monthly baseflow, $l/s\text{-}km^2$	Mean monthly discharge, m^3/s	Mean monthly baseflow, $l/s\text{-}km^2$	Mean monthly discharge, m^3/s	Mean monthly baseflow, $l/s\text{-}km^2$
October	9.0	4.3	2.7	1.3	15.0	7.2
November	9.0	4.3	2.9	1.4	15.0	7.2
December	5.5	2.6	4.1	2.0	10.9	5.3
January	7.4	3.6	2.0	1.0	7.3	3.5
February	4.8	2.3	1.4	0.7	7.1	3.4
March	4.2	2.0	1.0	0.5	6.6	3.2
April	5.5	2.6	1.0	0.5	7.0	3.4
May	6.0	2.9	1.6	0.8	8.0	3.9
June	6.5	3.1	1.8	0.9	10.0	4. 8
July	7.0	3.4	2.0	1.0	12.0	5.8
August	8.0	3.9	2.2	1.1	13.0	6.3
September	8.5	4.1	2.5	1.2	14.0	6.8
Mean annual baseflow, $l/s\text{-}km^2$		3.3		1.0		5.1

Also, the relationship between baseflow and mean elevation of drainage basin was determined. Five types of dependences were recognised. They are shown by the curves in Figure 2. Curve I characterises baseflow within the basement rocks, curves II, III and V within the volcanic rocks and curve IV within both the basement rocks and the overlying volcanics. Notice that on curve I the baseflow increases from 1.73 up to 2.79 $L/s\text{-}km^2$ with increasing mean elevation of drainage basin. Orographic effects, climate, and proximity to the sea influence on baseflow of station 8. Climate appears to exert more influence on baseflow on curve II, as it increases from 2.25 $L/s\text{-}km^2$ (station 25) up to 2.99 $L/s\text{-}km^2$ (station 12) from west to east. The baseflow changes from 1.69 up to 3.82 $L/s\text{-}km^2$ on curve III. There is also a dependence of baseflow on the elevation of the drainage basin in curve IV. Curve V exhibits large baseflows from 4.87 up to 6.15 $L/s\text{-}km^2$. Here, the drainage basin is composed of volcanogenic rocks containing more than 30% highly cavernous basalts. Apparently this aspect of the geological structure of the drainage basin contributes to increased baseflow to streams. There are some stations for which baseflow is not consistent with the general trend of dependences. Such stations are not taken into account when drawing curves.

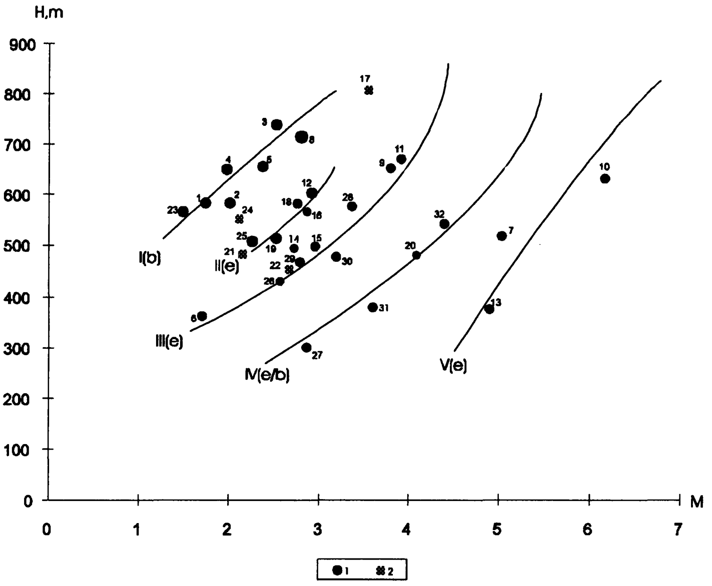

Figure 2. Dependence of baseflow (horizontal axis, $L/s\text{-}km^2$) on mean elevation of the drainage basin (vertical axis, m). Dependence curves of winter baseflow on drainage basin elevation: I(b) - water-bearing fracture zones of basement rocks; II(e),III(e),V(e) - water-bearing complexes and fracture zones of effusive rocks; IV(e/b) - water-bearing complexes and fracture zones of effusive and basement rocks. Explanation: 1 (solid circles)-station #, 2 (solid squares)-station #, the data of which were omitted from the plotted curves.

As might be expected, there appears to be a strong dependence of baseflow on the geology of the drainage basin. This dependence is shown in Figure 2. Curve (I) characterises the baseflow of water-bearing fracture zones of bedrocks, and baseflow varies from 1.73 up to 2.79 L/s-km^2. The drainage basin of stations 7,10,13 (curve V) are composed of 30-40% cavernous basalts. Here, baseflow ranges from 4.87 up to 6.15 L/s-km^2.

As shown in Figure 3, there is a tendency toward increased baseflow towards to the sea. At distances up to 5 km from the sea, baseflow varies little from the average and is equal to 5 L/s-km^2 or more. At distances from 5 to 40 km there is large variation in baseflow. At distances greater than 40 km, the sea appears to have little influence.

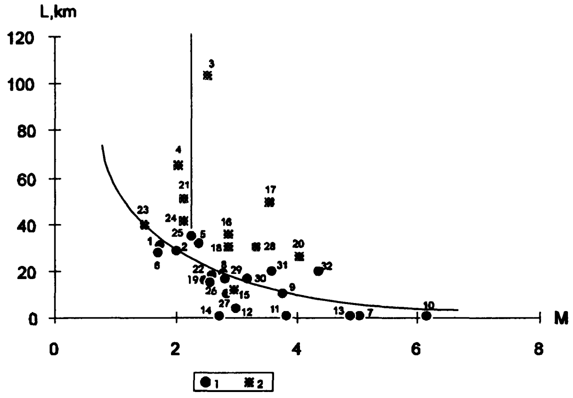

Figure 3. Dependence of baseflow (horizontal axis, L/s-km^2) on the distance of the station from the sea (vertical axis, km) for two classes of station elevation. Explanation: 1-station #, the elevation of which is less than 100 m, 2-station #, the elevation of which is more then 100 m.

Based on the information presented above we can make a conclusion about the contributions of baseflow to rivers in the ESAVB. The baseflow for the winter period is 2-3 L/s-km^2 over the larger part of the territory. In the south and central regions of the territory (along the shore) these magnitudes increase up to 6 L/s-km^2. In the north part of the territory the baseflow modules are sometimes less then 2 L/s-km^2.

4. Stream Underflow

Stream underflow is defined as the groundwater flow in alluvial sediments under the river or stream channel. To estimate the stream underflow, all rivers of the region flowing into the Japan Sea were divided into three categories. The first category applies to the Tumnin River (length of 364 km), the second category is rivers with length of more than 150 km (Koppi, Samarga), and the third category - with length from 50 to 150 km (25 rivers). Rivers with length of less then 50 km were not included for the calculations of stream underflow as they generally have no alluvium or its thickness is relatively insignificant.

The Tumnin River is the largest in the region, both in terms of drainage basin area and runoff. Two wells near the mouth of the Tumnin River valley indicate thicknesses of at least 36 m of Quaternary alluvium. But bedrock was not reached, therefore alluvial sediments of 40 m thickness were used in the calculations. Alluvium is typically fine-grained sand in the upper part (up to 5 m) of the section and sand and gravel in the lower part (up to 40 m). The average hydraulic conductivity of these sediments estimated from these wells was 4.0 m/day. The cross-sectional area of alluvium in the 2.5 km-wide valley is 100000 m^2. The magnitude of stream underflow of the Tumnin River is estimated at 288 m^3/day with stream gradient of 0.0007.

The Samarga and Koppi Rivers belong to the second category. The valley width of these rivers near the mouth averages 2 km. The thickness of alluvial sediments is 30 m and the hydraulic conductivity is 8.0 m/day. The gradient of these rivers is 0.001, and the stream underflow of the Samarga and Koppi Rivers is 480 m^3/day.

Twenty five rivers belong to the third category. The valley width of these rivers averages 1 km. The alluvium thickness equals 20 m and is composed of sand, loam, sandy loam and pebbled-rubbly sediment. The hydraulic conductivity is 12.0 m/day. The average gradient for these rivers is 0.0015. Hence, the magnitude of stream underflow for these rivers averages 360 m^3/day. The total magnitude of stream underflow for all rivers which belong to this category is 9000 m^3/day.

Thus, the total quantity of stream underflow from the eastern slope of the Sikhote-Alin' into the Japan Sea is 10240 m^3/day or 118.5 L/s, and the module of stream underflow from the territory of 90000 km^2 (subaerial part) is 0.0013 L/s-km^2.

5. Spring Flow

Comparatively small groundwater discharge in the form of spring flow has been identified and estimated along the coast. The term spring flow is used for direct flow to the Japan Sea not entering into the river network. The estimation of the quantity of spring flow is realised by the delineation of zones occupied by the bays and zones of steep banks at the coast. On the whole the length of coastline contributing spring flow from the Sikhote-Alin' eastern slope is near 2000 km. About 1/4 of this coastline is occupied by the bays (i.e., near 500 km).

The linear spring flow averages 0.8 L/s-km on the bays. Since the length of the bay coastline is 500 km then the average spring flow discharge for such zones will be near 400 L/s. The average spring flow for the steep abrasion bank zones is 0.3 L/s-km. Then, the spring flow discharge for the similar zones of the whole coastline is 450 L/s. Thus, the general spring flow is approximately 850 L/s and the area module of spring flow (applied to the whole area of the drainage basin) is near 0.01 L/s-km^2; the linear flow module for the 2000 km coastline is about 0.4L/s-km.

One peculiarity of the magnitudes of spring flow should be noted. It concerns zones where are exposures of effusive rocks, represented by cavernous basalts and their tuffs, for example in the regions of Palaeocene-Eocene, Oligocene-Miocene, Pliocene-Early Quaternary rocks, and other similar complexes. Thus, in the regions of Tabo, Susheva, Chikhachevo, Siziman Bays, and also in the regions of such rivers as: Sobolevka, Peya, Nel'ma and others, the spring flow is very intensive with local spring discharge up to 5 L/s and with linear module averaging 1.75 L/s-km.

Groundwater discharge from volcanic rocks of the eastern slope of the Sikhote-Alin' in the form of icings is of great interest. Icings are defined as groundwater discharge in the exposures of the shore line in the form of ice. More then 300 large and moderate size icings and also a large number of small ice accumulations have been located. They are attached to the various water-bearing strata, complexes, and fracture zones. The majority of icings are connected with the zones of spreading of Pliocene-Eocene and Oligocene-Miocene basalts in the regions of Tabo, Chikhachevo, and Siziman bays and others. Icing distributions, which characterise the groundwater discharge from the topographic divides, occur in specific patterns. They are fixed on the slopes along the coast and they occur along geological contacts and fracture zones. Icing volumes were determined in key regions as they melted, and volumes were as much as 300-500 m^3. The linear storage module averaged 30 m^3/km (approximately). The total, ice storage in the region (Rudnaya Pristan'-Nikolaevsk-na-Amure) was near 45000 m^3. The icings are formed from November to April. Therefore the linear flow module from icings is near 3.5 L/s-km, and flow module from melting of icings in the coastal zone averaged over the study area is 0.00004 L/s-km^2. Thus, the total area module of spring flow (including icings) is 0.01004 L/s-km^2, and the linear module is about 3.9 L/s-km.

6. Subaqueous Groundwater Discharge

At present, it is impossible to estimate accurately the quantity of groundwater discharge into the sea. Discharge points appear to occur in zones of basalt sequence outcrops of Palaeocene-Eocene, Oligocene-Miocene and Pliocene-Early Quaternary ages. It appears that groundwater discharge is concentrated in fault zones. Subaqueous groundwater discharge has been mapped at the depth of 1 up to 15 m in the coastal area (from the coast up to 1 km) of the Japan Sea in the region of Tabo-Chikhachevo bays (the length of coast line here is nearly 32 km). In Tabo Bay proper, submarine observations identified springs from 1-2 cm and rarely up to 10 cm in height. Gas bubbles emanating from the springs aided in their identification. Discharges were estimated at 0.001 L/s. Sampling of these springs revealed they were of lower salinity than sea water. Water salinity from the springs varies from 26.1 to 29.4 g/l in comparison with sea water salinity of 35 g/l in the Japan Sea (Table 6). Numerous (more then 30) fresh groundwater discharges were discovered along the coast during low-tide, filtering through the beach pebbles with discharges from 0.1 up to 0.2 L/s. In addition, in the north part of Chikhachevo Bay 300 m from the Tatarka River mouth the water is fresh during low-tide, indicating a significant amount of groundwater discharge.

Thus, value of subaqueous groundwater discharge into the sea or through the beach pebbles in the region is up to 10 L/s. The linear module of subaqueous flow in this region is estimated at 0.31 L/s-km. Groundwater discharge in the form of springs in beach pebbles are observed in the other regions, in particular near the Peya and Maksimovka Rivers.

Table 6. Sea water chemical composition in Tabo Bay.

Sample location #	Distance from the coast, m	Depth of sampling, m	Formula of water chemical composition
648	1000	12	$M_{28,4}\frac{\mathrm{Cl}\ 92}{\mathrm{Na}\ 77\ \mathrm{Mg}\ 17}$
648a	1000	from surface	$M_{28,9}\frac{\mathrm{Cl}\ 93}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 16}$
648b	500	7	$M_{26,1}\frac{\mathrm{Cl}\ 93}{\mathrm{Na}\ 76\ \mathrm{Mg}\ 18}$
648c	500	from surface	$M_{28,2}\frac{\mathrm{Cl}\ 92}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 16}$
648d	250	6	$M_{27,9}\frac{\mathrm{Cl}\ 93}{\mathrm{Na}\ 78\ \mathrm{Mg}\ 17}$
648e	250	from surface	$M_{29,0}\frac{\mathrm{Cl}\ 92}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 16}$
648f	100	1.6	$M_{28,6}\frac{\mathrm{Cl}\ 94}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 17}$
648g	500 N-E # 648	12	$M_{28,6}\frac{\mathrm{Cl}\ 94}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 17}$
648h	800 N-E # 648	8	$M_{28,5}\frac{\mathrm{Cl}\ 94}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 16}$
648i	300 S-W # 648	11	$M_{28,6}\frac{\mathrm{Cl}\ 92}{\mathrm{Na}\ 78\ \mathrm{Mg}\ 17}$
648j	800 S-W # 648	10	$M_{29,0}\frac{\mathrm{Cl}\ 94}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 16}$
648k	800 S-W # 648	from surface	$M_{28,1}\frac{\mathrm{Cl}\ 93}{\mathrm{Na}\ 78\mathrm{Mg}\ 17}$
648l	1000 S-W # 648	2.5	$M_{29,4}\frac{\mathrm{Cl}\ 93}{\mathrm{Na}\ 80\ \mathrm{Mg}\ 16}$
648m	200 W # 648	4.5	$M_{28,8}\frac{\mathrm{Cl}\ 93}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 17}$
648n	200 W # 648	from surface	$M_{29,2}\frac{\mathrm{Cl}\ 94}{\mathrm{Na}\ 80\ \mathrm{Mg}\ 16}$
648o	400 W # 648	4	$M_{28,6}\frac{\mathrm{Cl}\ 94}{\mathrm{Na}\ 79\ \mathrm{Mg}\ 17}$

7. Conclusions

Having identified and quantified the groundwater flow components, it is possible to estimate the total groundwater flow in the coastal zone of the ESAVB. Baseflow to the rivers during the winter period was determined to be 2.87 L/s-km^2. Stream underflow was estimated to be 0.0013 L/s-km^2, while spring flow (including icings) is estimated at 0.01004 L/s-km^2. Subaqueous groundwater discharge was estimated to have a linear module of 0.3 L/s-km. Hence, the module of area flow is nearly 2.9 L/s-km^2, and the module of linear groundwater flow (consisting of spring flow, icings, and subaqueous discharge) for coastal zone is 4.2 L/s-km. Thus, baseflow to rivers is the largest component of the groundwater flow. The aforementioned magnitudes are minimum groundwater flow components for the ESAVB.

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*GROUNDWATER FLUX TO THE OCEAN: DEFINITIONS, DATA, APPLICATIONS, UNCERTAINTIES

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1. Abstract

There are a wide range of reasons and applications for the study of groundwater relationships in the coastal zone. This diversity, in combination with the range of disciplines and of time and space scales involved, complicate the use of data derived from specific studies for purposes by other researchers with different application interests. The challenge is particularly great in the case of local type or case studies designed for global or regional extrapolation, since errors or inappropriate assumptions will be greatly magnified. This paper examines the conceptual approaches, data needs, and limitations of various types of studies, and makes recommendations concerning precautions and presentation of results.

2. Introduction

The definitions and techniques used for the study of groundwater discharge to the coastal ocean are very scale- and problem-dependent, and the differences inherent in various applications undoubtedly contribute to the scientific fragmentation of the study of groundwater discharge to the coastal ocean (see Section 1, this Proceedings). This paper focuses on the needs implicit in the global biogeochemical modelling task of the Land-Ocean Interactions in the Coastal Zone (LOICZ) core project of the International Geosphere-Biosphere Programme (Holligan and de Boois, 1993; Holligan, 1990; Pernetta and Milliman, 1995). There are two reasons for this focus: organisationally, the requirements of this effort led LOICZ to co-sponsor the Symposium and attendant review of coastal groundwater processes; scientifically, applications at this "meso-scale" (tens to hundreds of km) in the coastal ocean place the greatest demands on system conceptualisation and understanding.

3. Applications and Issues

The following incomplete list of applications permits a general overview of some of the typical approximations that are used in coastal groundwater studies -- and that are generally not applicable to many of the problems of LOICZ applications (which are summarised below).

1. Global (or regional long-term) geochemical and water budget studies -- there are many such efforts addressing (for example) the role of the ocean in natural global climate cycles. Some recent examples that specifically address questions involving groundwater flux and composition are publications of Milliman and co-workers (Milliman, 1993; Milliman and Droxler, 1996). Such studies, focused on time scales comparable to or longer than whole-ocean residence times and on budgets at the ocean basin or regional scale, can appropriately ignore the complexities of the coastal zone and consider the ocean as one or a few relatively simple homogeneous reservoirs. Estimates or measurements used for this purpose may serve to establish magnitudes or boundary conditions for more detailed studies, but almost invariably lack the spatial and temporal resolution needed for coastal ocean budget models.
2. Coastal water resource studies -- although often too localised, these may address scales appropriate to coastal biogeochemical modelling. However, they tend to ignore the details of discharge pathways, and to treat the ocean as a simple uniform sink (in the case of fresh water loss or contaminant transport) or source (in the case of saltwater intrusion). Further, attention is usually focused on a single dominant aquifer (often but not always the shallowest) to the exclusion of other groundwater bodies and of surface water-groundwater interactions. If focused on the time scales of aquifers the temporal resolution will be inadequate for coastal processes, but studies that address interactions on seasonal or tidal time scales my be appropriate to the marine biogeochemical budgets. In most cases boundary conditions or limiting estimates of flux are the most that can be extracted.
3. Marine geochemistry or biogeochemistry studies -- such studies often focus on the scales and compartments of interest to LOICZ, but the marine research perspective can be difficult to couple to the concepts and data of terrestrial hydrology. For example, "groundwater" to a marine chemist may be operationally defined as any fluid that has interacted significantly with sediments or rocks -- see, for example, (Moore, 1996) -- whereas this grouping of circulating marine porewater with fresh and mineralised water of terrestrial origin complicates the budgeting process.

In pursuit of the goal of determining the role of the coastal oceans in the global cycle of carbon and other key substances (Smith and Hollibaugh, 1993), LOICZ has adopted a hierarchical approach to globalization of the highly dispersed coastal data sets available (Gordon *et al.,* 1995). The strategy is to use budgetary data to identify process controls and functional (e.g., source or sink) roles of generally identifiable types of coastal environments or habitats. Then, development of coastal typologies (LOICZ, 1996; Pernetta and Milliman, 1995) is intended to provide a framework for extrapolation of data from well-characterised environments to the much larger global inventory of functionally similar but unstudied environments -- and also to provide a methodological basis for incorporating social science components relating to the human dimensions of global change (Pernetta and Milliman, 1995).

Hydrologic issues enter this process at two key points -- in quantifying inputs to specific coastal budgets, and in characterising types of coastal environments in terms of behaviour that will support extrapolation to a global "model." Both are important, and their combined requirements represent a significant challenge. Beyond the hydrologic questions are the key issues of hydrochemical fluxes -- especially of nutrients, but also of carbon compounds and of other materials, natural or anthropogenic, that may affect biological and chemical cycles in the coastal zone. However, understanding of solvent behaviour is typically a prerequisite for predicting the action of solutes, so an initial focus on hydrology is essential.

4. Coastal Hydrologic Processes and Pathways

Construction of accurate material budgets within the coastal zone requires careful attention to the definitions of pathways and fluxes. Figure 1 shows a simplified schematic illustration of the coastal zone. Materials may enter a defined volume of the coastal ocean by precipitation from or exchange with, the atmosphere, inflow of terrestrial surface water, discharge of groundwater, exchange or reaction with sediment porewater, and by ocean water fluxes. Loss terms typically include longshore and offshore transport, sedimentation or sediment reaction, and transfer to the atmosphere (by evaporation, suspension, or gas exchange). Fluxes from the marine environment into terrestrial water bodies (aquifers and estuaries) may be significant in terms of impact on the fresh water environment, but usually negligible compared to other loss terms in the coastal ocean budget.

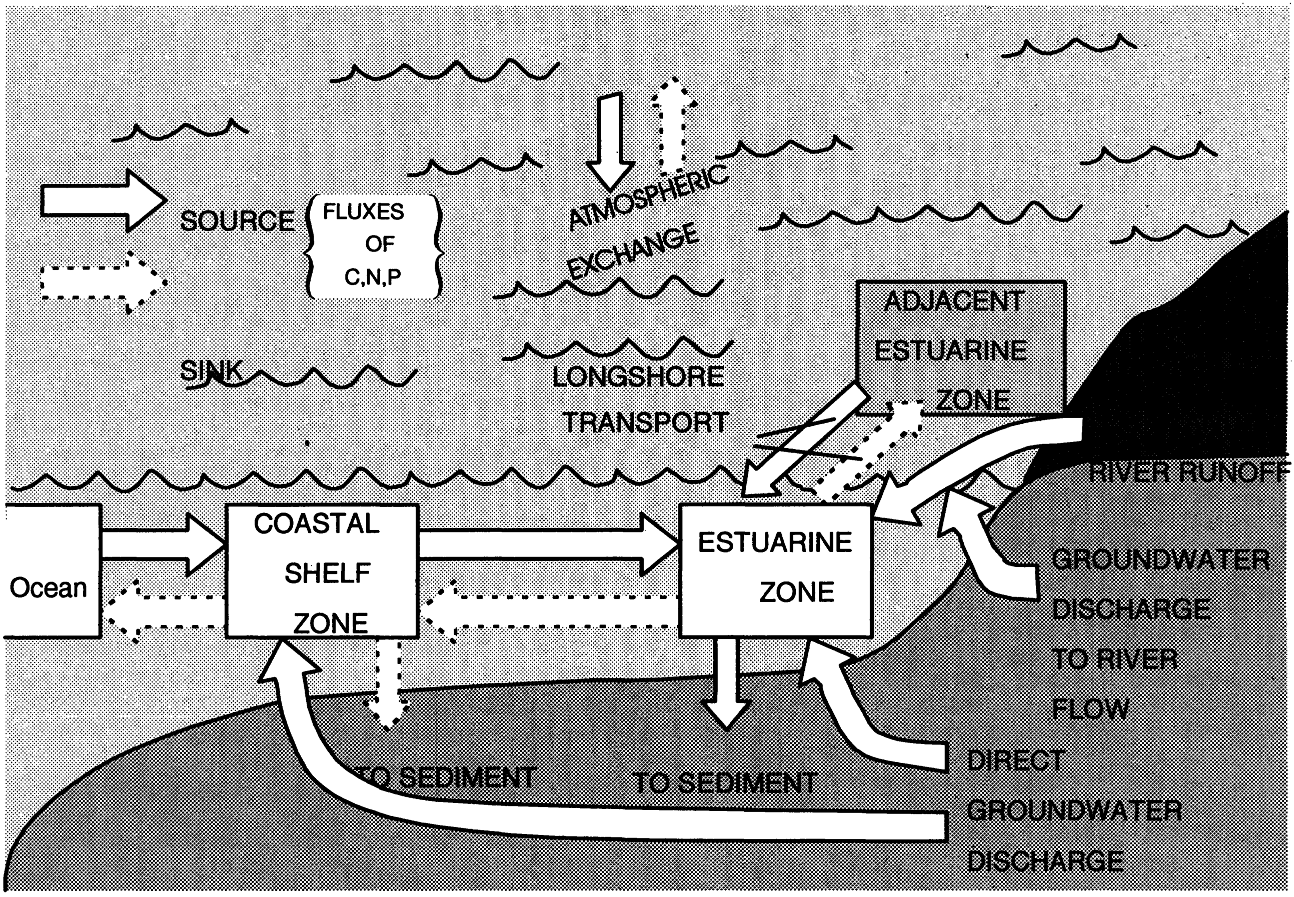

Figure 1: Stylised schematic view of the coastal zone, emphasising the different pathways of groundwater discharge and the distinctions among the terrestrial compartment and the "estuarine zone" and the "open shelf zone" within the marine compartment.

Figure 1 indicates two distinct subsets of the coastal marine environment -- one, the "estuarine zone," is intended to represent the typically narrow width of the marine environment that is most influenced by land, and which often has relatively high levels of variability as well as productivity. The estuarine zone includes true estuaries, but is further represented by a narrow band of nearshore water masses in locations where there are not streams adequate to form traditionally-defined estuaries (as illustrated in Figure 2). It is the area of the ocean most subject to direct anthropogenic alteration. On a global average, this zone is not dominated by fluxes from the world's major rivers; advective processes are primarily oceanic, and terrestrial inputs are often a mix of groundwater and runoff from local, ungauged (sometimes small) watersheds.

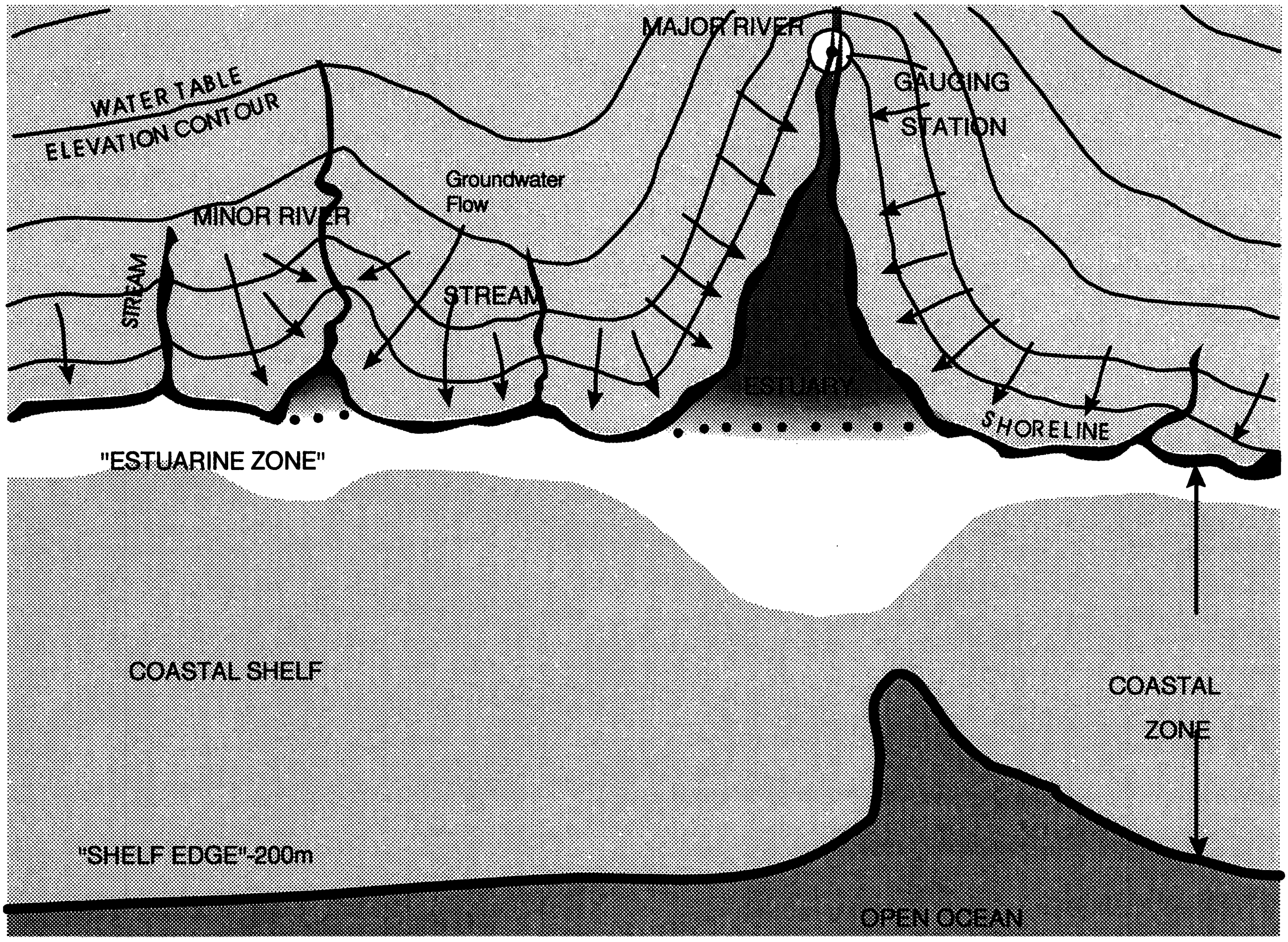

Figure 2: Plan view of the coastal zone, showing the relationships among the estuarine zone, open shelf zone, gauged and ungauged streams, and groundwater discharge to the ocean and to streams.

The remainder of the coastal marine environment is referred to here as the “coastal shelf zone.” This is the open-water part of the continental shelf that is dominated by oceanic advective processes and characterised by more nearly oceanic water characteristics. Figures 1 and 2, considered together, illustrate both a conceptual and an operational problem in considering hydrologic inputs to the coastal zone. Conceptually (and essentially be definition), most surface water flow enters the coastal ocean through the estuarine zone. Although this is a convenient assumption for shallow groundwater (Johannes, 1980), it is not necessarily correct; confined aquifer systems, karst formations, etc., may result in either localised or distributed discharges of groundwater relatively far out on the continental shelf or slope. This situation is illustrated in Figure 3, along with indications of processes that must be considered “groundwater” in the larger geophysical sense, although not in the terms usually employed by water resource hydrologists. These offshore discharges are likely to be insignificant in terms of the water budget of the “coastal shelf zone,” but because it is likely to be more highly mineralised it may be biogeochemically significant, and the flux of groundwater may also have an amplified influence on porewater environments and the benthic community (Tribble, 1990; Tribble et al., 1992). Large-scale physical phenomena with major geochemical implications, such as sediment erosion, deposition, and slumping, may also be linked to offshore groundwater fluxes (Rona, 1969).

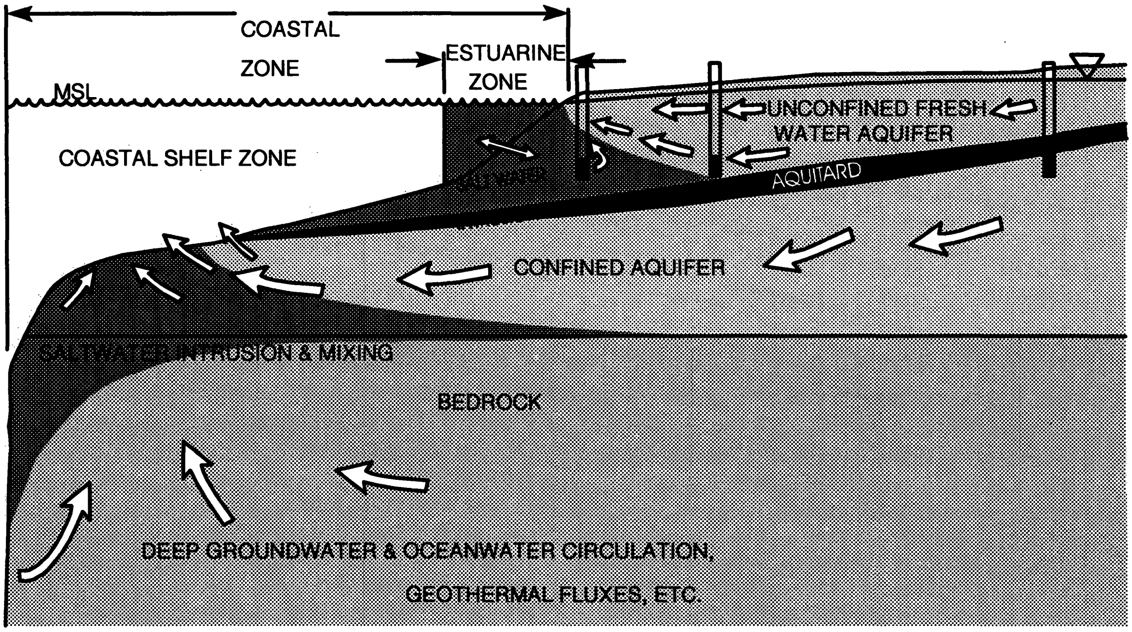

Figure 3: Cross-sectional views of the coastal zone, illustrating the types and pathways of fluid movements that may be considered "groundwater" for various purposes.

5. Problems of Measurement and Definition:
One part of the operational problem alluded to above may be seen in Figure 2 -- the fact that the most nearshore river gauging stations are often well inland of the major estuary and delta systems. Where good monitoring records exist, gauging stations can provide data not only on total flow, but also dissolved and suspended solids loads and on runoff-baseflow (groundwater separations). However, the best (and often only, or last) data set available is typically above not only the estuarine zone, but also much or all of the coastal plain -- the biogeochemically active terrestrial portion of the LOICZ region of interest. It is generally recognised that coastal runoff and groundwater discharge in between gauged streams is not included in river input data; somewhat more subtle is the fact that available river data often do not account for a substantial amount of distinctive flux in the lower reaches of the river.

Figure 4 illustrates in greater detail some of the uncertainties and potentials for error that arise when efforts are made to consider specific inputs to the estuarine zone with time constants suitable for comparison with marine data obtained on the scale of water residence times -- typically quasi-synoptic data oriented toward times of hours to weeks. This level of detail is required by the "typology" approach to achieve globalization of coastal zone data. Assumptions which may be valid or a source of minor error on the global scale may cause very large distortions in coastal process models at the local scale; if these errors are then amplified and propagated through the globalization process, the outcome could be prejudiced.

The terrestrial portion of the coastal zone is an area of high human activity (agricultural, urban and industrial), with attendant perturbations and high gradients in water and contaminant fluxes. The problems of pathway identification and flux measurement discussed above become more critical at local scales; often aquifer characteristics and chemical sources are not well understood, and even where they are, there may not be adequate measurement points or data -- local authorities and researchers tend to focus on the best resource or the worst problem, rather than the widely-distributed marginal-quality water that may carry most of the chemical load or system-relevant "signal." This is illustrated in Figure 4 by the chemical inhomogeneity of the shallow aquifer. Where salinity increases and surface contamination decreases with depth, Darcian flow estimates based on a limited number of measuring points may be highly misleading. Additionally, there may be problems of estimating consumptive water use (and therefore effective gradient or flux) between the sea and the lowest inland measuring point (monitoring well or gauging station).

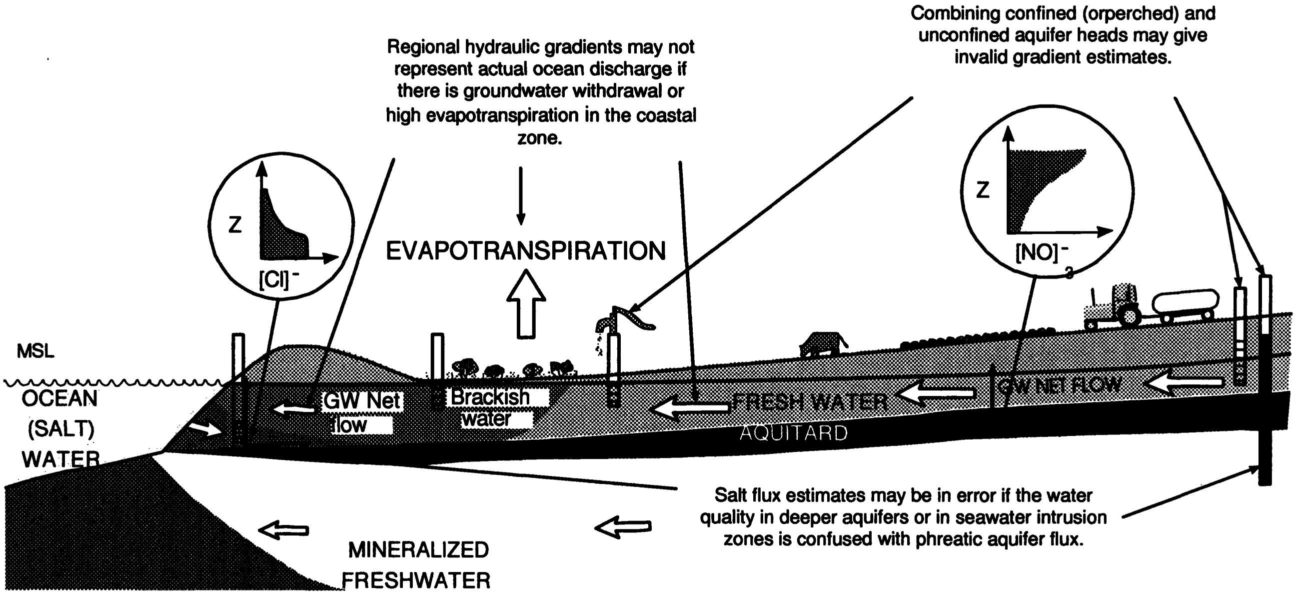

Figure 4: Detailed and expanded cross-section of the terrestrial coastal environment, depicting problems inherent in generalising limited measurements to obtain system-level water and chemical fluxes.

6. Requirements for Integration and Application of Data

It is not realistic to expect that all measurements, calculations or publications of data relevant to coastal groundwater fluxes will suddenly conform to the needs (Gordon et al., 1995) or standards (Boudreau et al., 1996) of the LOICZ project. However, one of the reasons for highlighting the disciplinary diversity in the origins and applications of the data is to encourage researchers both to seek out and to provide the data that will make their results more broadly useful --and in doing so, to encourage integration of the field of study.

In publishing or compiling groundwater flux results, a wide variety of information should be considered, included, or referenced. Examples include geographic co-ordinates of drainage basins or aquifer units, coastline segments, and well or study sites. Information on the sources of both water level and groundwater chemistry data. The groundwater data should include land and water level (or head) elevations, relevant times of measurement, and depth or elevation of the screened (sampled) interval. Measured or assumed hydrogeologic parameters and stratigraphic aquifer characteristics are also required for interpretation -- which means that information on methods of measurement or derivation is needed.

The challenge of effectively integrating and comparing diverse hydrologic and oceanographic measurements and models, often at very different spatial and temporal scales, demands extensive documentation of both primary data and methods, as well as rigorous analysis of uncertainties. The difference between semiquantitative groundwater flux estimates and determinations best adapted to budgets will be very great in terms of the quality of documentation and analysis required. At least as important, however, is the fact that estimates can be quite useful if the assumptions, methods, and uncertainties are specified. Without this evaluation, estimates produced for one application may be seriously misleading if used for others.

7. Summary

Measurements or estimates of groundwater and associated chemical fluxes, especially over substantial areas or time periods, are notoriously uncertain. "Groundwater discharge" may include the base flow component of stream and river discharge, direct seepage from phreatic aquifers though the intertidal and shallow subtidal zones into the coastal ocean, nearshore springs, deeper offshore discharge (as from confined aquifers), or any combination of these. Depending on the measurements made and definitions used, combining groundwater flux estimates with independent estimates of fluvial inputs and oceanic fluxes can result in over- or under-estimates (for example, double-counting river base flow as both river input and groundwater flux, or failure to account for riverine groundwater discharge between the lowest gauging station and the mouth). From the standpoint of accounting convenience it is probably best to treat all streamflow as surface water, but this runs the risk of obscuring some geochemically important pathways. Additional complications arise when one considers issues such as short-term interactions between streams and alluvial aquifers, or lateral "interflow" of water within the normally unsaturated zone -- processes which may be hydrologically but not biogeochemically insignificant.

Hydrologic calculations may overestimate fluxes by neglecting evapotranspiration losses in the coastal plain. Vertical stratification of both flow rates and water quality in coastal aquifers can lead to serious mismatches in calculation of chemical fluxes, as can ocean water intrusion into the aquifer. Assignment of chemical compositions to the hydrologic fluxes requires careful matching of data sets, and consideration of the correspondence between the two types of data, their sources, and their uncertainties.

Complete reporting of data and methods, and consideration of the wide range of potential applications for data relating to groundwater in the coastal zone are recommended. This will not only serve the needs of integrative projects such as LOICZ, but will also provide definition and cohesiveness to an important field of study that is now highly fragmented.

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TRACING GROUNDWATER FLOW INTO SURFACE WATERS USING NATURAL ^{222}RN

BURNETT, William C., CABLE Jaye E., CORBETT, Reide D., and CHANTON Jeffrey P.

1. Abstract

Several investigators have suggested that nutrients, especially nitrogen species, may be delivered in ecologically-significant amounts to coastal environments and lakes via submarine groundwater discharge (SGD). This process may be particularly important in areas where groundwater has become contaminated with nutrients from septic systems. Delivery of other soluble contaminants (metals, radionuclides, etc.) via this process may also be important in some circumstances. We have been examining the flow of groundwater into surface waters both by direct measurements using "seepage meters" and by use of ^{222}Rn as a natural tracer. Radon is a useful as a tracer because: (1) it is 2-4 orders of magnitude more concentrated in groundwater compared to surface waters; (2) it is conservative; (3) other inputs and outputs from the system in question can be estimated relatively precisely because of known source/decay terms; and (4) its radioactivity makes it relatively easy to measure, even at very low concentrations.

We summarise here our findings in two environments: (1) an uncontaminated area of the coastal north-eastern Gulf of Mexico off Florida; and (2) a freshwater lake (Par Pond) built as a cooling reservoir for two nuclear reactors at the Savannah River Site in South Carolina. The studies in Par Pond were enhanced by the availability of independent water budget information. A simple box model approach was used to interpret our radon data in terms of inputs of groundwater to the lake — these inputs were shown to be of the same order as direct rainfall, the only other significant input to the lake. Our results for the Gulf coast area showed that coastal water ^{222}Rn and CH_4 inventories varied directly with measured groundwater seepage rates.

2. Introduction

Groundwater may be an important source of nutrients and other dissolved constituents to the coastal ocean and other standing bodies of water (Kohout 1966; Kohout and Kolipinski 1967; Johannes 1980; Capone and Bautista 1985; Capone and Slater 1990; Valiela *et al.* 1990). However, the only estimates available for the global magnitude of submarine groundwater discharge (SGD) are based on water balance calculations, which yield widely varying results (Nace 1970; Garrels and MacKenzie 1971; Zektser *et al.* 1973). On a local and regional scale, estimates of the location and magnitude of groundwater flow are scarce, because measurements cannot be performed easily and sites of SGD are not always obvious. Since the chemical composition of groundwater and its rate of advection determine the effects of SGD on the overall chemical budget of receiving waters, the contribution will be significant when either flow rates or the ratio of components in groundwater relative to the surface waters is sufficiently high.

In addition to freshwater, many dissolved constituents, both natural and anthropogenic, can be carried by SGD to surface waters. Sewage, mining waste, and other soluble refuse percolating into an aquifer may eventually enter coastal waters via groundwater discharge. Depending on the concentrations and flow paths of these contaminated plumes, the ecology of the coastal waters could be impacted. It was shown, for example, that nutrient loading of several bays in New England increased eutrophication, thus increasing fin- and shellfish kills (Valiela *et al.* 1990). This nutrient input was attributed partially to sewage-contaminated groundwater as well as river water. In another example, when sediment pore waters from Great South Bay, New York, were analysed for nutrients, Capone and Slater (1990) recognised that contaminated groundwater accounted for up to 50% of the total nitrogen input to the bay. The importance of SGD to the coastal zone has also been documented in the Florida Keys (Lapointe *et al.* 1990); Australia (Johannes 1980); Jamaica (D'Elia *et al.* 1981); and the Yucatan Peninsula (Hanshaw and Back 1980).

Relationships between groundwater, the substrate through which it flows, and the receiving waters are of significant environmental concern since the magnitude of SGD is not yet assessed along most of the world's coastlines. One potential means of evaluating groundwater pathways and fluxes into the coastal zone is through natural tracers. The conservative nature and short half-life of ^{222}Rn ($t_{1/2}$ = 3.83 d) make it a strong candidate for tracing groundwater discharge. Although CH_4 has other sources and sinks in the marine environment, its use in conjunction with the chemically inert ^{222}Rn makes a convincing case for tracing groundwater discharge in the coastal zone (Bugna *et al.* 1996).

3. Northeast Gulf of Mexico

Our study site is near the Florida State University Marine Laboratory (FSUML) at Turkey Point, Florida, within the Big Bend region (Figure 1). This area consists of a broad carbonate system containing one of the United States' largest freshwater reservoirs, the Floridan Aquifer. This aquifer is part of the layered marine limestone and dolomite St. Mark's Formation, which is overlain by a clay, silt, and sand surficial aquifer (Hendry and Sproul 1966). Dissolution of carbonate rock within the deeper formation creates direct conduits for groundwater flow supporting offshore seepage and spring flow into the Gulf of Mexico. In addition, SGD can enter the ocean from the unconfined, water table aquifer as nearshore seepage (Bokuniewicz 1980; Cable *et al.* 1996a).

We established a seepage meter transect near FSUML to evaluate groundwater flow through the sediments in shallow nearshore waters. This transect consisted of 5 seepage meters placed approximately equal distances apart and extending 480 m perpendicular from the shoreline. Direct seepage measurements were made using methods developed by Lee (1977). Samples for ^{222}Rn and CH$_4$ analysis were collected from the overlying water column at each station along the transect on the same days that seepage rates were measured.

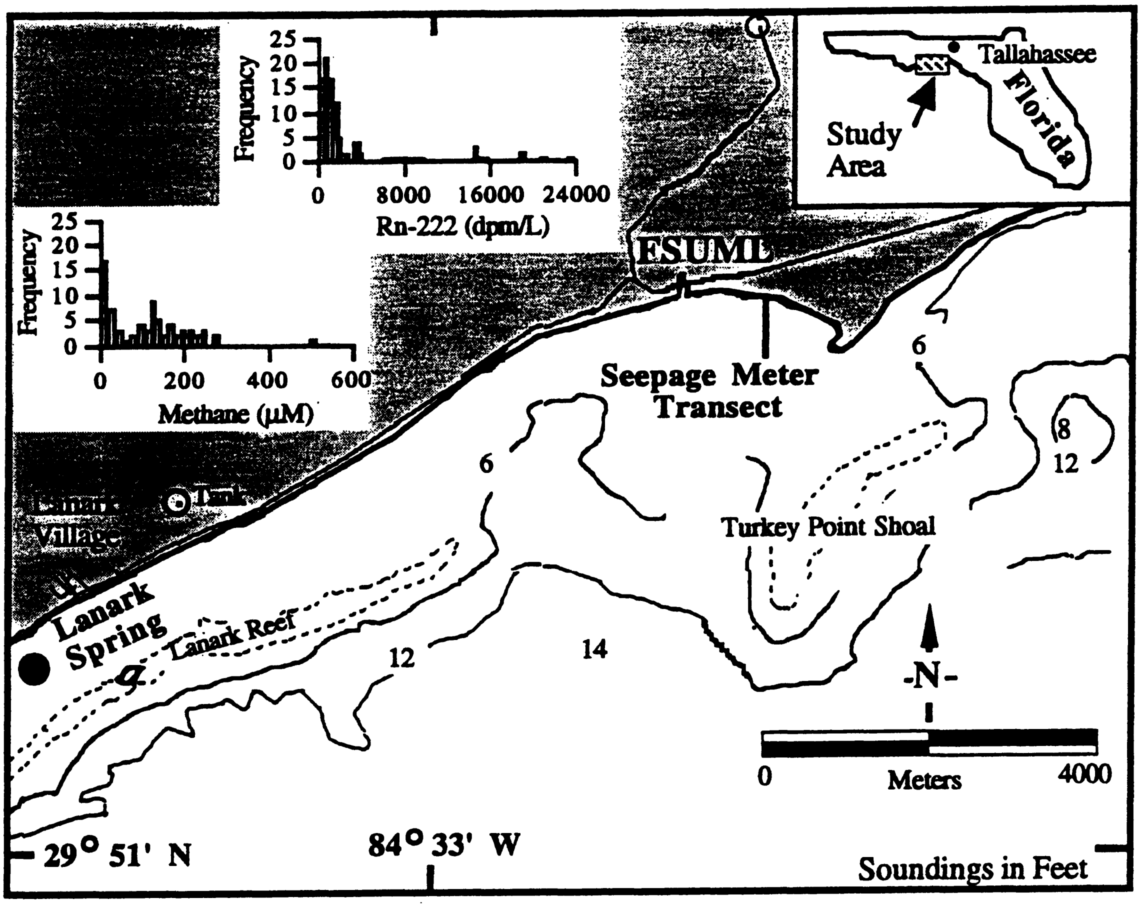

Figure 1. A map of the study site shows the location of the seepage meter transect. Insets show ^{222}Rn (dpm·L^{-1}) and CH$_4$ (mM) groundwater concentration frequency distributions for wells bordering the field site near FSUML.

Samples were collected from 59 private residence wells to determine concentrations of ^{222}Rn and CH$_4$ in groundwater along the shore bordering our field site. A frequency distribution of ^{222}Rn and CH$_4$ analyses (n = 98) of these wells between March 1992 and August 1994 revealed concentrations up to several orders of magnitude greater than would be expected in seawater (insets; Figure 1). While groundwater ^{222}Rn concentrations below 4,000 dpm·L^{-1} represented 83% of the data, ^{222}Rn values as high as 23,500 dpm·L^{-1} were measured. Most CH$_4$ concentrations were less than 10 mM with a secondary frequency maximum at 130 mM (inset; Figure 1). The results indicate a large spatial variability and non-uniform relationship between CH$_4$ and ^{222}Rn source terms within the aquifer. Despite this variability, measured concentrations of the trace gases were always orders of magnitude higher in groundwater than in seawater. Typical oceanic values of ^{222}Rn and CH$_4$ are 0.1 to 0.5 dpm·L^{-1} and 2 to 3 nM, respectively.

We examined the relationships between ^{222}Rn and CH_4 inventories and seepage in several ways including measurements from a single station (#1; the most shoreward seepage meter) for each of 14 separate sampling events (Figure 2). In this case, the ^{222}Rn and CH_4 concentrations were integrated over the measured water depth (m) and related to the corresponding seepage rate ($mL \cdot min^{-1} \cdot m^{-2}$) measured on that day. Assuming that the y-intercepts in these plots represent the diffusional supply (seepage = 0) of these tracers, we estimated the ^{222}Rn inventory supported by molecular diffusion to be 1240±970 $dpm \cdot m^{-2}$ (seepage rate = 0; r = +0.804; $p < 0.05$) and a CH_4 inventory of 7±30 $mmol \cdot m^{-2}$ (r = +0.717; $p < 0.05$). The large error in the CH_4 inventory reflects an anomalously high concentration measured during November 1994.

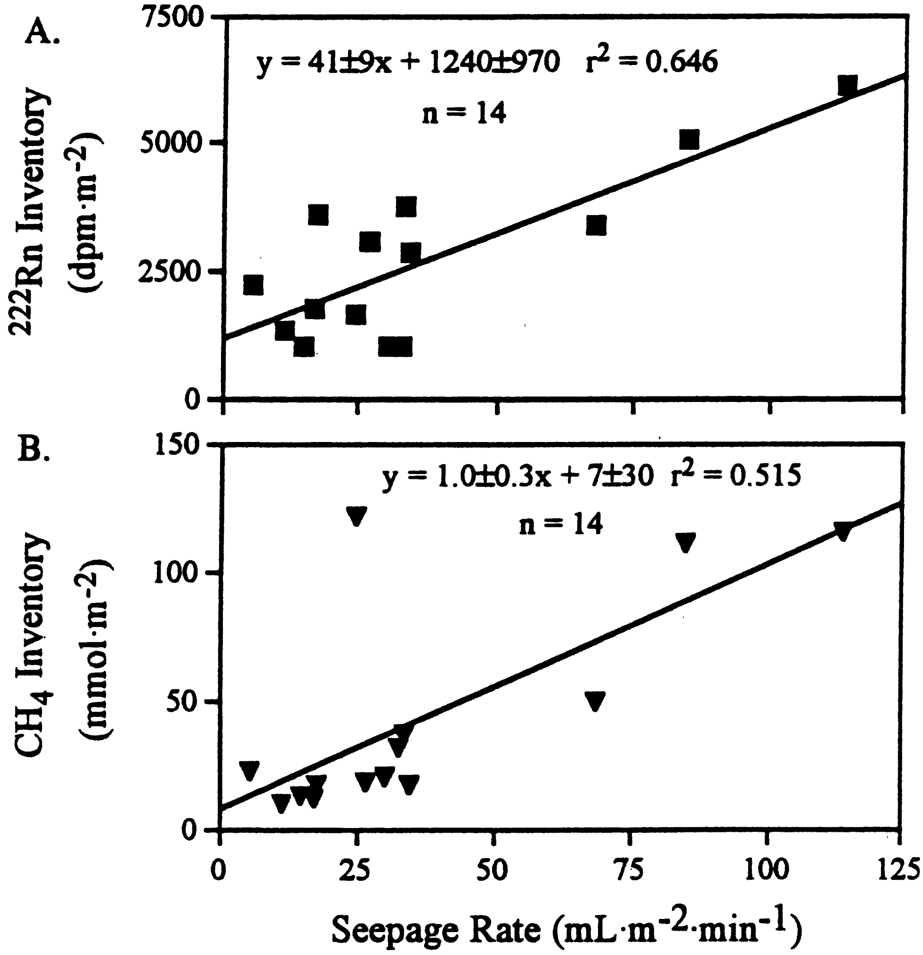

Figure 2. Relationship of trace gas inventories to measured seepage rates ($mL \cdot m^{-2} \cdot min^{-1}$) at a single station during 14 collection periods: (A) ^{222}Rn ($dpm \cdot m^{-2}$; r = +0.804; $p < 0.05$); and (B) CH_4 ($mmol \cdot m^{-2}$; r = +0.717; $p < 0.05$).

These results led us to believe that these tracers respond directly to variations in seepage and that the magnitude of nearshore groundwater flow in this area is highly significant. By integrating the water flux results with distance from the shore to the end of the seepage meter transit (Figure 1), we estimate that there is flow approximately equivalent to a first magnitude spring
(>1.7x105 L x min-1) just from the area shown.

4. Par Pond, Savannah River Site

Par Pond, a former thermal cooling reservoir, is located near the eastern edge of the U.S. Department of Energy's Savannah River Site (SRS) in western South Carolina (Figure 3). The reservoir was built in 1957 to augment the cooling requirements for the "P" and "R" nuclear reactors, built to produce plutonium and tritium for the atomic weapons program. Since the construction of the pond by the U.S. Army Corps of Engineers, an earthen dam 20 meters high and 1370 meters long has maintained the water level in the reservoir.

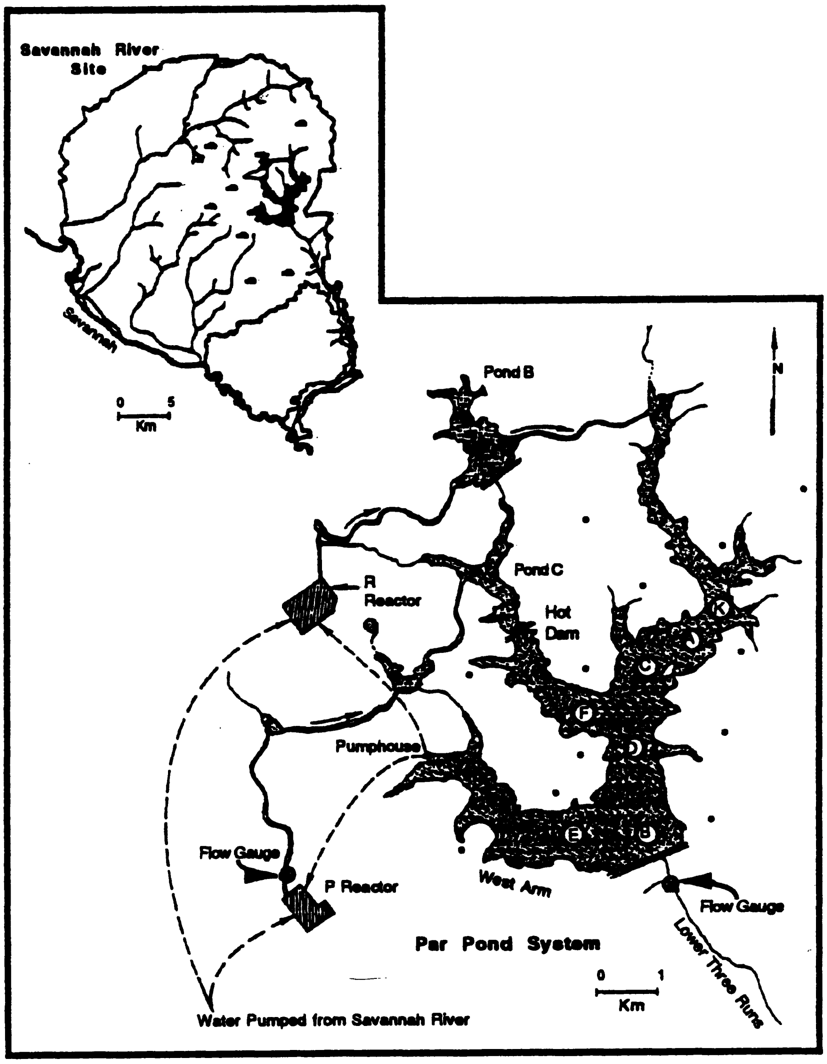

Figure 3. Map of Par Pond, Savannah River Site showing the locations of sampling sites and wells used for this study.

In the Spring of 1991, a depression was found in the downstream side of the impoundment. The reservoir's water volume was drawn down because of concern that failure of the Par Pond dam would be a threat to public safety and to the environment. The water level was lowered 6 meters over approximately a 90-day period beginning in June, 1991 — exposing 5.3 km^2 of radiologically-contaminated sediments (Whicker *et al.* 1993). In March 1995, Par Pond was refilled to its original water level using water pumped from the Savannah River, and the water level is now being maintained at 61 ± 0.3 m (200 ± 1 ft) above mean sea level (msl).

Par Pond occupies an area of approximately 10.1 km^2 with a maximum water depth of 18 m. The mean depth is 6.2 m and the volume is estimated to be 6.3×10^7 m^3. It is a warm, monomictic lake which normally stratifies from May through September, turns over in October, and is well-mixed from October through April. The Par Pond watershed is underlain by the Hawthorn, Barnwell, McBean, Congaree, and Tuscaloosa Formations, which contain aquifers separated by confining clay layers (Williams and Pinder 1990). The groundwater hydrology is such that both upward and downward vertical flow gradients occur in the area. The general horizontal transport of groundwater is thought to be towards the south at Par Pond (Westinghouse 1992).

In order to evaluate the groundwater contribution into Par Pond using ^{222}Rn, all possible sources and sinks must be considered. A mass balance equation may be used to describe this reservoir assuming a one-layered system:

$$(\upsilon C)_i + J_{\text{benthic}} + \lambda C_{Ra} - (\upsilon C)_o - J_{\text{Atm}} - \lambda C_{Rn} = 0$$

where *v* is the flow rate into or out of the system (m^3·min^{-1}); C represents the radon activity (dpm·m^{-3}) either entering (*i* = input) or leaving (*o* = output) the system; l is the decay constant of ^{222}Rn (min^{-1}); lC_{Ra} and lC_{Rn} accounts for production and decay of radon (dpm·m^{-3}·min^{-1}) in the water column, respectively; J_{Atm} is the radon flux lost to the atmosphere (dpm·m^{-3}·min^{-1}); and $J_{benthic}$ represents the combined advective and diffusive flux (dpm·m^{-3}·min^{-1}) to the overlying water column. All terms in this equation can be expressed either as a flux (dpm·m^{-2}·min^{-1}) or a velocity (dpm·min^{-1}) if the area of the reservoir is taken into account.

After an assessment of the ^{222}Rn inventory for the reservoir and the surface sources and sinks, the mass balance equation was used to calculate the total benthic flux, representing both diffusive and advective components. The total benthic flux ($J_{benthic}$) will exceed the estimated diffusive fluxes if there is also an advective flux present. However, the co-dependence of diffusion and advection requires that the two terms be considered together. Through the application of a one dimensional, vertical advective-diffusion model initially developed by Craig (1969) to describe radiocarbon profiles in the deep sea and later applied by Cable *et al.* (1996b) to model ^{222}Rn fluxes from sediment, the flux of radon supplied to the overlying water is estimated using:

$$\frac{dC}{dt} = K_z \frac{\partial^2 C}{\partial z^2} + \omega \frac{\partial C}{\partial z} + P - \lambda C$$

where C is the radon concentration in the sediments; *z* is depth positive downwards; K_z is the vertical diffusivity; $\frac{\partial^2 C}{\partial z^2}$ and $\frac{\partial C}{\partial z}$ are the ^{222}Rn concentration gradients across the sediment-water interface for diffusion and advection, respectively; w is the vertical advective velocity defined as positive downward (m·min^{-1}); P is a zero-order production term of radon in the pore fluids due to recoil and other processes after production via ^{226}Ra; and lC is radioactive decay. In order to model radon activity in sediments, K_z is set equal to D_S, the effective wet sediment diffusion coefficient.

This model allows for manipulation of the advective velocity in determining the total benthic flux required to balance the observed inventories in the water column. When fluid advection is included in this benthic exchange model, such as the case of groundwater seeping through sediments, it is necessary to estimate the radon concentration in these interstitial fluids to evaluate the total flux. Thus, the model allows determination of the average seepage velocity assuming one can measure or estimate the ^{222}Rn concentration in the advecting fluids, the ^{222}Rn inventory in the overlying water, and the total benthic flux ($J_{benthic}$) required to support this inventory.

Due to variations in flow rates and water column ^{222}Rn concentrations in surface inputs and outputs, a range in values, rather than only an average, was used to estimate the upper and lower limits of the ^{222}Rn balance (Table 1). Water samples were obtained from Pond C (minimum:10800 dpm·m^{-3},maximum:18800 dpm·m^{-3}) and streams entering North Arm (minimum: 1.02x10^5 dpm·m^{-3}, maximum: 1.71x10^5 dpm·m^{-3}). The addition of ^{222}Rn into Par Pond can then be estimated based on these concentrations and the upper and lower flow rates into Par Pond. The loss of radon via flow through Par Pond Dam was calculated based on: (1) the activity of the bottom 6 meters of water (minimum: 2330 dpm·m^{-3}, maximum: 7380 dpm·m^{-3}), since the siphons which regulate water flow are located in the near bottom water; and (2) the minimum and maximum flow rate for the study period (0.24 and 1.70 m^3·sec^{-1}, respectively).

Minimum inputs were used along with the maximum outputs to calculate the maximum benthic input of ^{222}Rn which would correspond to the greatest groundwater flow estimates. Conversely, the maximum inputs and minimum outputs were used for estimating the minimum ^{222}Rn benthic source term. If advective transport through the sediments were unimportant, diffusion and stream inputs should balance radon decay and other outputs. However, there is a significant imbalance in the ^{222}Rn budget (0.0 to 5.9 dpm·m^{-2}·min^{-1}, average = 3.1 dpm·m^{-2}·min^{-1}) which indicates that there must be another important source of radon to the lake. Thus, advective transport of radon in groundwater appears to be an important component of the total benthic flux ($J_{benthic}$). Since advection appears to be important, diffusion cannot be included directly in the mass balance calculation due to the inter-dependence of these two terms. After this term is removed from the balance, the total benthic flux (e.g. advection and diffusion) needed to bring the radon budget into balance is between 2.8 and 7.8 dpm·m^{-2}·min^{-1}, with a best estimate of 5.5 ± 1.0 dpm·m^{-2}·min^{-1}.

In order to estimate a volumetric discharge of groundwater based on the radon balance using the advection-diffusion model, a radon concentration term must be assigned to the advecting fluids. If there is no advective flux through the sediment, the pore water ^{222}Rn will reach an equilibrium concentration with the ^{226}Ra in the saturated sediment (C_{eq} x F^{-1}). An average porewater ^{222}Rn equilibrium concentration of $(1.10\pm0.24)\times10^6$ dpm·m^{-3} (n=7) was estimated based on sediment equilibration experiments. This concentration could be considered as a minimum fluid ^{222}Rn concentration since the pore fluids should equilibrate with the sediment if there is no advection. An estimated maximum concentration was taken as the geometric mean ^{222}Rn concentration (C_{gw}) of the groundwater wells, $(1.72\pm0.64)\times10^6$ dpm·m^{-3}. The estimated total flow of groundwater into Par Pond will ultimately be constrained by this range in concentration of radon in the advecting fluids. Using these estimates, one may now calculate fluxes of groundwater into the lake needed to bring the observed radon inventory into balance. Although this approach does not indicate where the groundwater originates, it does allow for estimates of the total discharge. It should be possible to use the ^{222}Rn observations in the overlying water to locate areas of higher and lower groundwater inputs.

Table 1: Input and output ^{222}Rn fluxes estimated for Par Pond. Data are presented as a maximum and minimum as well as an average to account for most experimental uncertainties.

Parameter	Minimum (dpm·m^{-2}·min^{-1})	Maximum (dpm·m^{-2}·min^{-1})	Average (dpm·m^{-2}·min^{-1})
Input:			
Diffusive Flux[1]	1.9	3.4	2.4 ± 0.1
North Arm Stream[2]	0.046	0.15	0.087 ± 0.033
Pond C[2]	0.0088	0.11	0.027 ± 0.034
Total	1.95	3.53	2.5 ± 0.1
Output:			
In Situ Decay[3]	2.9	6.0	4.9 ± 1.0
Atmospheric Evasion	0.11	1.8	0.67 ± 0.16
Par Pond Dam[2]	0.0039	0.074	0.023 ± 0.025
Total	3.01	7.87	5.6 ± 1.0

[1] From Corbett *et al.*, 1996.

[2] Maximum and minimum values are base on the highest and lowest values of flow rate and the corresponding water concentrations of ^{222}Rn

[3] Calculated from the maximum and minimum values of the total ^{222}Rn inventory multiplied by the decay constant of ^{222}Rn.

When flow velocities are converted to total discharge over the study area, the estimated groundwater discharge into Par Pond based on the ^{222}Rn balance is 0.35±0.16 m^3·sec^{-1}, with an upper limit of 0.76 m^3·sec^{-1}. This assessment agrees reasonably well with the values obtained from traditional water budget calculations (Table 2). This study indicates that a radon tracing approach can further constrain, and perhaps improve, final estimates of groundwater contributions into standing bodies of water.

Table 2: Estimated groundwater flow rates and discharge based on two independent assessments: (1) water balance; and (2) radon budget. Data for the water budget is presented as an upper limit since we were unable to quantify sheetflow.

Experimental Method	Groundwater Velocity (cm·day^{-1})	Groundwater Discharge (m^3·sec^{-1})
Water Budget	< 0.79 ± 0.10	< 0.92 ± 0.13
Radon Budget		
Range	0.15 - 0.64	0.17 - 0.76
Best Estimate	0.30 ± 0.15	0.35 ± 0.16

Based on the combined water budget - radon balance approach, groundwater provides between 0.17 to 0.76 $m^3 \cdot sec^{-1}$ to the reservoir, equivalent to 0.9 to 4.0 meters of water distributed over the entire lake during the study period. This represents 10 - 33% of the total estimated inflow from all sources into the lake. Since much of the total input to the lake is via active pumping, the groundwater flow actually represents a much larger fraction of the total natural inputs. Should pumping be discontinued, groundwater could supply as much as 52% of the inputs into Par Pond.

5. Acknowledgements

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METHANE AS AN INDICATOR OF GROUNDWATER DISCHARGE: EXAMPLES FROM THE NE GULF OF MEXICO AND FLORIDA BAY, FLORIDA, USA.

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1. Abstract

The concentration of methane in groundwaters was 1000 times greater (61±9 µM) than concentrations in nearshore (62±7 nM) and continental shelf waters (27±5 nM). Methane budgets for these waters of the NE Gulf of Mexico were consistent with the hypothesis that groundwater seepage or seawater recirculation through the seabed is the dominant source of CH_4 relative to benthic diffusive flux, riverine flux and *in situ* water column production. Seepage/recirculation methane inputs into the water column of the study area may account for 83-99% of the total CH_4 inputs In Florida Bay, we used the natural tracers radon and methane to survey for inputs of groundwater to the estuary. The greatest tracer concentrations were consistently near the Florida Keys, a chain of limestone islands formed from an ancient coral reef. Direct measurements of groundwater seepage confirmed the inferences made from interpreting the tracer data.

2. Introduction

Use of seepage meters to determine groundwater discharge to surface waters can be very time consuming. Our group has investigated the use of geochemical tracers to detect the input of groundwater to the marine environment. Both radon and methane have been investigated; this paper will briefly describe our methane work. Methane was used by Kulm *et al.*, (1986) as a tracer of hydrothermal activity. In the results presented here, we show that

1. methane (and radon) concentrations are elevated in the groundwater of our study area,
2. a linear relationship exists between methane amount and seepage quantity, and
3. based on a budget approach, seepage is the main input term for methane in the waters of our study area.

The study area is located offshore of Florida, USA, about 80 km south-west of Tallahassee, where Florida State University (FSU) is located. We collected groundwater samples from shallow wells; marine waters were collected near the coast and in offshore zones within a ~ 620 km^2 area which included the inner shelf in the north-eastern part of the Gulf of Mexico. The area referred to as the nearshore zone is the area within the barrier islands and sand shoals known locally as "reefs." A seepage meter transect was installed perpendicular to shore near the FSU marine lab (FSUML). Five seepage meters were placed in the transect which extended ~ 500 m offshore. Subsequently seepage measurements and samples for CH_4 were taken on a monthly basis.

Offshore in continental shelf waters we have observed an estuarine-like circulation. Fresh water from land runoff overlies the more saline Gulf waters. During the summer a strong density gradient develops, and warmer, less saline water floats over deeper water, forming a natural chamber over the bottom sediments. Our site in the offshore waters is denoted "K tower."

3. Methods

We collected groundwater samples from wells with a 60-mL syringe which had a three-way stopcock on the end. Samples were analysed within 6 hours. Other water samples were collected with a pump into 60-mL BOD bottles. These samples were always analysed within 12 hours. Dissolved methane concentrations were determined by using a *Shimadzu 8A* flame ionisation detection (FID) gas chromatograph. Nutrients were measured in groundwaters: well waters, springs, sinkholes and rivers. After filtration (0.45 µm) we analysed for phosphate, silicate (Strickland and Parsons, 1972), ammonia (Bower and Holm-Hansen, 1980), and nitrate (Braman and Hendrix, 1989). Chlorinity was determined by using a standard silver nitrate titration technique. We used seepage meters to determine groundwater seepage into the coastal zone (Lee, 1977; Cable *et al.*, 1996c).

Separate methane budgets for the nearshore and offshore bottom waters within our study area were produced to estimate the main source of CH_4 to the waters of the study area. Sources of methane which we considered included were benthic diffusion, groundwater seepage, riverine input and *in situ* production. Sinks or loss terms which we considered included methane oxidation and the flux across either the air-water interface in nearshore waters or across the thermocline in offshore bottom waters.

We used benthic chambers to determine the total (advective + diffusive) flux of CH_4 across the sediment-water interface. The chambers had on an open port to allow seepage during the experiments. Fifty nine L clear plastic chambers were used for nearshore work, and offshore we used a seepage-meter type drum. The total CH_4 flux was calculated from the increase in methane in the chambers over the incubation period, the chamber size, and the incubation time.

A peeper (porewater equilibration sampler) was used to measure porewater concentrations of methane at 1-cm intervals (Hesslein, 1976). Offshore, SCUBA divers collected porewater samples using perforated end stainless steel tubes. The flux of methane flux across the sediment-water interface due to molecular diffusion was calculated from the porewater CH_4 gradient by use of Fick's law (Berner, 1971).

River methane flux to the nearshore waters were calculated by factoring their dissolved CH_4 concentrations by their annual mean flow rates and dividing by the area of the sampled nearshore waters. Flow rates were taken from the USGS river data for north-west Florida in 1981 and 1993. An area of 120 km^2 was used in the calculations

To determine net methane production and/or oxidation in the water column we followed the methods of Shanks and Edmondson, (1989) to produce marine snow. We rotated 2lL of sea water in glass carboys. Marine snow formed in a day. Headspace samples were withdrawn on a daily basis and analysed on the gas chromatograph.

4. Results And Discussion

The mean concentration of CH_4 in well water was 86±11 µM (n=56; Figure 1), and values for ammonia, phosphate, silicate and nitrate+nitrite were 10±1 µM (n=58), 1.9±0.2 µM (n=59), 130±15 µM (n=30) and 0.25±0.05 µM (n=21), respectively (Figure 1). There was a significant correlation between ammonia and methane ($r = +0.751$, $p < 0.005$). Sinkholes and springs had CH_4 values of 540±290 nM (n=5) and 1600±1100 nM (n=10), (Figure 1). These systems have lower methane and ammonia and higher nitrate concentrations than those measured in well waters. The methane river value was 350±70 nM (n=9; Figure 1). The rivers contained 29±14 $dpm \cdot L^{-1}$ ^{222}Rn (n=9), 2.1±0.4 µM ammonia (n=7), 0.48±0.23 µM phosphate (n=7) and 69±28 µM silicate (n=7) (Figure 1). Fu and Winchester (1994b) reported nitrate concentrations of 16.4±0.7 µM, 42±3 µM and 3.6±0.4 µM in the Apalachicola, Ochlockonee and Sopchoppy Rivers, respectively.

^{222}Rn values were high in well waters and springs (Figure 1). Well water was enriched in CH_4 and ammonia, and depleted in NO_3+NO_2, but springs were depleted in CH_4 and contained NO_3+NO_2. The wells apparently sampled more reducing portions of the aquifer than did springs.

Methane concentration and seepage rates in the nearshore decreased going offshore (Figure 2). We calculated CH_4 inventories by integrating concentrations with respect to water depth along the transect and distance from shore. Seepage inventories were determined by integrating the measured seepage rates with distance from shore. Over 14 sampling periods integrated methane and seepage showed a positive correlation of +0.69 (significant at $p < 0.05$ (Figure 2c)). suggesting that an increase in seepage results in an increase in dissolved CH_4 concentrations in coastal areas. Similar results have been shown for Radon (Cable *et al.*, 1996a,b).

Over a hundred offshore sites were sampled for water column ^{222}Rn and CH_4 from July, 1992 to September, 1994. In offshore waters methane concentration increased with depth to 20-25 nM, especially in summer in the presence of a strong pycnocline. The data suggested a common benthic source for radon and methane.

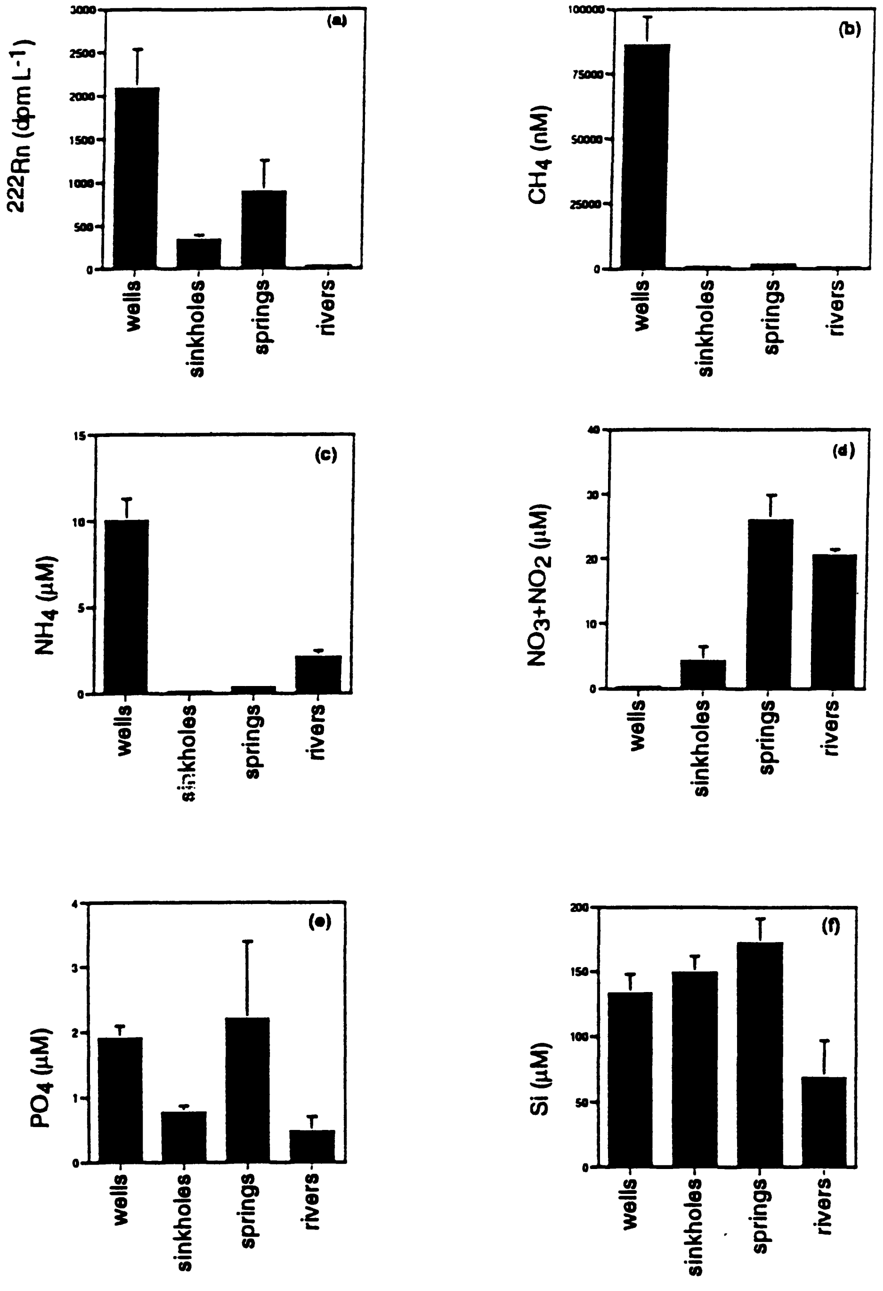

Figure 1. Concentrations for various constituents in wells, sinkholes, springs and rivers. NE Gulf of Mexico Sites.

5. Methane Budgets

Total benthic flux experiments, conducted to measure both diffusive and seepage methane flux gave a mean value of 21.6±2.7 nmol·m^{-2}·min^{-1} for nearshore waters (n=9; Table 1) and 1.6±0.9 nmol·m^{-2}·min^{-1}, n=12 for offshore waters. The offshore flux was 14 times lower than the nearshore benthic flux.

Table 1. Sources and sinks of methane in the NE Gulf of Mexico water column in the nearshore environment and for the bottom waters of the inner continental shelf near the K-Tower site. From Bugna *et al.*, 1996*.

source/sink	nearshore (nmol·m^{-2}·min^{-1})	K-Tower (nmol·m^{-2}·min^{-1})
sources		
net methane production	0.8±0.7 (a)	—
total benthic flux	21.6±2.7	1.6±0.9
molecular diffusion	0.6±0.5	0.013±0.008
total benthic flux - molecular diffusion	21.0±2.8	1.6±0.9
riverine flux	2.9±0.3 (b)	
sinks		
net methane oxidation	0.4±0.5 (c)	0.5±0.4
flux to the atmosphere	25.0±3.0 (d)	—
flux across the thermocline	—	1.1±1.0 (e)

(a) observed in three incubation experiments

(b) total CH$_4$ flux contributed by three rivers (Carabelle, Ochlockonee and Sopchoppy)

(c) observed in eight incubation experiments

(d) calculated as the difference between the total source flux and net methane oxidation; calculated fluxes across the air-water interface based on measured methane concentrations and wind speeds yielded values ranging from 11 to 34 nmol·m^{-2}·min^{-1}, with a mean value of 23±6 nmol· m^{-2} min^{-1}.

(e) calculated as the difference between the total source flux and net oxidation; fluxes across the thermocline calculated from measured methane concentrations ranged from 0.80 to 16 nmol·m^{-2}·min^{-1} with a mean of 5±2 nmol·m^{-2}·min^{-1} (n=9). However, 50% of the values were < 2 nmol·m^{-2}·min^{-1}

*Taken from Bugna *et al.*, 1996 Geochimica et Cosmochimica Acta, copyright 1996 with permission from Elsevier Science Ltd., The Boulevard, Langford Lane, Kidlington OX5 1GB, UK.

Diffusive methane fluxes were calculated from concentration gradients with Fick's law. For nearshore waters, the mean diffusive CH$_4$ flux was 0.6±0.5 nmol·m^{-2}·min^{-1}, 44 times smaller than the measured total benthic flux (Table 1). Offshore, a methane diffusive flux of 0.013 nmol·m^{-2}·min^{-1} across the sediment-water interface was calculated. Offshore, the diffusive methane flux was about 2 orders of magnitude smaller than the diffusive flux.

Apparently some processes other than diffusion play an important role in transporting methane from the sediment. We can rule some possible factors such out ebullition, which was never observed in our study area, and irrigation, as macroinfauna are scarce in the sandy sediments.

Using benthic flux values and porewater methane concentrations the seepage rates required to support the measured benthic fluxes were predicted by assuming that the seepage supplied methane to the chambers at a rate equal to the seepage rate times the methane concentration.

$$\text{seepage rate (mL}\cdot\text{m}^{-2}\cdot\text{min}^{-1}) = (J_{\text{benthos}} - J_{\text{diff}})/[\text{CH}_4]_{\text{pw}}) \qquad (1)$$

where J_{benthos} and J_{diff} are the total (advective+diffusive) and diffusive methane fluxes coming from the sediments in nmol·m^{-2}·min^{-1}, respectively, and $[\text{CH}_4]_{\text{pw}}$ is the porewater methane concentration in µmol·L^{-1}. At three sites, the seepage rates predicted (using Eq. 1) and the measured seepage rates were comparable, implying that the resulting methane flux to the water column may be due to upward advection of porewater methane due to groundwater seepage.

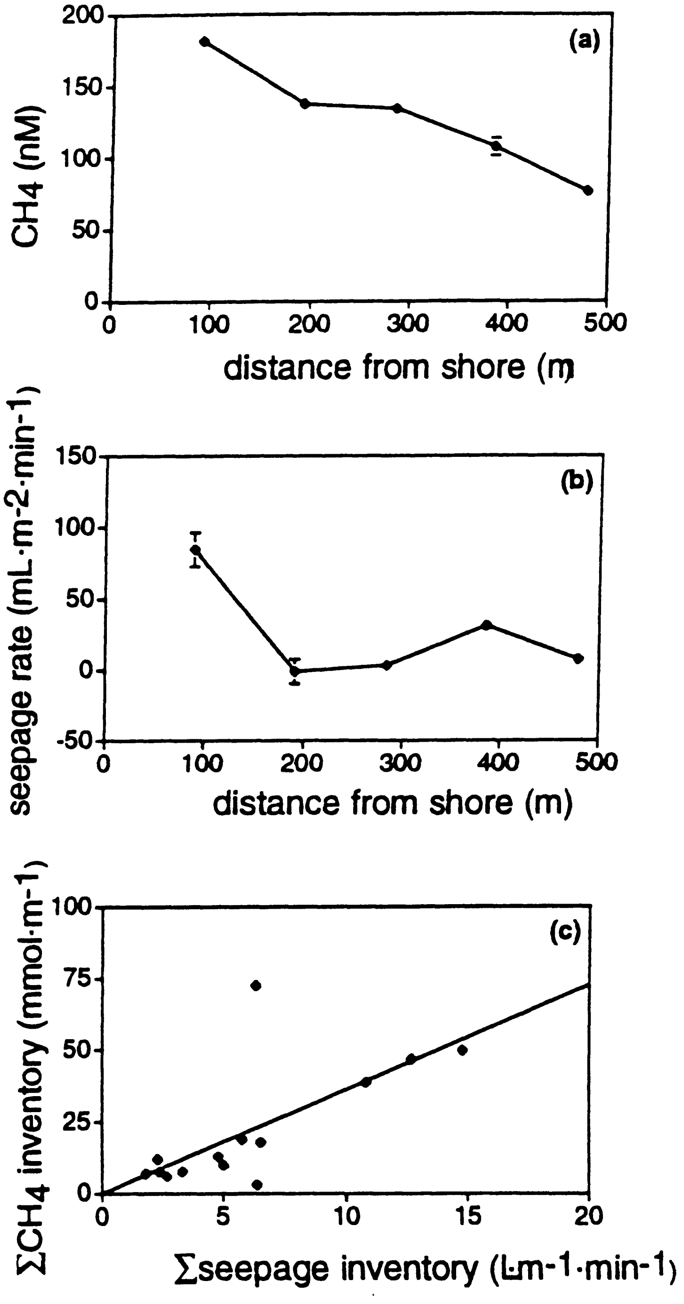

Fig. 2. Surface water methane concentration versus distance from shore (a), seepage rate versus distance from shore (b), and methane water column inventory versus the integrated seepage rate along the shore, from Bugna et al., 1996.

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If the total flux measurements ($J_{benthos}$) depend only on molecular diffusion and advection (seepage), then the methane flux due to advection (J_{seep}) would be the difference between $J_{benthos}$ and J_{diff}. The methane fluxes due to seepage (J_{seep}) for nearshore and offshore waters are thus 21.0±2.8 and 1.6±0.9 $nmol \cdot m^{-2} \cdot min^{-1}$, respectively (Table 1).

For the nearshore methane budget, a total riverine CH_4 flux to nearshore waters of 2.9±0.3 $nmol \cdot m^{-2} \cdot min^{-1}$ (n=3) was obtained, an order of magnitude lower than the seepage flux.

In nearshore experiments, net methane oxidation rates ranged from 0.1 to 2 $nmol \cdot L^{-1} \cdot day^{-1}$ while in offshore experiments rates ranged from 0.04 to 0.2 $nmol \cdot L^{-1} \cdot day^{-1}$ (n=4, Table 1). Rates were converted to an areal basis by multiplying the oxidation rate by the water depth. This resulted in a net oxidation rate of 0.8±0.7 $nmol \cdot m^{-2} \cdot min^{-1}$ (n=8) for nearshore waters and a value of 0.5±0.4 $nmol \cdot m^{-2} \cdot min^{-1}$ (n=4, Table 2) for offshore waters. On an areal basis, the mean net nearshore and offshore oxidation rates were comparable because offshore waters were deeper. These values were low compared to total benthic fluxes.

Table 2. Tracer concentrations by region, and significance (difference) relative to Key Basins in Florida Bay, Florida, USA. Key Basins were defined as sites located on the Florida Bay side of the upper Keys (Key Largo, Plantation Key and the Matecumbe Keys). North Coast Sties were along the Everglades Coast in muddy bottomed areas. Mid NE sites were in the Northeastern areas of the bay and typically had very little sediments overlying a rock bay floor. Mid Bay sites were typically basins within the mud-banked areas of the middle bay. (See Chanton and Burnett, 1995).

Region Rate	222Rn dpm/L, s, n p	226Ra dpm/L s, n, p	CH4 nM s, n, p	Seepage mL x m^{-2} min^{-1}
Key Basins	3.23 (1.98, 21)	1.30 (0.56, 21)	46.1 (23.2, 21)	20 (19)
Mid Bay	2.03 (1.16, 28, .005)	1.24 (0.34, 28, 0.32)	17.0 (8.9, 27, 0.00)	6 (2)
N. Coast	1.37 (1.01, 5, 0.03)	0.73 (0.40, 5, 0.02)	21.8 (18.5, 5, 0.02)	8 (6)
Mid NE	2.44 (1.92, 10, 0.15)	1.25 (0.39, 9, 0.42)	12.5 (6.5, 10, 0.00)	--

In addition to methane oxidation, sinks of methane were the flux across the air-water interface in nearshore waters and across the thermocline in offshore bottom waters. The methane flux across the air-water interface was calculated using the equation from Macintyre *et al.* (1995)

$$J_{air\text{-}water} = k(C_w - aC_{atm}) \qquad (2)$$

where $J_{air\text{-}water}$ is the methane flux across the air-water interface in $nmol \cdot m^{-2} \cdot min^{-1}$, C_{atm} is the atmospheric methane concentration in $nmol \cdot m^{-3}$, C_w is the dissolved methane concentration in $nmol \cdot m^{-3}$, a is the Ostwald solubility coefficient, and k is the gas exchange transfer coefficient in $m \cdot min^{-1}$. NOAA coastal wind speed data from north Florida range from 1.6 to 3.4 $m \cdot s^{-1}$ and were used to estimate "k." We calculated k values that ranged from 1.9×10^{-4} to 5.6×10^{-4} $m \cdot min^{-1}$ (Macintyre *et al.*, 1995).

For offshore bottom waters, the flux across the thermocline ($J_{thermocline}$) was calculated by using equation (3), and assuming steady state.

$$J_{thermocline} = K_v(\Delta C / \Delta z), \qquad (3)$$

where K_v is the vertical eddy diffusivity in $cm^2 \cdot s^{-1}$ and ($\Delta C / \Delta z$) is the measured methane concentration gradient across the thermocline. We used a K_v value of 0.2 $cm^2 \cdot s^{-1}$ (e.g., Ward *et al.*, 1987; Ku and Luo, 1994). Fluxes across the thermocline were estimated to range from 0.8±0.2 to 16±0.7 $nmol \cdot m^{-2} \cdot min^{-1}$ with a mean of 5±2 $nmol \cdot m^{-2} \cdot min^{-1}$ (n=9). Summaries of the sources and sinks of methane to the nearshore and offshore waters are shown in Table 1. The $J_{air\text{-}water}$ and $J_{thermocline}$ values required to balance the methane input terms were 25±3 and 1.1±1.0 $nmol \cdot m^{-2} \cdot min^{-1}$ for nearshore sites and K-Tower, respectively. Nearshore air-water methane fluxes calculated using measured methane concentrations and wind speed ranged from 11 to 34 $nmol \cdot m^{-2} \cdot min^{-1}$ with a mean of 23±6 $nmol \cdot m^{-2} \cdot min^{-1}$. For offshore waters, the methane flux across the thermocline required to balance the methane budget was only 25% of the calculated mean value of 5±2 $nmol \cdot m^{-2} \cdot min^{-1}$. However, the range of calculated fluxes across the thermocline was high, and over 50% of the values obtained were less than 2 $nmol \cdot m^{-2} \cdot min^{-1}$ (n=5), which were within the range of the $J_{thermocline}$ value required to balance the methane budget for offshore waters.

Even though not strictly conservative, we suggest that CH_4 may be a good tracer of SGD into coastal waters. In general, groundwater had concentrations 3 orders of magnitude higher than coastal and continental shelf waters, which had mean methane concentrations of 62±7 nM (n=51) and 27±5 nM (n=133), respectively. It was also demonstrated that the predominant source of methane to the water column is consistent with a benthic source. Measured seepage rates factored by porewater methane concentrations are sufficient to support measured benthic fluxes. Additionally, CH_4 and seepage inventories measured at a nearshore seepage meter transect were correlated suggesting that dissolved CH_4 is derived from groundwater discharge.

7. Application to Florida Bay

The purpose of our work in Florida Bay was to perform a preliminary evaluation of the significance of groundwater discharge as a source of nutrient elements to this large shallow coastal lagoon lying between the southern tip of the Florida mainland and the Keys. The seagrass die-offs and water quality problems observed in the bay could be related to excess nutrient loading (LaPoint and Clark, 1992). Groundwater-derived nutrients, therefore, whether from sewage or natural sources, may be important to the overall budget of Florida Bay. Groundwater flow rates in the limestone in the Florida Keys are as great as 3.7 $m\ d^{-1}$ (Lapoint *et al.*, 1990).

We have attempted to locate areas in the bay where groundwater seepage is more pronounced by reconnaissance surveys of the concentrations of radon and methane in the bay waters. These trace gases appear to function as natural indicators of seepage of groundwaters into standing bodies of water (Cable *et al.*, 1995a,b; Bugna *et al.,* 1996). Using the tracer information as a guide, we made direct measurements of groundwater seepage at selected sites using an instrument design modified from Lee (1977).

As shown above, for results from the NE Gulf of Mexico study sites, the results of the tracer analyses for groundwater samples collected on and offshore of Key Largo exhibited elevated tracer concentrations relative to surface waters. Therefore the first criterion for the application of these tracers to the problem of estimating groundwater discharge to Florida Bay was met.

In Florida Bay surface waters radon concentrations varied from <1 dpm/L to >20 dpm/L while methane varied from 5 to 100 nM. Samples from the Key Basins were more elevated in groundwater tracer concentrations (e.g. radon and methane) than were samples from the other regions (Table 2). The tracer results suggest that the greatest groundwater seepage into Florida Bay occurs from and along the Keys, and that seepage in mid-bay, East Bay and North Bay sites is of lesser importance. A lack of correlation between radon and methane in surface waters was observed, but this is not a source of concern as the correlation between these tracers was not observed in groundwaters in the Keys either. Radon in groundwater is elevated because of production from radium while methane is produced from the decay of organic matter. While both processes occur within the aquifer and result in elevated tracer concentrations within groundwaters, they are not linked.

The results of direct measurements of groundwater seepage are grouped in three geographic groupings: (1) open bay; (2) northern and eastern Florida Bay; and (3) areas near the Keys. In presentation of the seepage results, we report a mean and standard deviation for the seepage rate for each location averaged over at least two days of repeated measurements (Table 2). As predicted from tracer concentration, greatest seepage was observed in the areas near the Florida Keys.

8. Acknowledgements

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GROUNDWATER DISCHARGE AND FRESHWATER-SALINE WATER EXANGE IN KARSTIC COASTAL ZONES

DROGUE, Claude

1. Abstract

Coastal zones consisting of karstified carbonate rock can be the sites of very large underground flows of water into the sea and, in some cases, massive entry of sea water into the karst subsoil. Among the regions studied, the Mediterranean coasts of southern and south-eastern Europe and the Middle East possess representative examples of these phenomena.

Exchanges of fresh water and salt water are caused by hydrodynamic mechanisms related to the formation and structure of karst networks, hydraulic gradients at the interface between the land and the sea and the contrasts in density between sea water and underground fresh water. Thus, in the Mediterranean, underground springs and deep coastal aquifers formed during ancient marine regressions. One of the most marked occurred 7 to 9 million years ago (during the Messinian) with regression to nearly 2,000 metres below the present level. There was also a 150-m regression during the Würm glacial stage 35,000 years ago. Springs and caves that formed then are now below sea level. Some are known at 30 m below sea level in the South of France, as much as 60 m below sea level on the coast of former Yugoslavia, 80 m below sea level near the coast of mainland Greece, 180 m below sea level off the Lebanon, etc. Brackish water flows from them at discharges of 10 to 30 $m^3 s^{-1}$ or more.

Hydraulic gradients at the coast are caused by the following factors : the flow of underground water, fluctuations in sea level resulting in particular from tides and wind and differences in the density of underground fresh water and sea water (the difference is about 0.0264 kg dm^{-2} at 25° centigrade in the Mediterranean).

These factors can sometimes cause a reversal of the current and massive penetration of sea water into the karst, for example 0.3 to 0.4 $m^3 s^{-1}$ on the island of Cephalonia in Greece and in the South of France.

Tidal waves may be propagated in the karst for distances of several kilometres. The difference in phase and the reduction in amplitude of these waves are used for calculating the diffusion features of the aquifer.

2. Introduction

Karstic aquifers in coastal zones can discharge large quantities of underground water into the sea. The special feature of these flows—in comparison with those of other types of aquifer—lies in the occasional flow concentration, which can reach 30 $m^3 s^{-1}$ at karstic springs. These springs may be on the coast or at sea at depths of up to several tens of metres. The flow state (discharge) of underground water depends on the piezometric conditions in the aquifer (infiltration of meteoric water and infiltration of watercourses) and fluctuations in sea level. With, for example, the effect of ocean tides, complex hydrodynamic mechanisms result in certain regions in the phenomenon of massive inflow of sea water combined with equally substantial outflow of underground brackish water.

These phenomena are the consequences of the special way in which karstic aquifers are formed. Several examples are described here.

2.1 The Formation Of Coastal Karstic Aquifers

Substantial flow of underground water in massive carbonate rock can only take place after the degradation of the rock as a result of first, tectonic fracturing, and then, the karstification of the fracture planes by aggressive water. With a coastal carbonate rock massif, if sea level is stable during a karstification period (0.5 million years is sufficient), springs will form at this level on the coast (Figure 1 A).

In diagrammatic terms, two types of development may then occur: either a comparative fall in sea level (regression), with the springs left 'hanging' above the sea, as can be seen in particular in south-east Java (Figure 1B), or a rise in sea level (transgression) and the resulting submersion of the springs. This can be observed today in coastal karstic aquifers around the Mediterranean (Figure 1C).

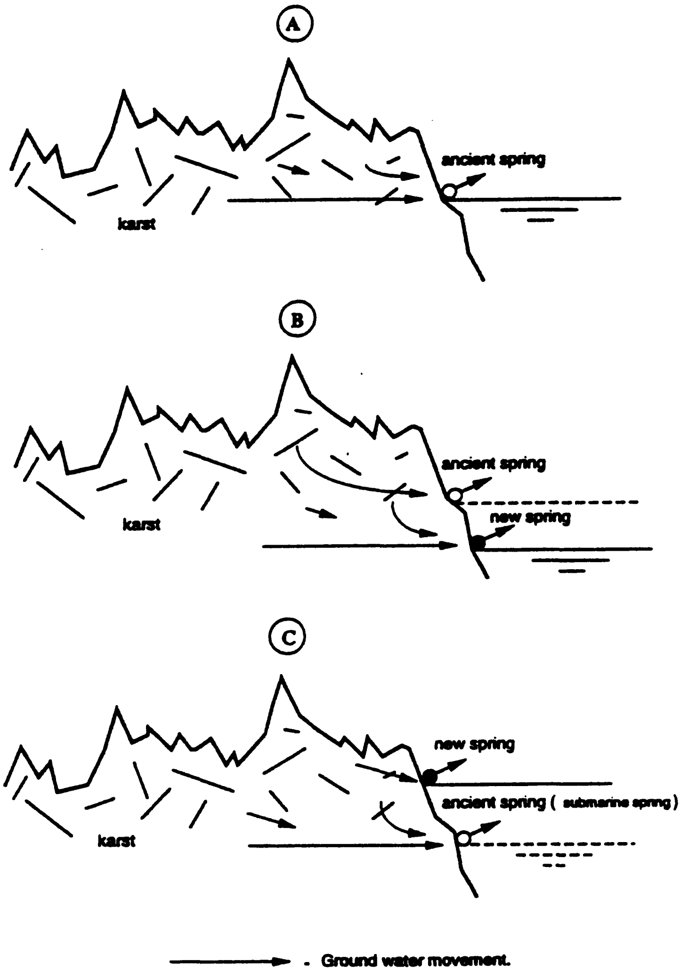

Figure 1. The effects of fluctuations in sea level on the creation of coastal karstic springs. A, former sea level; B, marine regression; C, marine transgression.

Indeed, in the Cainozoic era, the Mediterranean was in a closed basin with a hot climate. The sea level then fell to nearly 2,000 m below the present level during the Messinian (7 to 9 m.y. BP) (Hsu *et al.* 1978; Steckler and Watts, 1980). After a general relative transgression to - 110 m, the Würm glacial stage occurred 35,000 y. BP (Monaco *et al.* 1972). These marine transgressions therefore submerged the springs that had formed during periods in which the Mediterranean had been at a low level. For example, some are known at 30 m below sea level in the South of France, as much as 60 m below sea level on the coast of former Slovenia, 80 m below sea level near the coast of mainland Greece, and 180 m below sea level in Lebanon.

2.2 Underground Flows Connected With The Sea In Coastal Karstic Aquifers

The features of karstic underground water flows in coastal zones are firstly the existence of flows of several tens of cubic metres per second from time to time from coastal or underwater springs, and secondly the possibility of occasional massive intake of sea water by the aquifer. This sea water mixes with the underground water and flows out in brackish form. The most frequent case is probably that of coastal springs whose natural flow is reversed during very high tides as the level of the sea is temporarily higher than that of the underground water near the coast. The current is reversed at half-tide and low tide, the sea water is discharged and normal flow returns at the spring. This was described in particular in the Bahamas (Stringfield and Legrand, 1971; Kohout, 1960) and on the Adriatic coast of Croatia (Kuscer, 1950). At Spring Bayou in Florida (USA), brackish water from the estuary of the Enclote River flows underground for 3 km to Tarpon Lake when the water level in the lake is lower than that of the river.

These are both examples of inflow alternating with outflow. It is more rare to observe intake of sea water occurring simultaneously with the discharge of underground water. Two examples of this phenomenon are described below.

In the South of France, the flood flow of the coastal Roubine Spring can reach 6 $m^3.s^{-1}$. The flow is only 0.1 to 0.2 m^3 s^{-1} during low water periods. Intake of sea water occurs during these periods of small flow (Figure 2 and 3). A salt water current enters the spring, sliding below the outflow of underground water. The highest flows observed were 0.20 m^3 s^{-1} sea water flowing in and 0.18 m^3 s^{-1} underground water flowing out (Drogue and Bidaux, 1986). The underground water discharged is brackish, with conductivity of 4.2 to 4.3. $ms.cm^{-1}$ at 28°C; the conductivity of the sea water inflow is 48 to 56 $ms.cm^{-1}$, whereas that of the uncontaminated karstic underground water is 0.6 ms cm^{-1} (Figure 2). The superposition at the spring of two flows in opposite directions is caused by the difference in density. The density of the underground water is 0.924 kg dm^{-3} and that of the sea water is 1,0258 kg dm^{-3}. Intake occurs during a tide (amplitude 0.4 in the region) coinciding with wind that raises the sea level.

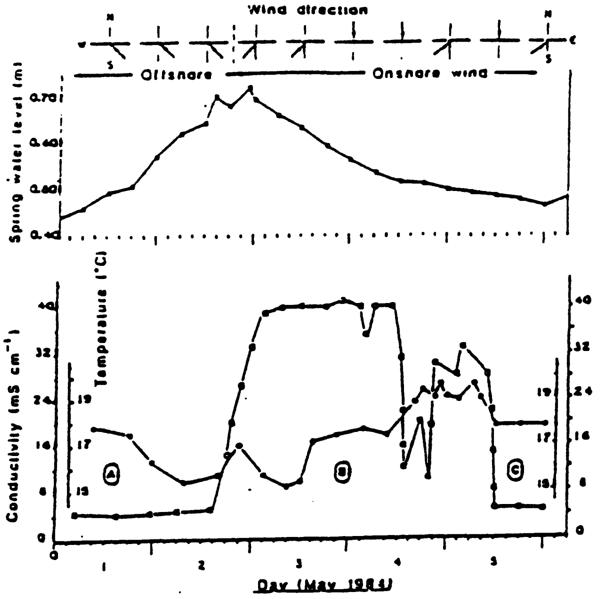

Figure 2. - Roubine Spring (South of France) Example of the time-evolution of conductivity (●) and temperature (O) in the spring into which the salt-water flows, compared with water levels in the spring (■) and with wind direction (arrows). A, No inflow of salt water, but start of return flow is indicated by a fall in temperature. This is fresh water in the channel affected by the outside temperature. B, Inflow has started suddenly and is revealed by stable conductivity ; however, temperatures are irregular. this is the effect of the thermal heterogeneity of the water in lagoon. The lowest temperature of the water flowing in is 14.9°C; the highest is 19.8°C (the temperature of the spring water is 17.8°C). C, Inflows ceases suddenly. The spring flows normally once more. Inflow occurs when there is a rise in water level of 0.35 m caused by easterly winds. (Drogue and Bidaux, 1986)

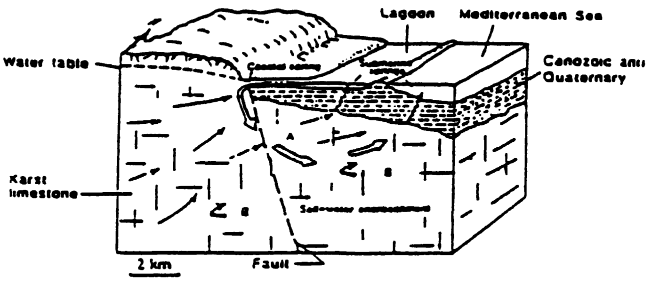

Figure 3. - Roubine Spring (South of France) Diagrammatic representation of the karstic aquifer and the organisation of flows. Fine arrows, fresh water; bold and shaded arrows, salt water. The flow of salt water that runs into the spring must descend by gravity through the aquifer (A) to the deep salt water encroachment (B). This flow is then carried to submarine springs. There is thus double contamination of underground water by sea water : from below in the aquifer and from above. Note that the large-scale flow of water into the spring carries large quantities of organic matter into the underground zone ; this could form the basis for a totally unknown biotope. (For reasons of simplicity, the arrows in A do not show any dispersion that may take place in the aquifer). (Drogue and Bidaux, 1986)

On the south coast of the island of Cephalonia in the Ionian archipelago in Greece, an almost permanent sea current of up to 0.4 $m^3 s^{-1}$ enters the karstic subsoil. Maurin and Zoetl (1967) used a tracer to show that the sea water reappears on the other side of the island at brackish springs. The apparent underground route is 15 km long. Various hypotheses were put forward for over a century to account for the phenomenon although none has been supported by experimental data (Crosby and Crosby, 1896; Fuller, 1906; Glanz, 1965; Zolt, 1974; Bogli, 1978; Cooper *et al.* 1964; Stringfield and Legrand, 1969). A new study demonstrated the hydrodynamic mechanism (Drogue and Soulios 1988; Drogue, 1989).

A permanent current crosses the Ionian archipelago from SSE to NNW (Figure 4 and Figure 5). Because of this, the sea level on the side of the island facing the current (where inflow occurs) is higher than the sea level on the opposite side (where the sea water reappears). Comparative levelling using laser sighting showed a difference in level of up to 0.30 m, ±0.02 m, according to the wind direction. Sea water intake is the result of this hydraulic gradient and is maintained by the differences in densities (density currents) of the sea water (1.0258 kg dm^{-3} at 28°C) and the underground water discharge (1.0002 kg dm^{-3})

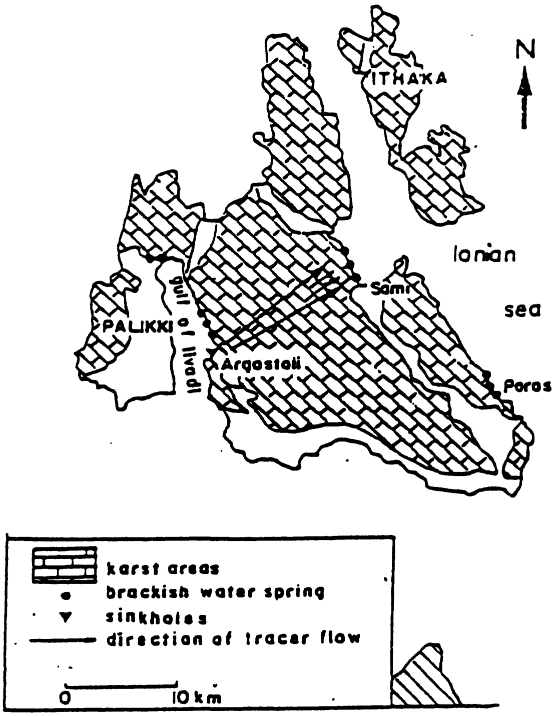

Figure 4. - The island of Cephalonia in the Ionian Sea Location of the seawater inflow zone (sinkholes) and the Sami springs where resurgence of salt water occurs (Drogue, 1989).

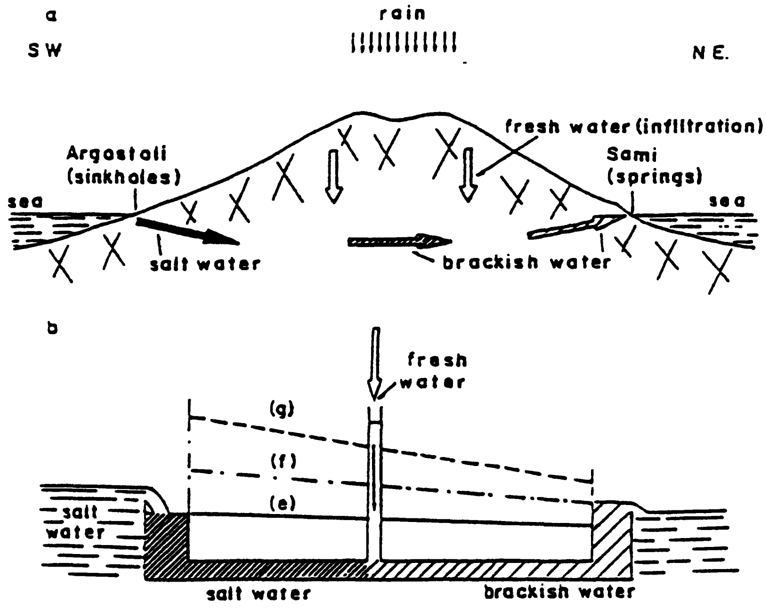

Figure 5. - a) Diagram of underground flow in the karst in Cephalonia between sinkholes where there is inflow of sea water and the brackish springs (vertical exaggeration 3 : 1). Inflowing salt water is mixed with fresh water (infiltrated rainwater) in the deep karst. (b) Simplified representation, not to scale, illustrating the underground flow system. Piezometric lines are traced above the conduit for constant fluid densities along the flow route : sea water (e), brackish water (f) and fresh water (g). It will be noticed that fresh water recharge by infiltration into the karst must not result in a piezometric surface higher than that at Argostoli (calculated for the density of fresh water) ; if it were higher, inflow of salt water would stop, and the Argostoli sinkholes would even function as springs. (Drogue, 1989)

2.3 The Propagation Of Sea Tides In Karstic Coastal Aquifers

Hydrodynamic study of a coastal karstic aquifer is performed by analysing the effect of the sea tide on the water table. Under certain conditions, this approach, which involves fairly simple data processing, may show the hydrodynamic parameters of the aquifers and especially diffusivity.

Studies were performed on coastal aquifers on the Atlantic coast in southern Portugal. There is medium-developed karst in Miocene limestone (Razack *et al.* 1980) and in the karst of Trst bay on the Adriatic coast of Slovenia (Drogue *et al.,* 1984).

Two calculation methods can be used, depending on the changes in the form of the free water table:
(1) a Carson - Laplace transform, or
(2) adjustment of a sinusoidal variation law to the fluctuations.

This enabled characterisation of the general hydrodynamic behaviour of the aquifer. The model that gives the most satisfactory reconstitution of the observations indicates seepage that fits the known geological conditions of the aquifer quite well. (Figures 6 and 7).

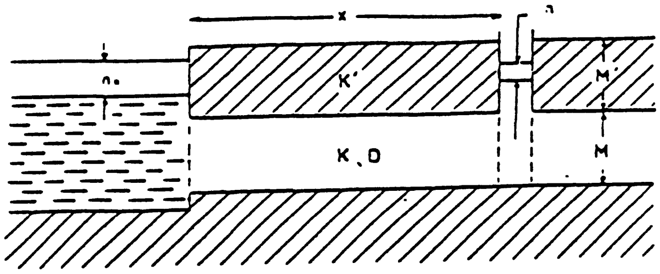

Figure 6. Semi-confined and semi-infinite groundwater h_0 = half-amplitude of the tide ; h = half-amplitude observed at borehole ; x = distance to the seaside ; D = diffusivity ; K, K'= hydraulic conductivity ; and M, M'= thickness. (Razack, Drogue *et al.*, 1980)

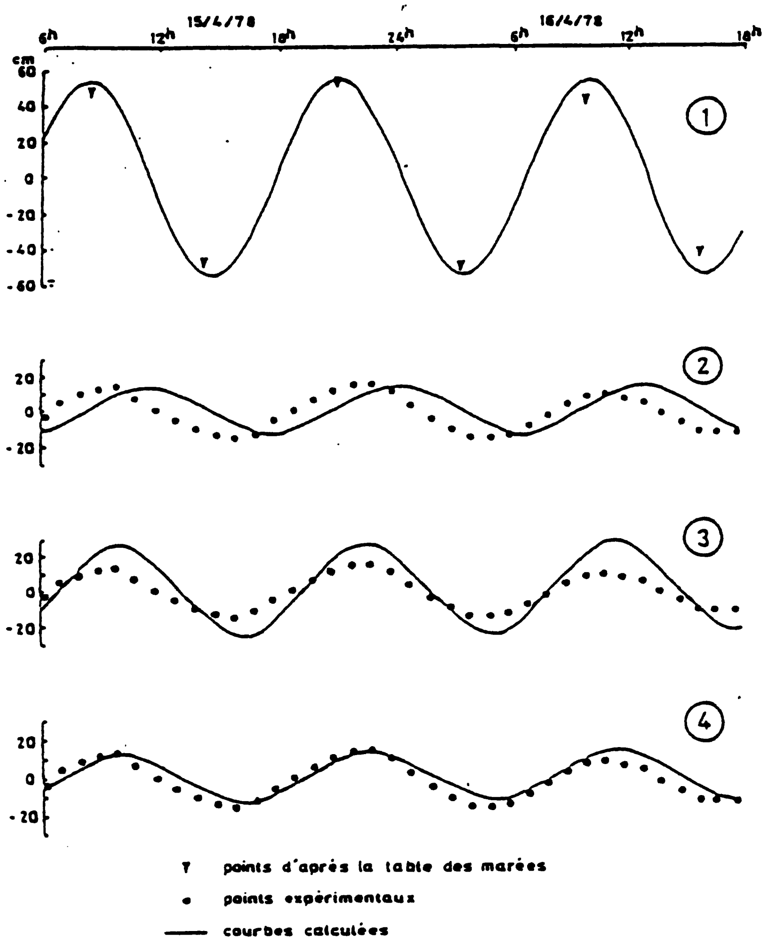

Figure 7. Reconstitution of fluctuations at the borehole in South of Portugal after the following assumptions: 1 = coastal tide (equivalent sinusoid) ; 2 = confined groundwater : D = 7,975 m^2/hr., computed from damping of waves ; 3 = confined groundwater : D = 30,603 m^2/hr., computed from time lag ; and 4 = semi-confined groundwater : D = 15,650 m^2/hr. (Razack, Drogue *et al.*, 1980)

3. Conclusion

It has been shown that the flow regimes of coastal karsts in the sea are not stationary. Flow variations in time causes variations in the physicochemical and biological composition of the underground water.

The effects on coastal water must also be non-stationary. Future studies should aim at better definition of these phenomena, especially as the saline content of the underground water discharge is not solely the result of mixing with the massive quantities of water flowing into coastal karstic cavities. Sea water also penetrates the entire fissured mass of karst and feeds the deep saline encroachment.

There are therefore complex equilibriums and exchanges between karstic coastal aquifers and coastal zones.

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*METHODICAL APPROACHES TO REGIONAL ASSESSMENT OF GROUNDWATER DISCHARGE INTO THE SEAS

DZHAMALOV, R. G.

1. Abstract

The study and quantitative evaluation of groundwater discharge to seas may be subdivided into two groups: (1) methods based on quantitative analysis of generation of conditions of groundwater discharge to the sea within coastal zone and (2) methods for marine hydrogeological studies. The first group includes: hydrogeodynamic methods for computation of groundwater discharge (analytically and by modelling), combined hydrological and hydrogeological methods, and the method of the average long-term water balance of groundwater discharge areas. The hydrodynamic method is the principal method for quantification of submarine groundwater discharge. For aquifers delineated, potentiometric and transmissivity maps are constructed reflecting the conditions of submarine groundwater discharge. The submarine groundwater discharge along all the coastal line is determined by using Darcy's relationship for streamtubes. Of great interest is the determination of areas with the most intensive groundwater discharge, and clearing up the picture of submarine groundwater discharge distribution. Piezometric profiles are constructed for some streamlines, based on maps of head distribution in the aquifer. Then, these profiles are extended into the sea area, which requires determination of the function $y = f(x)$ describing them with a sufficient accuracy. Applying equations for approximating curves, piezometric profiles may be extended into the sea area as far as any assumed elevation. This procedure permits construction of a fairly substantiated map of the potentiometric surface of an aquifer within the coastal zone of the sea. Such maps may be used for quantitative estimation of groundwater leakage into the sea by mathematical modelling using computers. If sufficient data representing regional conditions of groundwater flow are available, various calculation and modelling methods may be used for estimating groundwater discharge to seas. The method, based on the interrelation of artesian aquifers should be considered the most suitable for this purpose. The method permits obtaining at each estimation point the horizontal and vertical components of groundwater flow from known areal distribution of head and transmissivity values. The groundwater discharge to the Caspian Sea has been determined by this technique. In the combined hydrological and hydrogeological method, normal specific groundwater discharge values are determined for main aquifers within the coastal zone under study, using the procedure of separating the hydrograph of river runoff for a long-term period. Then, using the analogy approach, the discharge values obtained are extended to coastal areas having similar hydrogeological conditions but in which groundwater discharges directly to the sea, bypassing the river network. This method is applicable only to basins with a well-developed river network. The average long-term water-balance method can be used for estimating groundwater discharge to seas from deep artesian aquifers, which have a distinct area of recharge. A long-term water-balance equation is composed for the area of recharge, and the value of deep percolation is determined. This method is useful for computation of the specific discharge from aquifers from which flow reaches the sea rather than leaks to other aquifers. The groundwater discharge estimates obtained by one of the methods, should be subsequently proved and controlled by other methods.

2. Introduction

The study and quantitative evaluation of groundwater discharge to seas and oceans should be based on reliable methods of research permitting location of groundwater discharge sites and determination of discharge values. These methods may be fairly distinctly subdivided into two groups: 1) methods based on quantitative analysis of generation of conditions of groundwater discharge to the sea within the drainage area and, above all, within the coastal area of land and 2) methods for marine hydrogeological studies.

Methods based on studying the drainage area adjoining the sea, comprise the analysis of geological and hydrogeological conditions of the coastal area. These methods are: hydrodynamic methods for computation of specific groundwater discharge (analytically and by modelling), combined hydrological and hydrogeological methods, and the method of the average long-term water balance of groundwater discharge areas. These methods, and primarily those based on studying processes of groundwater movement, are the principal methods for direct quantitative estimation of groundwater discharge to seas within the zone of the geological section for which data on hydrogeological parameters are available.

The dynamics of the groundwater of artesian basins adjacent to seas indicates that the groundwater flow of the upper hydrodynamic zone is commonly directed to the sea and generates submarine groundwater discharge. Submarine groundwater discharge occurs as concentrated outflow along faults and in fractured and karst areas, as well as leakage through semipermeable deposits, as has been established for many artesian basins within regions with both natural and disturbed hydrogeological regimes. Leakage processes define the dynamics of the groundwater of an artesian basin on the whole or its major parts. In other words, leakage plays an in important or even determining role in submarine groundwater discharge.

3. Methods of Regional Assessment

The hydrodynamic method is principal in quantification of submarine groundwater discharge. It consists of the following. Based on the analysis of geological, structural, and hydrogeological conditions of the coastal part of artesian basins, aquifers or aquifer systems whose water discharges directly to the sea bypassing the river network are distinguished. For the aquifers delineated, potentiometric and transmissivity maps, reflecting the conditions of submarine groundwater discharge, are constructed. The submarine groundwater discharge along all the coastal line is determined by using Darcy's relationship for streamtubes. This traditional method, being simple, permits obtaining fairly reliable values of groundwater discharge to the sea from any aquifer. Particular attention should be given to the reliability and representativeness of initial hydrogeological parameters and of the hydrogeodynamic maps based on these parameters.

The analysis of the hydrogeodynamic situation of the coastal region allows one to distinguish a number of areas with similar hydrogeological conditions. Within these areas, specific groundwater discharge is calculated from streamtubes with allowance for all main initial parameters characteristic of the relatively narrow coastal band of groundwater discharge. As a result, initial hydrodynamic parameters are not averaged for large areas, they are refined and detailed for an estimation area and for each streamtube.

Another important way of direct groundwater contribution to seas is discharge by leakage through semipermeable layers and bottom sediments. Therefore, of great interest is determination of areas with the most intensive groundwater discharge and clearing up the picture of submarine groundwater discharge distribution. To distinguish these submarine areas, a procedure, discussed in detail in the paper by Dzhamalov *et al.* (1976), has been used. Based on maps of head distribution in the aquifer, piezometric profiles are constructed for some streamlines. Then, these profiles are extended into the sea area, which requires determination of the function y = f(x) describing them with a sufficient accuracy. This approximation of piezometric curves of various types can be made by the method of least squares using standard computer programs.

Applying equations for approximating curves, piezometric profiles may be extended into the sea area as far as any assumed elevation, i.e. up to the boundary of possible groundwater discharge through leakage. This procedure permits construction of a fairly substantiated map of the potentiometric surface of an aquifer within the coastal zone of the sea. Such maps may be used for quantitative estimation of groundwater leakage within sea area by mathematical modelling using computers. This technique has been applied to delineation of offshore areas of submarine artesian groundwater discharge through leakage in the Caspian and Baltic seas.

If sufficient data representing regional conditions of groundwater flow are available, various calculation and modelling methods may be used for estimation of groundwater discharge to seas. The method based on the interrelation of artesian aquifers should be considered the most suitable for this purpose. The method of estimating the relation of aquifers in artesian basins is most applicable to these calculations; it allows one to obtain from the known areal distribution of heads and transmissivities the horizontal and vertical components of groundwater flux for each point (Dzhamalov, 1973; Dzhamalov *et al.*, 1977; Zektser *et al.*, 1984).

Where aquifers occur in a stage-like manner (as happens in the majority of cases), the process of steady-state flux may be described fairly accurately by differential equations in partial derivatives with the following boundary conditions:

$$\begin{cases} \dfrac{\partial}{\partial x}\left(T_0 \dfrac{\partial H_0}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(T_0 \dfrac{\partial H_0}{\partial y}\right) + C_1 (H_1 - H_0) + W = 0 \\ \dfrac{\partial}{\partial x}\left(T_1 \dfrac{\partial H_1}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(T_1 \dfrac{\partial H_1}{\partial y}\right) + C_1 (H_0 - H_1) + C_2 (H_2 - H_1) = 0 \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ \dfrac{\partial}{\partial x}\left(T_n \dfrac{\partial H_n}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(T_0 \dfrac{\partial H_n}{\partial y}\right) + C_n (H_{n-1} - H_n) + Q = 0 \\ H_i \big|_{\Gamma_{1i}} = f(\Gamma_{1i}) \\ T_i \dfrac{\partial H_i}{\partial n_i} \Bigg| = q_i, \quad i = 0, 1, \dots\dots\dots, n \qquad x, y \in D \end{cases}$$

where: **H_i** = head in *ith* aquifer below land surface, in m; **T_i** = transmissivity of *ith* aquifer, in m^2/day; **W** = rate of recharge (discharge) of groundwater through the water table, in m/day; **Q** = rate of recharge (discharge) through the bottom of the lowermost estimated aquifer, in m/day; **C_i** = coefficient of leakage through semipermeable layer, in l/day; **f_i** and **q_i** = known coordinate functions; **G_{1i}** and **G_{2i}** = boundaries of I and II kinds for *ith* aquifer; **D** = lateral seepage area.

The coefficient of leakage through confining clay layers (C) is the parameter most difficult to determine in this system. The leakage coefficient is directly proportional to the coefficient of permeability of semipermeable rocks (perpendicular to their bedding) and is inversely proportional to their total thickness.

To solve the system of equations for C one should have data on distributions, over the flow domain, of values of head, transmissivity, and recharge (discharge) through the upper, lower and lateral boundaries of the aquifer system. Determination of the C coefficient is an inverse groundwater flux problem. At the same time, these methods are classed with direct methods for solution of inverse problems since the C coefficient is defined directly from the system of equations without using additional information. As is known, such a statement is incorrect. The solution obtained may be unstable because small errors in determination of initial data lead to large errors in solution. In this case, the error in the determination of the head of the aquifer, being estimated, affects more appreciably the solution results as compared to the possible error involved when adopting transmissivity values. The cause of possible errors in determination of the leakage coefficient is that it is calculated through the derivative of the experimental function H(x,y) and this procedure is surely incorrect.

To obtain a stable solution, one should smooth the fields of head and transmissivity distribution. In a general case, for eliminating errors, the distribution of the main initial parameters of the flow domain, being estimated, should be in the form of functional relationships. However, the determination of the polynomial that describes with sufficient accuracy the variation of parameters over the flow domain, involves certain difficulties. Smoothing the fields of initial parameters occurs to a certain extent in interpolation of parameter data.

In addition, when adopting parameters in discrete form, one should seek the least net step, i.e., divisions of flow domains where the functions $H_i(x, y)$ and $T_i(x, y)$ are sure to be not monotonic (large flow gradients, sharp changes in the lithological composition of enclosing rocks or their thickness). In this connection, the scale of the division of flow domains should be selected in accordance with the density of distribution of experimental points (wells) with initial information and also taking into consideration the analysis of the most complicated areas, presented on groundwater flow maps.

The combined hydrological and hydrogeological method consists of using the procedure of separating the hydrograph of river runoff for a long-term period within the coastal zone of the sea basin under study, so that normal specific groundwater discharge values are determined for the main aquifers. Then, using the analogy approach, the discharge values obtained are extended to coastal areas that have similar hydrogeological conditions, but where groundwater discharges directly to the sea and bypasses the river network. The groundwater outflow to the sea from the upper hydrodynamic zone is evaluated by multiplying the specific groundwater discharge values obtained by the respective areas of the coastal zone. This method is applicable only to basins with a well-developed river network. In this case, the discharge from the upper hydrodynamic zone is evaluated; this largely includes fresh groundwater, rather than all the groundwater outflow to this sea. Therefore, the method under discussion is reasonable to use together with others, e.g., the average long-term water-balance method or hydrogeodynamic method.

The average long-term water-balance method can be used for estimating groundwater discharge to seas from deep artesian aquifers, which have a distinct area of recharge. A long-term water-balance equation is composed for the area of recharge and, using the difference between rainfall, evaporation, and river runoff, the value of deep percolation, i.e., the portion of the rainfall that recharges artesian water, is determined. This method is temptingly simple, however, its application is restricted by some circumstances. First, it is useful for computation of the specific discharge from aquifers that are safely isolated by confining layers from overlying and underlying aquifers, i.e., one should be aware that aquifer flow reaches the sea rather than leaks to other aquifers. Second, this method may be reliably applied where the estimated deep percolation value exceeds the accuracy in determination of other components of the water-balance equation (precipitation, evaporation, and river runoff).

4. Methods for marine hydrogeological studies

Groundwater discharge causes various anomalies in sea water and bottom sediments, whose study makes it possible to locate and estimate groundwater discharges. Therefore marine hydrogeological studies include mainly examination of indirect indicators, characterising variations in physical and chemical fields due to groundwater movement through the sea bottom.

Research on the effect of submarine groundwater discharge on the formation of anomalies in the physical and chemical environments of bottom sediments and the near-bottom layer of sea water is the methodological basis of marine hydrogeological studies. Today's technological level of marine investigations makes it possible to measure with a high accuracy such hydrogeologically important factors as temperature, heat flow, electric conductivity, natural electric and electromagnetic fields in bottom sediments, as well as to determine the chemical, minor element, gas and isotopic compositions of pore solutions in bottom sediments and of sea water. However, anomalies in the distribution of each of these parameters are not a direct indicator of groundwater discharge at the sea bottom. Hydrogeological information is appreciably increased if simultaneous measurements are made at one point of parameters of several physical and chemical environments, or if various components of the same environment are measured frequently (ideally continuous profiling).

5. Conclusions

The methods for quantitative evaluation of groundwater discharge to seas and oceans enable us to determine, with sufficient accuracy, the total submarine groundwater outflow from all estimated aquifers, and to obtain a picture of its distribution in the coastal areas of land and the sea with allowance for aquifer interrelation. The groundwater discharge estimates, obtained by one of the methods, should be subsequently proved and controlled by other methods. Combined use of several methods permits obtaining the most reliable results.

6. Acknowledgements

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RELIABILITY IN GROUNDWATER RECHARGE ESTIMATION USING FUZZY ARITHMETIC

GANOULIS, J.

1. Summary

Uncertainties due to imprecise values of physical parameters and input boundary conditions are quantified in estimating groundwater recharge using fuzzy logic calculus (fuzzy arithmetic). This is useful for assessing the reliability of different methods for groundwater recharge estimation. Uncertainties are propagated by combining mathematical modelling with interval operations of different confidence values. Analytical solutions, explicit finite-difference and finite-element methods may be used along with this technique in order to formulate fuzzy logic based groundwater models. Output variables, such as capillary pressure and water content are computed directly as fuzzy numbers without repeating a large number of computations. The methodology is illustrated in a simplified case of one dimensional convective diffusion in soils.

2. Introduction

The fuzzy set theory in combination with various methods of evaluation of groundwater recharge is proposed in order to assess uncertainties and errors of estimate in the amount of water entering an aquifer through the saturated zone. Such a study is necessary in order to compare different methodologies for estimation of groundwater recharge in terms of reliability, sensitivity and accuracy.

Groundwater recharge should be divided into *direct* or *natural*, when it is due to precipitation and *indirect*, when deriving from rivers, channels or urban areas. Different methods have been developed for quantifying each type of recharge, such as: direct measurements, tracer techniques, water balances and mathematical modelling based on Darcy's Law (Smith and Ferreira, 1989).

To assess the reliability in groundwater recharge estimation, it is necessary to account for imprecise information in data, values of physical parameters and boundary conditions. For example, the different terms in water budgeting methods are difficult to estimate accurately, as are the physical parameters in mathematical modelling, such as unsaturated conductivity and aquifer transmissivity.

Uncertainties in hydrological processes should be distinguished by two main types (Duckstein and Plate (eds.) 1987; Ganoulis (ed.) 1991; Ganoulis, 1994):

(1) *Aleatory Uncertainties*: These are due to natural variability or randomness
(2) *Epistemic Uncertainties*: All the man-induced uncertainties in (a) input data,
(b) modelling and (c) technological applications.

Deterministic modelling introduces sharp values of physical parameters and boundary conditions. This approach is not adequate to incorporate imprecision of data and propagate uncertainties. Two main methodologies are appropriate to quantify uncertainties:

(1) stochastic simulation
(2) fuzzy modelling.

According to stochastic simulation, physical parameters and input loads are considered as random variables. This is a frequency-based approach to propagate uncertainties (Ganoulis, (ed.) 1991). Results of probability theory (stochastic arithmetic) may be introduced in stochastic modelling in form of analytical functional relationships between random variables or by repeating a large number of realisations (Monte Carlo method).

In this paper, the fuzzy set theory (Kaufmann and Gupta, 1985) in combination with mathematical modelling is proposed in order to assess uncertainties in groundwater recharge estimation. Uncertainties in input loads and values of groundwater parameters are first formulated as fuzzy numbers. Then, uncertainties are propagated by using fuzzy calculus.

With fuzzy logic based modelling it is possible to assimilate imprecise data, propagate uncertainties, and produce directly, in form of fuzzy numbers, imprecise output, without repeating a large number of computations (Ganoulis *et al.*, 1996). An example of application in a simplified case illustrates the capabilities of the above methodology and the precautions to be taken for their successful implementation in groundwater recharge problems.

3. Methodology of Fuzzy (Imprecise) Modelling

3.1 Problem Identification

The system approach is used to identify the general mathematical problem of flow in soils and coastal aquifers. A groundwater system may be characterised by a *set of s parameters* noted by the vector

$$\mathbf{k} = \{k_1, k_2, \ldots, k_s\} \qquad (1)$$

These parameters express the physical or physico-chemical interactions between groundwater variables.
For example, regional groundwater flows may be simulated by introducing aquifer parameters such as
-aquifer transmissivity (T^{-1})
-vertical conductance (T^{-1})
Solute transport in coastal aquifers induce parameters such as
-hydraulic conductivity (LT^{-1})
-dispersion coefficients (L^2T^{-1})
The groundwater system receives some *inputs*, which may be defined by a set of m independent variables

$$\mathbf{x} = \{x_1, x_2, \ldots, x_m\} \qquad (2)$$

These are, for example, water discharges along the boundaries of the system or given pollutant concentrations at certain locations. The *response or output* of the system may be the water content or n pollutant concentrations at different locations noted as the vector

$$\mathbf{y} = \{y_1, y_2, \ldots, y_n\}. \qquad (3)$$

In real groundwater systems available information concerning both the parameters of the system and the inputs is scarce. Data coming from the field may belong to one of the following two types:
(1) *in-situ or laboratory data* : measurements at given locations or sampling and analytical determination of data values in the laboratory
(2) *interval-type data* : the exact value is not known but the upper and lower bounds of a given piece of data may be specified.

Interval-type information is that resulting from indirect measurements, qualitative description, subjective interpretation and expert judgement (Lou *et al.*, 1996). In real ecological systems, data are usually of the second type, due to various uncertainties and physical variabilities. In order to incorporate interval-type information in ecological modelling and find how imprecise could be the output, a methodology may be outlined in three steps:
(i) formulation of a crisp model (crisp modelling)
(ii) model fuzzification (fuzzy modelling)
(iii) solution by use of fuzzy calculus (fuzzy solution formulation).

3.2 Crisp Modelling

Groundwater recharge may be estimated by using soil water flow models based on Darcy's Law, with appropriate boundary conditions. It is the case of plant-soil zone simulation models developed by USDA-Agricultural Research Service (ARS) for unsaturated flow in soils (Smith and Ferreira, 1989). By combining the Darcy's Law and the mass continuity principle, the following Richard's equation may be obtained, for one dimensional vertical flow in the unsaturated zone

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}(k(\theta)\frac{\partial\psi}{\partial z}) + \frac{\partial}{\partial z}(k(\theta)) \qquad (4)$$

where
θ = is the volumetric water content
k = is the hydraulic conductivity (LT-1)
ψ = is the matric suction potential (L)
t = is the time (T)
z = is the vertical ordinate, positive downward (L)

Both the matric potential ø and the hydraulic conductivity k are function of the unknown water content è.
The dependence of ø and k on è is usually determined from experiments. Introducing the soil moisture diffusivity $D\theta$ in the form

$$D(\theta) = k(\theta)\frac{d\psi}{d\theta} \tag{5}$$

we get the following equation

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}(D(\theta)\frac{\partial\theta}{\partial z}) + \frac{\partial}{\partial z}(k(\theta)) \tag{6}$$

If the hydraulic conductivity is sufficiently small, a non linear *diffusion equation* results, having the form

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}(D(\theta)\frac{\partial\theta}{\partial z}) \tag{7}$$

The above equation is similar to the one dimensional *convective dispersion equation*, written as

$$\frac{\partial\theta}{\partial t} + U\frac{\partial\theta}{\partial x} = D\frac{\partial^2\theta}{\partial x^2} \tag{8}$$

where U is the convective velocity and D the dispersion coefficient. The approximate analytical solution of Eq. (7) with boundary condition θ (0,t)= θ_0 is

$$\theta = \theta_0 + \frac{1}{2}\{1 - \mathrm{erf}(\frac{z - Ut}{2\sqrt{Dt}})\}. \tag{9}$$

where erf is the *error function* (Abramowitz and Stegun, 1965).

3.3 Model Fuzzification

The formulation of this part is crucial to obtaining the correct solution. In fact, fuzzy modelling produces enclosures for the range of output variables. However, results of fuzzy calculus depend on the way fuzzy equations are written. Generally, it is clearly preferable to apply fuzzy algebra (see Appendix B) to explicit equations such as finite-difference explicit schemes or analytical expressions. When this is not possible, the solution of fuzzy linear systems of equations may be obtained through interval methods (Moore, 1979; Neumaier, 1990). These methods are under development, they are approximate and may lead to enclosures which overestimate the real range of the solution (Ganoulis *et al.*, 1996; Dou *et al.,* 1996).

Even in the case of explicit or analytical expressions, the application of fuzzy arithmetic without taking into account the algebraic properties of fuzzy operations (Appendix B) may lead to erroneous results. One basic rule is to rearrange the explicit equations so that variables do not occur repeatedly in the final expression. Otherwise, an overestimation of the real range of the solution is obtained. It is necessary to emphasise that the range overestimation problem in fuzzy modelling is equivalent to the error estimation problem in classical numerical methods.

Let us now formulate an explicit scheme for the numerical integration of equations (7) and (8). It is known (Ganoulis, 1994) that better results are obtained by separating the convective from the dispersion part. A set of points (Lagrangian) is moved over a stationary grid (Eulerian) to solve numerically the convective part of Eq. (8). Each moving point p, located at x_p, y_p is assigned a water content θ_p. From the physical point of view every point may represent a large number of fluid or pollutant particles. Then, the dispersive part of Eqs. (7,8) are super-imposed by using a finite difference algorithm. The change in water content in Eq. (7) due to dispersion is

$$\theta_i^{n+1} = \theta_i^n + \Delta t\ \ (\Delta_x^2 D_i^n \theta_i^n) \tag{10}$$

where θ_i^{n+1} is the water content θ at time (n+1) at the location i, and Δ_x^2 the finite difference operator for the second derivative. The mixed Lagrangian-Eulerian algorithm has been tested in one-dimensional and two-dimensional flow and the reliability of the numerical computations has been checked by comparing the numerical results with the analytical solution.

When the dispersion coefficient D is considered as a fuzzy number, then the output water content (dependent variable) θ should also be imprecise or fuzzy. In this case, Eq. (10) should be written as

$$\tilde{\theta}_i^{n+1} = \tilde{\theta}_i^n + \Delta t\ \ (\Delta_x^2 \tilde{D}_i^n \tilde{\theta}_i^n) \tag{11}$$

where the symbol ~ represents fuzzy numbers (Appendix A). The above equation (11) defines the explicit fuzzy model of the non-linear diffusion model given by Eq. (7).

Respectively the fuzzy analytical solution of Eq. (8) may be formulated from the solution given by Eq. (9) in the following form

$$\tilde{\theta} = C_o + \frac{1}{2}\{1 - \mathrm{erf}(\frac{z - Ut}{2\sqrt{\tilde{D}t}})\} \tag{12}$$

3.4 Fuzzy Logic Based Solution

The problem now is to define the membership functions of the output, i.e. of the water content $\tilde{\theta}$. Considering the h-level cuts and the extension principle (Appendices A and B), interval arithmetic operations may be applied at different values of h.

From Eq. (11) and using the notation $\overline{A}(h)$ for the h-level cut of the fuzzy number $\tilde{A}$ we obtain:

$$\overline{\theta}_i^{n+1}(h) = \overline{\theta}_i^n(h) + \Delta t \ \ (\Delta_x^2 \overline{D}_i(h)\overline{\theta}_i^n(h)) \tag{13}$$

Applying the extension principle in Eq. (12) at every time t, when D is considered as fuzzy and varies between 5 and 15 m^2/s, we have:

$$\mu_{\tilde{\theta}}(\theta) = \{ \begin{matrix} \sup\{\mu_{\tilde{D}}(D);\ \theta = \theta_o + \frac{1}{2}\{1 - \mathrm{erf}(z - Ut)/2\sqrt{Dt})\},\ \theta \in [0,\ 1],\ D \in [5,\ 15]\} \\ 0 \qquad \text{otherwise} \end{matrix} \tag{14}$$

When D is considered as the triangular fuzzy number $\tilde{D} = (5,\ 8,\ 15)\ m^2\ /\ s$, the solution represented by Eq. (14) is given in Figure 1. The same results are obtained numerically.

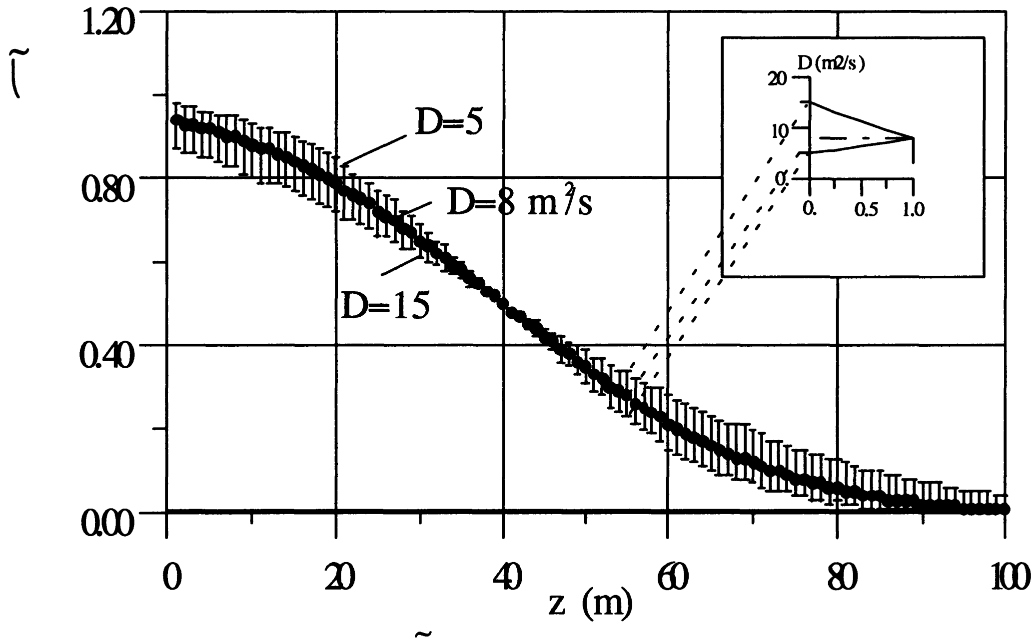

Figure 1. Distribution of fuzzy $\tilde{\theta}$ for One Dimensional Convective Dispersion.

Figure 1 shows how uncertainties due to imprecision in values of the dispersion coefficient D may influence the output dependent variable è. Fuzzy logic based modelling can incorporate and propagate uncertainties without repeating a large number of calculations.

4. Conclusions

Uncertainties due to imprecision in values of physical parameters and input boundary conditions are incorporated into groundwater modelling for estimating aquifer recharge. The methodology may proceed in three steps: (a) crisp modelling, (b) model fuzzification, and (c) solution by fuzzy calculus. It is indicated that explicit finite difference methods and respect for the algebraic properties of fuzzy operations may produce reasonable enclosures for the range of output variables. As shown in the case of one dimensional convective dispersion, the methodology is very useful for detecting the influence of input uncertainties on the range of output dependent variables.

Appendix A: Definition of Fuzzy Numbers

Fuzzy Numbers

A fuzzy number $\tilde{X}$ may be formally defined as a set of ordered pairs

$$\tilde{X} = \{(x, \mu_{\tilde{X}}(x)) : x \in R; \mu_{\tilde{X}}(x) \in [\, 0, 1 \,]\} \qquad \text{(A.1)}$$

where x is a particular value of $\tilde{X}$ and $\mu_{\tilde{X}}(x)$ represents its membership function. Values of the membership function are located in the closed interval [0,1]. The closer $\mu_{\tilde{X}}(x)$ is to 1, the more "certain" one is about the value of x.

A fuzzy number $\tilde{X}$ is normal and convex when its membership function takes one maximum value equal to 1 and is always increasing to the left of the peak, and decreasing to the right. As can be seen in Figure A.1, there are two values of x where the membership function reaches zero, and at least one where it reaches a value of 1. A fuzzy number can be characterised by these three points and the shape of the curve defined by a pair of functions, one to the left and one to the right of the peak, since left-right symmetry is not a necessary condition. A *real*, or *crisp* number, is a fuzzy number whose elements comprise only one number with a non-zero membership value, which is equal to 1.

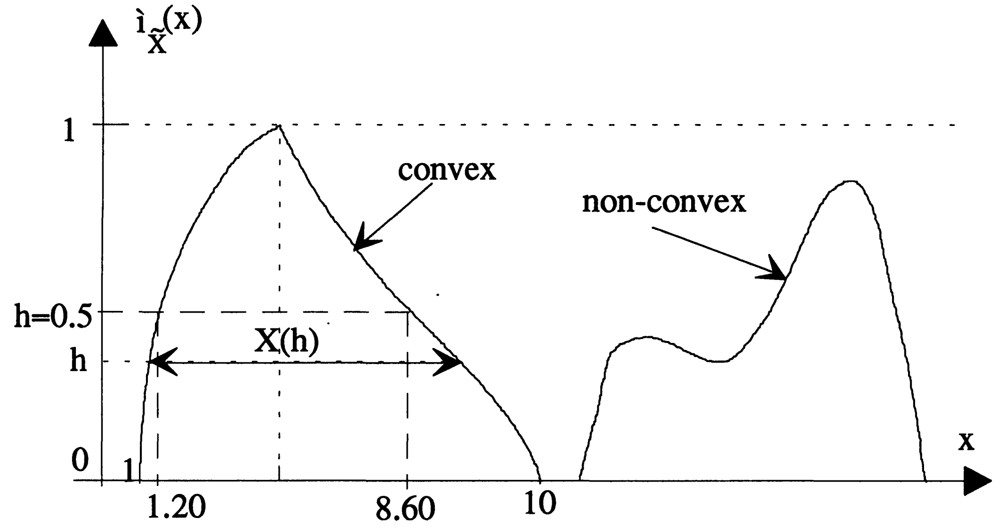

Figure A.1. Convex (a) and non-convex (b) fuzzy numbers.

Triangular Fuzzy Numbers

The simplest type of fuzzy number is the triangular, that is, one having linear membership functions on either side of the peak. A fuzzy triangular number can be characterised by three real numbers: two values of x where the membership function reaches zero and one where it reaches a value of 1. Figure A.2 gives an example of a triangular fuzzy number (TFN). This may be described by the values of x at points x_1, x_2 and x_3.

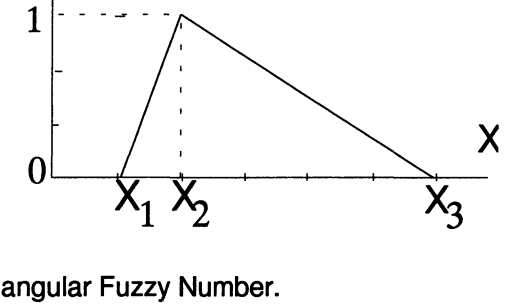

Figure A.2. Triangular Fuzzy Number.

Thus, $\tilde{X} = (x_1, x_2, x_3)$ completely characterises a triangular number. It follows that any real or "crisp" number can be defined as a triangular fuzzy number, with $x_1=x_2=x_3$. A more general definition and further details about fuzzy numbers may be found in Dubois and Prade (1980) and Zimmermann (1985).

h-level of a Fuzzy Number

The h-level set of a fuzzy number $\tilde{X}$ is the ordinary set or interval $\overline{X}(h)$, defined as

$$\overline{X}(h)=\{x: \mu_{\tilde{X}}(x) \geq h)\} \qquad \text{(A.2)}$$

Figure A.1 illustrates the above definition. Referring to the Figure A.1, at the so called credibility level h=0.5 corresponds the 0.5-level cut, which is the ordinary set [1.2,8.6]. For h=0, the 0-level cut is [1,10].

Appendix B: Fuzzy Number Operations

Extension Principle

The extension principle is a method of computing membership functions of fuzzy sets which are functions of other fuzzy sets. Using this principle, which is a basic tool of fuzzy arithmetic, we can perform point-to-point operations on fuzzy sets.

Let X and Y be two ordinary sets and f a one-to-one mapping from X to Y i.e.

$$f = x \rightarrow y \ \forall x \in X, y = f(x), y \in Y \qquad \text{(B.1)}$$

Function f is deterministic and can be extended to the fuzzy set situation as follows.

Let $\tilde{X}$ be a fuzzy set in X with membership function $\mu_{\tilde{X}}(x)$. The image of $\tilde{X}$ in Y is the fuzzy set $\tilde{Y}$ with membership function given by the extension principle as follows

$$\mu_{\tilde{Y}}(y) = \begin{cases} \sup\{\mu_{\tilde{X}}(x); y = f(x), x \in X, y \in Y\} \\ 0 \quad \text{otherwise} \end{cases} \qquad \text{(B.2)}$$

Arithmetic Operations on Fuzzy Numbers

Let us define two triangular fuzzy numbers $\tilde{A}$ and $\tilde{B}$ by the triplets $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$. We have

i) Addition: $\tilde{A} + \tilde{B} = (a_1 + b_1, a_2 + b_2, a_3 + b_3)$ (B.3)

ιι) Subtraction: $\tilde{A} - \tilde{B} = (a_1 - b_3, a_2 - b_2, a_3 - b_1)$ (B.4)

Multiplication or division between two triangular fuzzy numbers does not give a triangular fuzzy number. However we can approximate them as follows

iii) Multiplication

$$\tilde{A} * \tilde{B} = [\min\ (a_1 * b_1,\ a_1 * b_3,\ a_3 * b_1,\ a_3 * b_3),\ a_2 * b_2,\ \max\ (a_1 * b_1, a_1 * b_3, a_3 * b_1, a_3 * b_3)] \qquad \text{(B.5)}$$

iv) Division

$$\tilde{A} / \tilde{B} = [\min\ (\frac{a_1}{b_1}, \frac{a_1}{b_3}, \frac{a_3}{b_1}, \frac{a_3}{b_3}),\ \frac{a_2}{b_2},\ \max\ (\frac{a_1}{b_1}, \frac{a_1}{b_3}, \frac{a_3}{b_1}, \frac{a_3}{b_3})] \qquad \text{(B.6)}$$

Algebraic Properties of Fuzzy Numbers

Assume that $\tilde{A}$, $\tilde{B}$ and $\tilde{C}$ are fuzzy numbers. The following laws hold:

$\tilde{A}+\tilde{B}=\tilde{B}+\tilde{A}$	$\tilde{A}\,\tilde{B}=\tilde{B}\,\tilde{A}$	Cummutativity
$(\tilde{A}+\tilde{B})\pm\tilde{C} = \tilde{A} +(\tilde{B}\pm\tilde{C})$	$(\tilde{A}\,\tilde{B})\tilde{C}=\tilde{A}(\tilde{B}\,\tilde{C})$	Associativity

However, subdistributivity and subcancellation is not always valid. In particular we have

$\tilde{A}(\tilde{B}\pm\tilde{C})\subseteq \tilde{A}\,\tilde{B}\pm\tilde{A}\,\tilde{C}$	$(\tilde{A}\pm\tilde{B})\tilde{C}\subseteq \tilde{A}\,\tilde{C}\pm\tilde{B}\,\tilde{C}$	Subdistribution
$\tilde{A}-\tilde{B}\subseteq(\tilde{A}+\tilde{C})-(\tilde{B}+\tilde{C})$	$\tilde{A}/\tilde{B}\subseteq \tilde{A}\,\tilde{C}/\tilde{B}\,\tilde{C}$	Subcancellation

Overestimation usually occurs because of the failure of the distributive and cancellation laws.

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GROUNDWATER DISCHARGE TO COASTAL SWAMPS IN THE TORRES STRAITS ISLANDS: HIGH WATER TABLE AND MOSQUITO HABITAT

JACOBSON, G. and T. GRAHAM

1. Abstract

On Badu Island, in the Torres Strait between Australia and Papua New Guinea, groundwater discharges into coastal swamps. Radiocarbon and thermoluminescence (TL) dating confirm that the coastal sequence of dune ridges and swampy valleys relates to high stands of late Pleistocene and Holocene sea level. The swamps have been identified as the habitat of mosquitoes carrying the dangerous virus, Japanese Encaphilitis. Investigation of the groundwater hydrology indicates that the swamps have a base of green estuarine clay at shallow depth, which impedes downwards infiltration. Drainage of the swamps is feasible, but possible side effects include the release of some acid sulphate to the sea and the removal of phreatophytic trees.

2. Introduction

The Torres Strait Islands (Figure 1) are located between Australia and Papua New Guinea, and form a biogeomorphological bridge between them. Nowadays the existence of this bridge has led to a series of environmental, health and quarantine issues between the two countries.

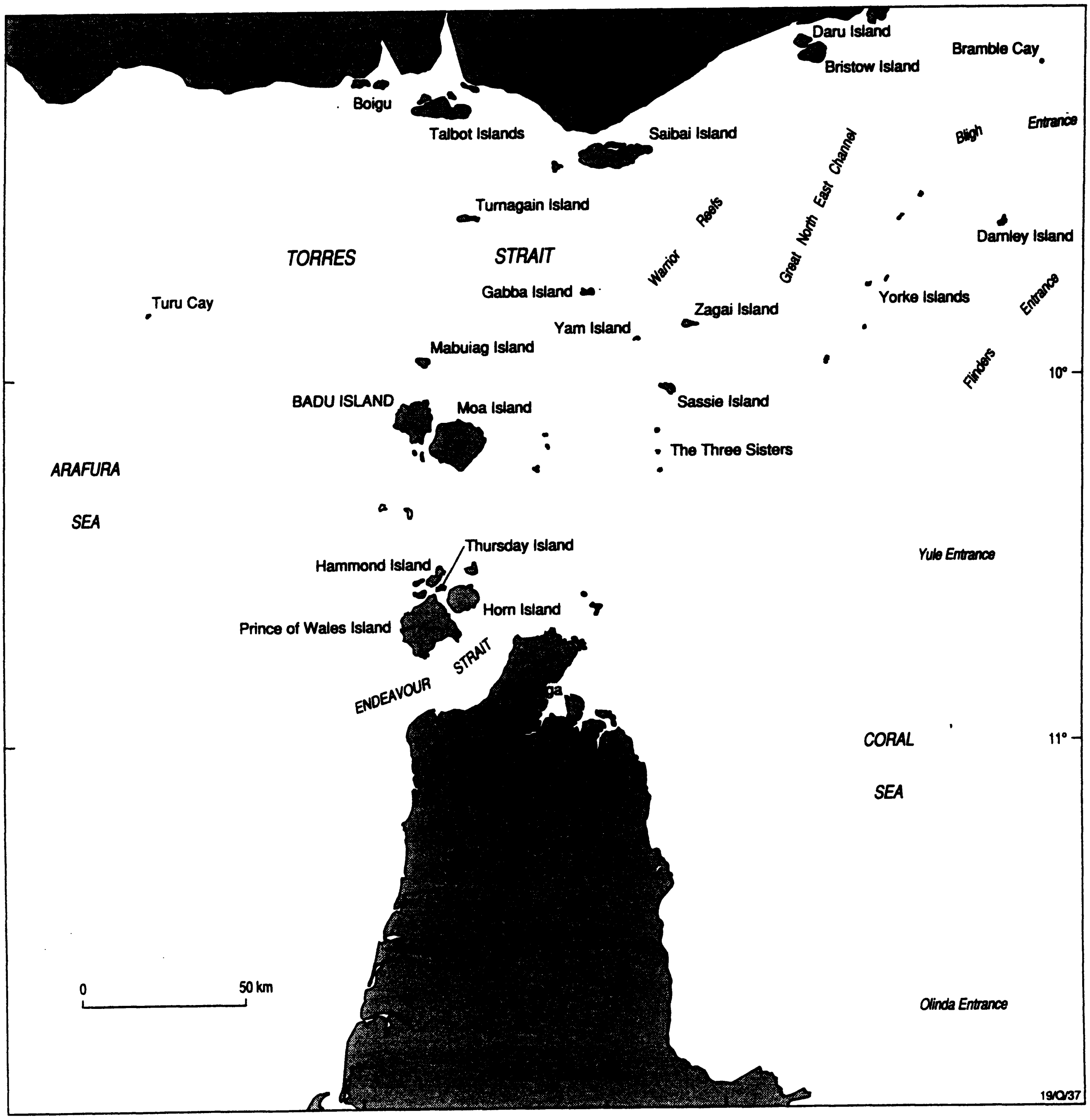

Figure 1. Location map.

In April 1995 an outbreak of Japanese Encaphilitis (JE) led to two deaths on Badu Island in the Torres Strait (Hanna *et al.*, 1995). JE is a mosquito-borne flaviviral disease, and a major public health problem in Asia where there are 50 000 cases per year. This is the first time that JE has been identified in Australia.

The fatal outbreak of JE led to proposals for the drainage of coastal swamps on the island to reduce the mosquito habitat. The high water table in the coastal region was identified as a major factor in forming the extensive areas of mosquito habitat that existed when the village was hit by the fatal outbreak of JE (Bailey *et al.* 1995). Other environmental factors that have been identified include: the presence of pigs which host, amplify and maintain the virus; the presence of horses which add nutrients to the swampy valleys where the mosquitoes breed; and leaking and overflowing septic tanks which also form nutrient-rich mosquito breeding sites near houses.

During November 1995 we investigated the causes of the high water table beneath Badu village, in the southeast of the island, at the request of the Torres Strait Health Council. We drilled and sampled 15 holes to depths of up to 5 m using a hand auger and a drive-sampling device. This was sufficient to establish the subsurface geology and hydrology beneath the village, and account for their evolution.

3. Geology of Badu Island

Badu Island is one of the western islands of the Torres Strait that were formerly the peaks of a ridge that extended from Cape York Peninsula to Papua (Figure 1); the seabed along the now submerged ridge is generally less than 11 m deep. The island is 100 km^2 in area and rises to 198 m above sea level.

The geology of Badu Island is shown in Figure 2. The core of the island is formed of Carboniferous granites and associated volcanic rocks (Willmott and Powell, 1977). A number of major lineaments have been recognised and form the basis of groundwater exploration for the island's water supply. Residual sand of Late Tertiary and Quaternary age, floors the lower parts of the island and has been reworked in the Late Quaternary to form dunes. There are extensive freshwater swamps in the south of the island, which have been formed by discharging groundwater.

Badu village is in the southeast of the island and is sited on the Quaternary coastal deposits. There are four dune sand ridges and four inter-ridge valleys (swales) orientated NE/SW, parallel to the coast. Figure 3 shows a cross-section through these deposits. Low hills of granite bound the village to the south and to the west.

The highest dune ridge, to the northwest of the village, is at an elevation of 12-15 m above sea level (a.s.l.), and by analogy with similar deposits that have been dated along the eastern Australian coastline, is thought to have formed at the worldwide high sea-level stand of 125 000 years ago. The middle two dune ridges are at elevations of about 7 m and about 9 m a.s.l. respectively, and are less distinct features which have been modified by housing and gardens; they are also considered to be related to the Late Pleistocene high sea level. The lowest, coastal dune ridge is at about 4 m a.s.l. and probably formed in a period of higher sea level which commenced 6000 years ago.

The valley behind the highest dune ridge is underlain by lateritic hardpan, a residual surface developed on weathered granite, at a depth of 1 m. This hardpan impedes the vertical infiltration of heavy rainfall which forms a large pond in the wet season. Since the JE outbreak, the Badu village council have constructed a drain to connect the pond with the natural drainage to the northeast.

Swamps have formed in the swales beneath the central part of the village. Drilling shows that the swamps are underlain by light green sandy clay at a depth of 1.0 - 1.5 m below the surface. The green clay pre-dates the formation of the sand dunes, and may represent an older estuarine deposit. It has the effect of impeding the downwards infiltration of groundwater. The swamps are vegetated, with pandanus and bamboo, and the water table is maintained at a depth of 0.5 - 1.0 m.

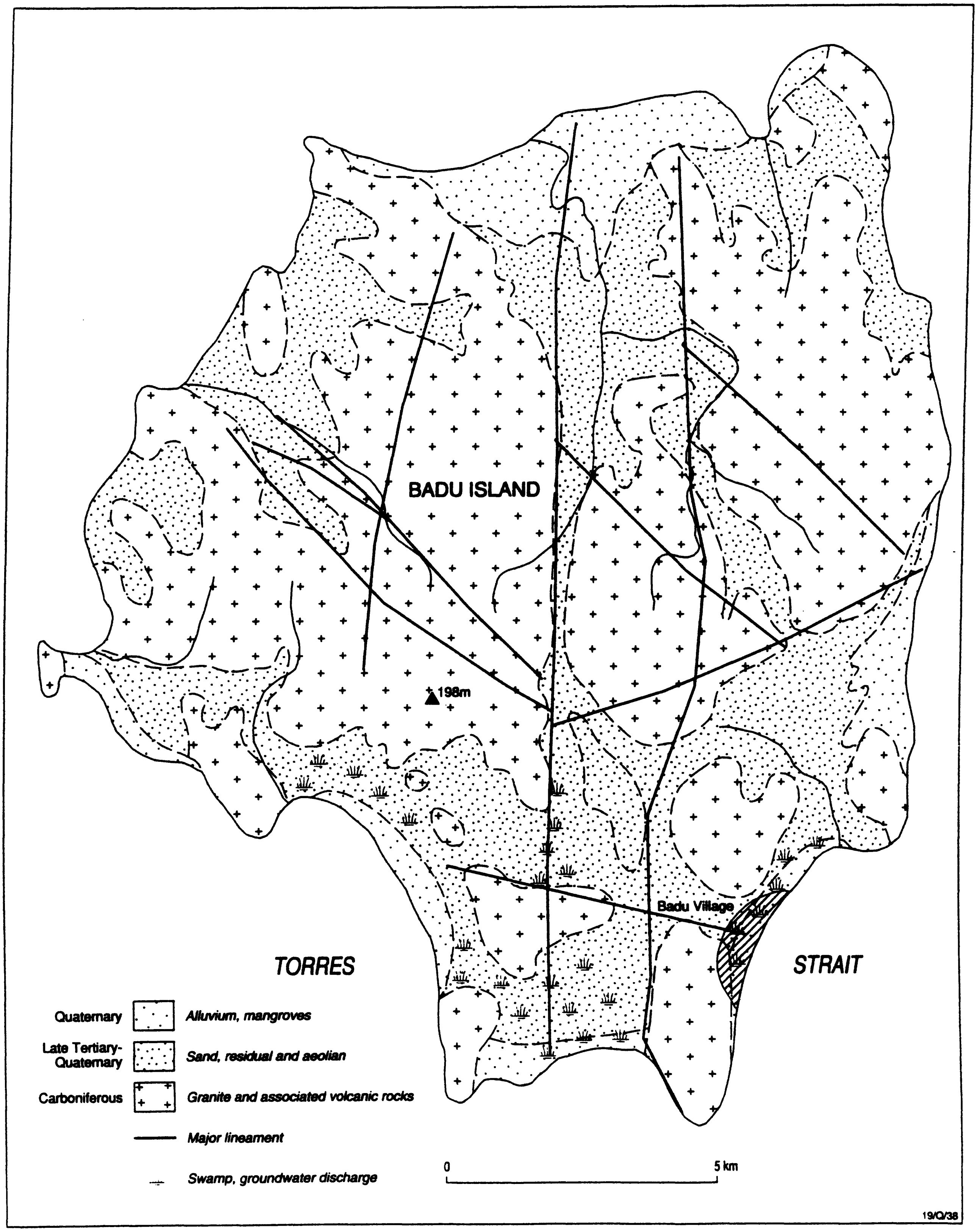

Figure 2. Geology of Badu Island (after Willmott and Powell, 1977).

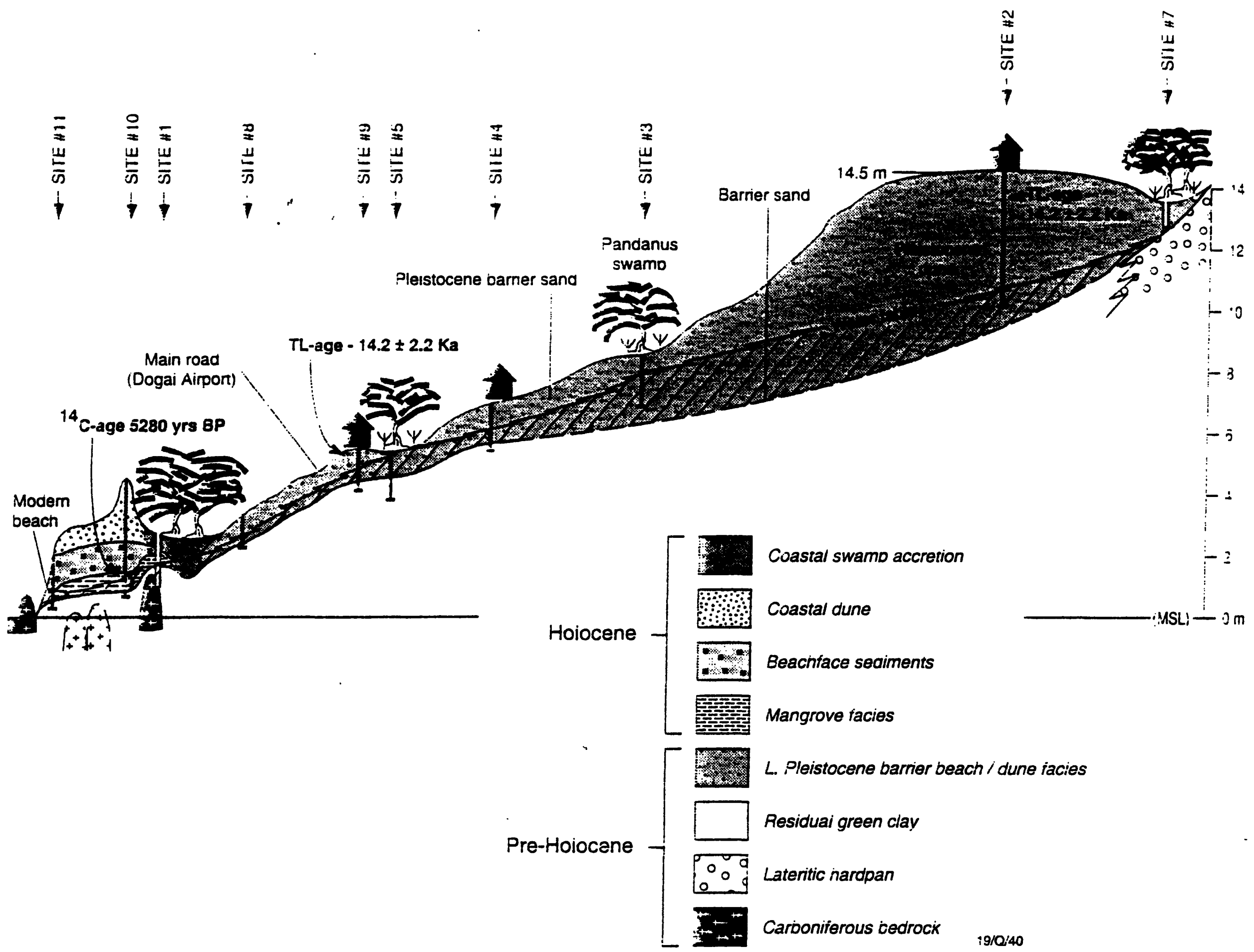

Figure 3. Cross-section of Badu village showing coastal dune deposits and the groundwater system.

4. Coastal Evolution

The coastal barrier sediments on which Badu village is located, evolved in two distinct periods related to successive high sea level stands (Figure 4). The present high sea level stand commenced around 6000 years ago, and the previous high sea level stand was about 125 000 years ago. In the intervening period sea level was below that of the present village leaving it remote from the shifting coastline. The Torres Strait is believed to have been dry land between approximately 60 000 and 8000 years ago (Jennings, 1972).

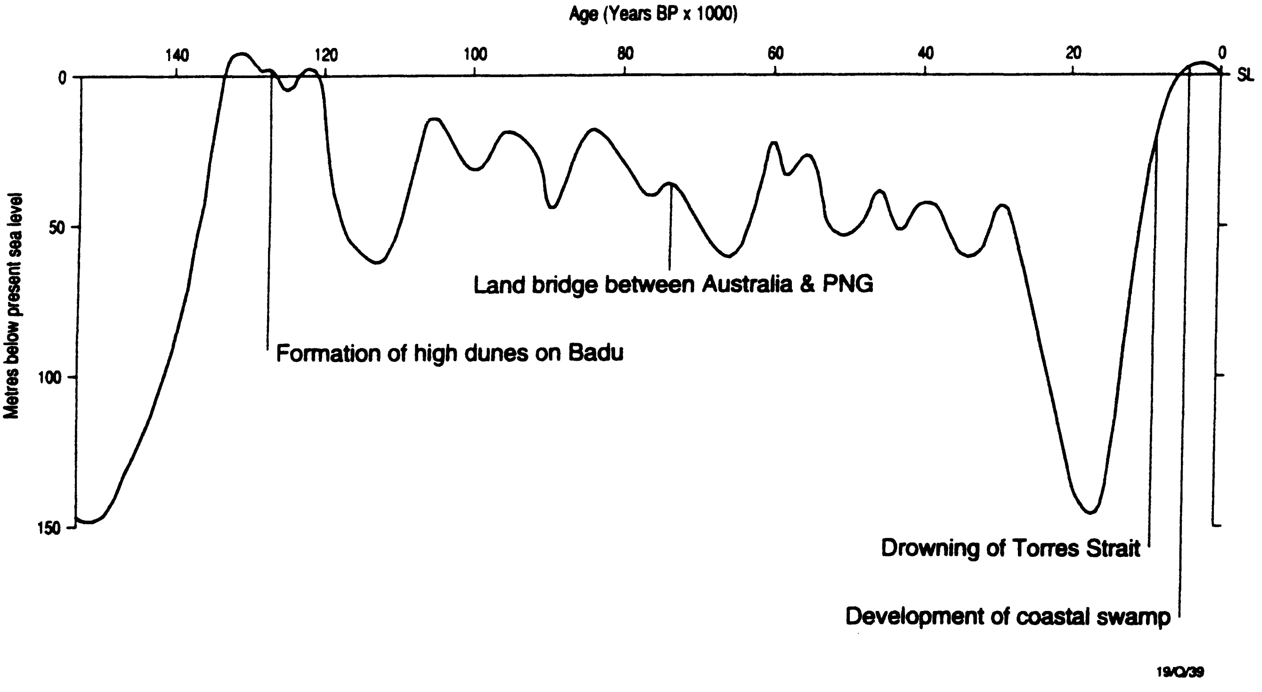

Figure 4. Sea-level changes over the last 150 000 years in the Australian region (after Chappell, 1987)

The Late Pleistocene (about 125 000 years) barrier sand forms the land surface through most of Badu village. Although degraded through time, these barrier formations have determined the shore-parallel lineations of high ground occupied by roads and houses, and the intervening low swampy ground. In the present investigation, a sand sample taken from a depth of one metre in the highest dune has given a TL date of 14 900 (+- 2300) years B.P. Another sand sample from a depth of one metre in one of the the intermediate dunes gave a TL date of 14 200 (+- 2200) years B.P. This suggests near-surface reworking of the dune sand at that time, when the Torres Strait was dry land. This period, at the very end of the Pleistocene, is known to have been an arid and windy period elsewhere in Australia, including the northeast (Kershaw, 1989).

The 125 000 year sea level is known to have been about 5 m higher than present sea level along the eastern Australian coast (Marshall and Thom, 1976; Drury and Roman, 1983). At that time the sea penetrated inland at Badu. A large dune formed in front of the rising sea, anchoring on the granitic bedrock northwest of the present village site. From this shoreline the series of sand barriers developed in a seawards direction.

The Holocene barrier has evolved from 6000 years ago to the present day. The Holocene sea penetrated inland and drilling shows that the initial shoreline had a narrow belt of mangrove swamp behind which a low ridge developed (Figure 3). Radiocarbon dates of 5280 (+- 100) and 6000 (+- 100) y B.P. have been obtained for drillcore samples taken from this buried mangrove shoreline in the present investigation. This is concordant with other dated coastal sequences in northeast Australia (Crowley and Gagan, 1995) which indicate that mangroves reached their greatest extent around 6000 y B.P. as the rise in sea level slowed. A modern analogue for the mangrove shoreline occurs further east along the Badu coast.

Sand washed over the top of the initial barrier ridge in storms, to construct a surface sloping gently landwards. As the ridge developed in height and moved seawards, the area behind was isolated from the sea and became the present freshwater swamp. This swamp has since filled with organically rich sediments.

5. Groundwater Hydrology

Coastal sand deposits have captured and modified the original surface drainage off the granite hills which form the core of Badu Island. From about 125 000 years ago, the natural surface drainage off the granite island was disconnected by the development of the sand deposits and it has not yet had time to re-establish itself. Groundwater flows along lineaments in the granite and in the sand dunes, and discharges to the swamps in the south of the island.

The sand dune ridges and intervening valleys in Badu village contain a large amount of groundwater. The entire village has an impermeable base at a depth of 1-2 m below surface, formed mostly by the green clay, but also by the lateritic hardpan to the west. The impermeable base impedes the downwards movement of the groundwater and the aquifer is thus shallow, with a thin tabular geometry. Groundwater recharge occurs in the wet season (Dec-April) when an average of close to 2000 mm of rain falls. The aquifer fills up early in the wet season and the excess water ponds at the surface of the swales to form swamps, i.e. recharge is rejected. There is some evaporation and some transpiration by trees but the natural surface drainage is not effective in removing this excess water from the swamps.

The highest dune ridge acts as a reservoir for groundwater which discharges in the swales throughout the dry season, thus prolonging the discharge of water and delaying the runoff of the annual (wet season) rainfall. In the natural system the groundwater level stays near the surface during the dry season and transpiration by the swamp vegetation is balanced by discharge from the dune. In the present situation there is an urgent need to reduce mosquito habitat, and drainage works are necessary to remove excess water ponded at the end of the wet season.

6. Swamp Drainage Considerations

The main areas of mosquito habitat that have been identified include the swamp behind the frontal coastal dune. This is underlain by green clay at a depth of 1 - 2 m, and there also some bedrock high spots beneath it. The Badu village council have started to drain this swamp. The central swamp belt in the village is underlain by clay at a depth of 1.0 - 1.5 m, and this area is constantly recharged from the sand dunes that flank it, maintaining the high water table. There are limits to the effective depth of drains because of the widespread occurrence of the green clay layer at shallow depths.

The seasonal pond in the valley behind the highest dune forms because of an underlying lateritic hardpan. This is largely a surface water drainage problem and action has already been taken by the village council to drain this pond. The valley on the south side of the village is also a major mosquito habitat. It was dry when inspected in November 1995. Inspection shows that this valley contains granite outcrops which form subsurface barriers to drainage, and selective excavation by blasting may be necessary to drain off the wet season flows quickly.

The drainage problem is seasonal, as there is an urgent need to remove excess wet season water. Additional surface drains are needed for this, but there is also a need to limit the clearing of trees which actually transpire groundwater in the dry season. Trees should also be re-planted where possible in the swamps, and alongside newly excavated drains. It is observed that most natural drainage channels near Badu village are lined with trees such as *Melaleuca*.

The main drains will drain to the sea and their outlets will need to be carried across the beach. It will be necessary to project the drains beyond the influence of littoral sediment drift. We have also considered the possible effects of drainage outlets on nearshore/offshore biological communities. The nearshore area at Badu village is characterised by a shallow, sandy seabed colonised by seagrass species. This sandy bed and the associated water turbidity, have excluded coral growth within several hundred metres of the shore. Augmented drainage would not substantially affect these biological communities.

The possible production of acid water by draining Holocene-age estuarine sediments is a consideration on Badu Island. This is a widespread environmental problem on the east coast of Australia wherever estuarine sediments, which are commonly buried beneath coastal floodplains, are exposed to an aerobic environment as a result of drainage works (Walker, 1972). Acid sulphate soils develop when oxidation of the pyrite in the sediments produces more sulphuric acid than can be neutralised by the soil system (Pons *et al.*, 1982). The process releases phytotoxic aluminium and ferrous iron. These products can have an immediate effect on aquatic flora and fauna leading to fish and crustacea mortality and to sterile water bodies. They also produce longer term, more insidious effects which include: the pollution of water supplies with aluminium and acid resulting in significant health problems for humans and animals; the corrosion of concrete, aluminium and iron structures by the acid water; and also ulcerative diseases in fish, which cause losses of up to 75% in some fish catches in Asian and Pacific waters (White and Melville, 1993).

Our drilling has shown that sediments of this type are restricted in extent beneath Badu village. Two samples of drillcore from drillhole 6 beneath the Holocene swamp were analysed for potential acidity by G.M. Bowman using the procedures of Dent and Bowman (1993). The sample from 2.7 m depth produced 1446 moles of acid per cubic metre of soil, and the sample from 3.5 m produced 575 moles of acid per cubic metre of soil. These two samples are rated as having extreme and high potential acidity hazard, respectively. However only the organic mud deposits beneath the Holocene coastal dune and swamp, have the potential to generate acid drainage waters.

The groundwater underlying the village has been an important resource for the village water supply; it is good quality water (50 - 80 mg/L Total Dissolved Solids), but there are an increasing number of septic tanks in the vicinity and this aquifer is vulnerable to pollution. It is nevertheless suitable for irrigation and other purposes and its use is to be encouraged as an additional measure to lower the water table. The community presently draws its drinking water from a stream bed 1.5 km west of the village, and from two deeper bores sited on lineaments several kilometres inland.

7. Aftermath

At the time of writing (October 1996) the swamp drainage works are still being considered for Badu Island. The estimated high cost and possible environmental consequences are significant deterrents. The population of Badu Island and the other outer islands of the Torres Strait has been vaccinated against JE as a precautionary measure (Hanna *et al.*, 1996). Unfortunately the virus has re-appeared in the Torres Strait in 1996 and is known to be present on several of the outer islands (Shield *et al.*, 1996). Significantly, broadly similar coastal swamp conditions related to groundwater discharge are apparent on several other populated islands of the Torres Strait.

8. Acknowledgements

Our work was partly funded by the Queensland Department of Health, and was assisted by the Badu Council. We thank Graham Henderson (Australian Institute of Aboriginal and Torres Strait Islander Studies) and Phillip Mills (Queensland Department of Health) for facilitating the investigation; Greg Bowman (CSIRO Division of Soils) for acid sulphate tests; the ANU Quaternary Dating Laboratory for radiocarbon dates; David Price of the University of Wollongong for TL dates; and John Marshall of AGSO for comments on the manuscript. . The paper is published by permission of the Executive Director of the Australian Geological Survey Organisation.

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*SOME URGENT PROBLEMS OF SEA WATER INTRUSION INTO FRESH AQUIFERS

KHUBLARYAN, M.G.

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 Bleak and the Caspian sea coasts of the Caucasus, where a real threat of sea water inleakagae 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 cloys, 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 in 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 characterized both confined and unconfined groundwater flows in heterogeneous and anisotropic water - bearing layers.

By introducing into consideration fresh water head,

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

and relative dissolved sea salts concentration,

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

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

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

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

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

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

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

$$A = \begin{bmatrix} \kappa_x & 0 \\ 0 & \kappa_y \end{bmatrix}, \tag{6}$$

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

Equations (3) - (4) a 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, $y = \hat{o}(x,t)$ is given by pressure $p = 0$, on a free surface of filtration flow, i.e. $\psi = y = \hat{o}$.

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

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

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).

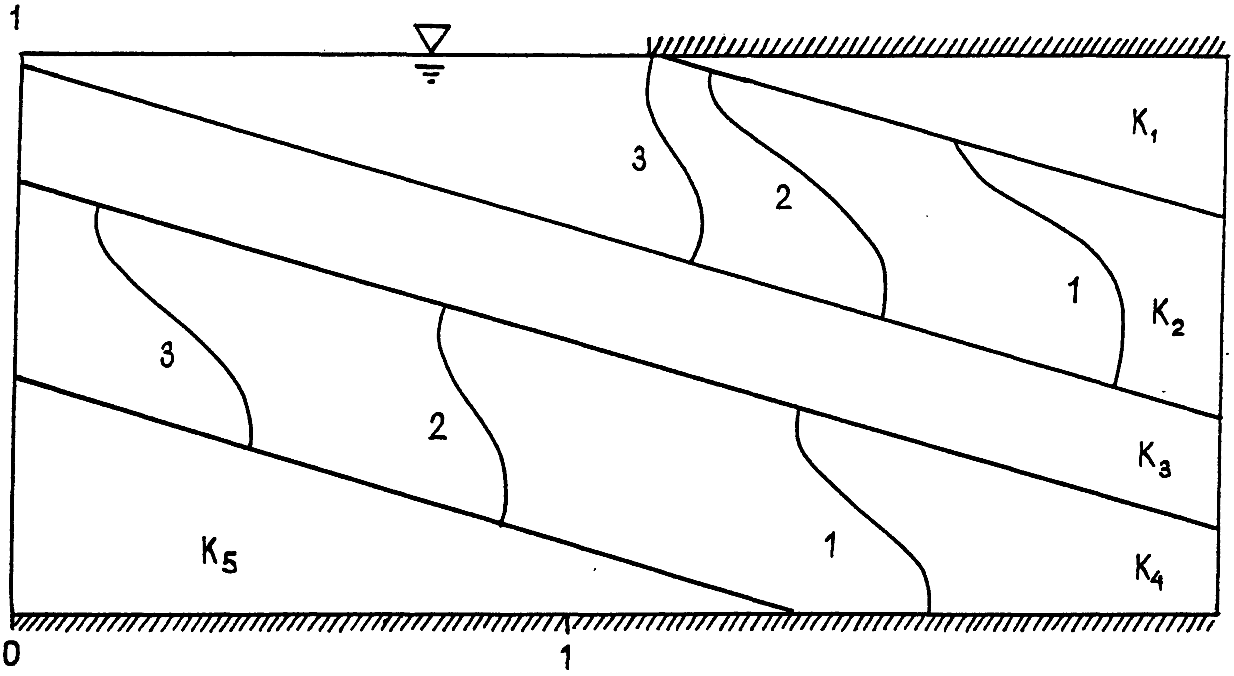

Figure 1. Lines of equal sea salts concentrations under intrusion into a layered aquifer : 1 - c = 0,27; 2 - c = 0,51; 3 - c = 0,76, with the following meanings permeability coefficient for layers and diffusion coefficient: κ_1 =0.001 m/d, κ_2 = 10 m/d, κ_3 = 0.001 m/d, κ_4 =1 m/d, κ_5= 0.001 m/d, $D = 7{,}0 \cdot 10^{-2}$ 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.

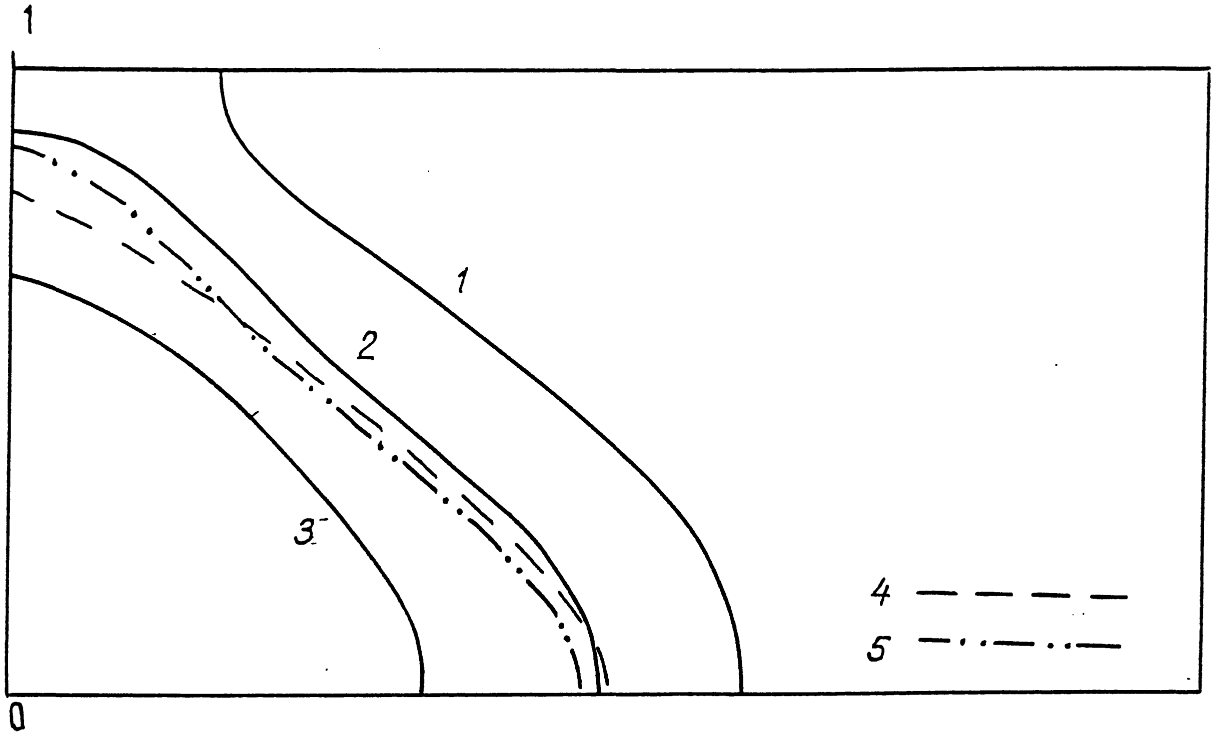

Figure 2. Correlation of field data with the results of finite-difference and finite-element methods for calculating the distribution of sea salts concentration in the intrusion zone in natural layers: 1- 3 - c = 0,25; 0,5; 0,75 correspondingly (according to the authors), 4 - c = 0,5 (Lee, Cheng, 1974)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

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*CLIMATE CHANGE AND DIRECT GROUNDWATER FLUXES TO THE OCEAN

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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 $km^3 \cdot yr^{-1}$, and that the global dissolved salt throughput carried by direct ground water flux is approximately 1,300 x 10^6 $t \cdot yr^{-1}$ (1 $t \cdot yr^{-1}$ ≡ 1 metric ton per year =1,000 kg per year). The estimated annual ground water volumetric flux compares with an estimated 38,000 $km^3 \cdot yr^{-1}$ 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 x 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 $km^3 \cdot yr^{-1}$. The equation of conservation of water mass can then be expressed in differential form as follows (Δ denotes change over time):

$$\Delta P = \Delta E + k_S \cdot \Delta R_S \tag{1}$$

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:

$$\Delta P = \Delta E + k_G \cdot \Delta R_G \tag{2}$$

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 be 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 ($W \cdot m^{-2}$). 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):

$$\Delta A = L \cdot \Delta E + \Delta H \tag{3}$$

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:

$$\Delta A = \Delta R_n - \Delta G - \Delta B \tag{4}$$

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:

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

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 CO_2 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 CO_2 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:

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

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 $kg{\cdot}s^{-1}{\cdot}m^{-2}$. On the other hand, the ΔE term appearing in (the water balance) equations (1) and (2) has dimensions of $km^3{\cdot}yr^{-1}$. 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 $km^3{\cdot}yr^{-1}$. The transformed equation (6) becomes (L, the latent heat of vaporization, is equal to 2.46 x 10^6 $J{\cdot}kg^{-1}$ and ΔR_n must be in dimensions of $W{\cdot}m^{-2}$):

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

in which S_L is the world's land area (150 x 10^6 km^2), ρ is the density of freshwater (10^3 $kg{\cdot}m^{-3}$), 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 $km^3{\cdot}yr^{-1}$; the change in land precipitation, ΔP, must be in $km^3{\cdot}yr^{-1}$ also):

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

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

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

$$M_G = C_G \cdot R_G \tag{10}$$

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:

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

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 $C_G = 542 \times 10^3$ t·km^{-3} (which is equivalent to 542 mg·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 W·m^{-2} (Ramanathan, 1988; Ramanathan *et al.*, 1989; Loaiciga *et al.*, 1996), of which about 3 W·m^{-2} would directly heat the atmosphere and about 1 W·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 $\Delta R_n = 1$ W·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 $\Delta A = \Delta R_n = 1$ W·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 W·m^{-2} and assigned values below and above the predicted mean, such as 0.5 and 1.5 W·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 km^3·yr^{-1}, or 73 cm·yr^{-1} (Budyko, 1977) over an estimated total land area of 150 x 10^6 km^2. GCMs predict that under the 2 x 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 x 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]	$W \cdot m^{-2}$
Salt concentration in direct groundwater, C_G	542 x 10^3 (b)	$t \cdot km^{-3}$
Precipitation change over the continents, ΔP	10,950 (c)	$km^3 \cdot yr^{-1}$
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 x 10^6 (f)	$J \cdot kg^{-1}$
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 Zekster 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:

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

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 $L = 2.46 \times 10^6$ J·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 $C_G = 542 \times 10^3$ t·km^{-3}
- The freshwater density is $\rho = 1{,}000$ kg·m^{-3}
- The Bowen ratio $\beta = 0.85$
- The dimensions of ΔR_S and ΔR_G are in km^3·yr^{-1}
- The dimensions of ΔR_n are W·m^{-2}
- The dimensions of ΔM_G are in t·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 km^3·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 W·m^{-2} and a precipitation change of + 10% from its mean (or ΔP = 10,950 km^3·yr^{-1}) is ΔR_S = + 9,300 km^3·yr^{-1}. These latter levels of net radiation and continental precipitation change are commonly predicted by GCMs. The figure of + 9,300 km^3·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 $km^3 \cdot yr^{-1}$, based on equation (8) for a range of mean continental precipitation change, ΔP, and net radiation change, ΔR_n.

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

Notes:

(a) For a current mean continental precipitation of 109,500 $km^3 \cdot yr^{-1}$ or 73 $cm \cdot yr^{-1}$ distributed over 150 x 10^6 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 $km^3 \cdot yr^{-1}$, by Budyko, 1977), L_0 the latent heat of vaporization for sea water (about 2.5 x 10^6 $J \cdot kg^{-1}$), S_0 the ocean surface (361 x 10^6 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 $kg \cdot m^{-3}$). The water/energy conservation equation for the ocean, written in differential form, is:

$$\Delta P_0 = \frac{K \cdot \Delta R_n \cdot S_0}{\rho_0 \cdot L_0 (1 + \beta_0)} - k_S\ \Delta R_S \qquad (13)$$

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 ΔR_S = + 9,300 $km^3 \cdot yr^{-1}$ associated with a + 10 % continental precipitation change (or ΔP = 10.950 $km^3 \cdot yr^{-1}$) and a net radiation change ΔR_n = 1.0 $W \cdot m^{-2}$, occurs simultaneously with a drop in mean global oceanic precipitation of about ΔP_0 = 5,780 $km^3 \cdot yr^{-1}$. The balance between the + 1.063 x 9,300 = 9,890 $km^3 \cdot yr^{-1}$ (= $k_S \Delta R_S = R_T$) gain in total runoff and the 5,780 $km^3 \cdot yr^{-1}$ loss in precipitation is made up by an increment of 4,110 $km^3 \cdot yr^{-1}$ 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 x 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 $km^3 \cdot yr^{-1}$):

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

Given that (i) a 10 % increase in continental mean precipitation is equivalent to 10,950 $km^3 \cdot yr^{-1}$, (ii) the drop in mean oceanic precipitation has been established at 5,780 $km^3 \cdot yr^{-1}$, and (iii) the rise in mean oceanic evaporation is 4,110 $km^3 \cdot yr^{-1}$, it follows from equation (14) that the mean continental evapotranspiration rises by 1,060 $km^3 \cdot yr^{-1}$ under the 2 x CO_2 scenario. It is concluded then that a rise in continental precipitation of 10,950 $km^3 \cdot yr^{-1}$ (a 10 % rise), triggered by 2 x CO_2 warming, is partitioned into a 9,890 $km^3 \cdot yr^{-1}$ rise in total global runoff and 1,060 $km^3 \cdot yr^{-1}$ rise in continental evapotranspiration. The rise in total global runoff is divided into a 9,300 $km^3 \cdot yr^{-1}$ increment in streamflow delivered through the river network and about 590 $km^3 \cdot yr^{-1}$ 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 km^3·yr^{-1}) and direct salt discharge (within parentheses, and reported in 10^6 t·yr^{-1}) associated with a range of mean continental precipitation changes and net radiation changes that may be triggered by 2 x 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 x CO_2 net radiation and mean precipitation changes of 1.0 W· m^{-2} and + 10 %, respectively, Table 4 indicates that the changes in direct ground water flux and salt discharge are 590 km^3·yr^{-1} and 317 x 10^6 t·yr^{-1}, respectively. Using the estimated baseline values of 2,400 km^3·yr^{-1} and 1,300 x 10^6 t·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 x 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 km^3·yr^{-1}) and salt discharge in direct ground water (ΔM_G, within parentheses, in 10^6 t·yr^{-1}) associated with 2 x CO_2 global warming.

% Change in land precipitation (a)	Net radiation change (W·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 km^3·yr^{-1})	625 (338)	590 (317)	558 (301)
+20 (21,900 km^3·yr^{-1})	1,268 (685)	1,243 (671)	1,211 (654)

Notes:

(a) For a current mean continental precipitation of 109,500 km^3·yr^{-1} or 73 cm·yr^{-1} distributed over 150 x 10^6 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 ΔR_n = + 1.0 W·m^2, ΔP = +10 % from mean value or 10,950 km^3·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 $\Delta R_n = 1.0$ W·m^{-2}, $\Delta P = +10\ \%$ (= 10,950 km^3·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 km^3 (Margat and Forkasiewicz, 1981) and 68 km^3 (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 makingcapture 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, paleogegraphical zones and structures, different from those of today; accordingly, the karst structure of porosity is displaced above and below the current sea level (Figure1).

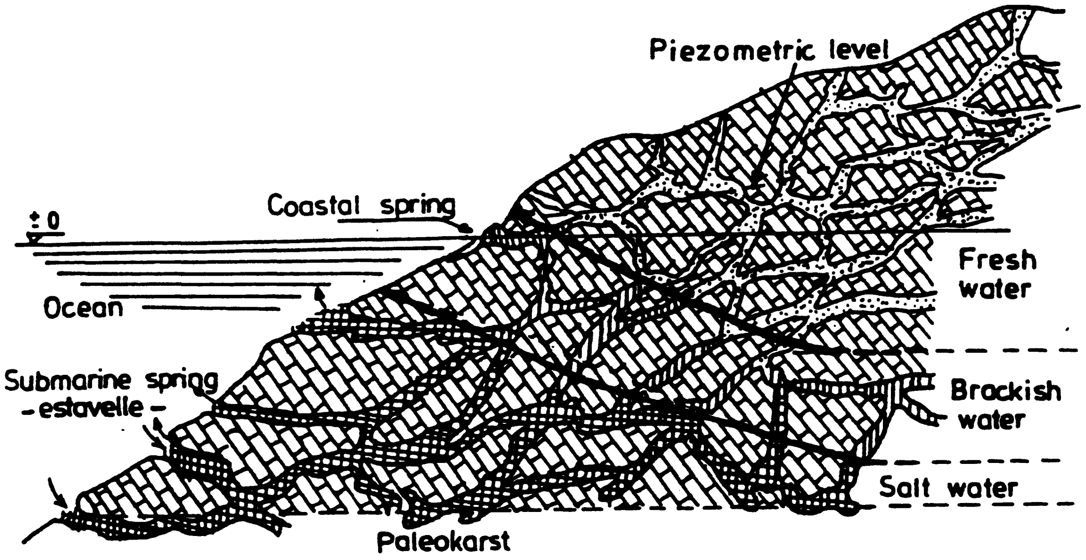

Figure 1. Schematic representation of ground water circulation in the karstic coastal zone.

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.

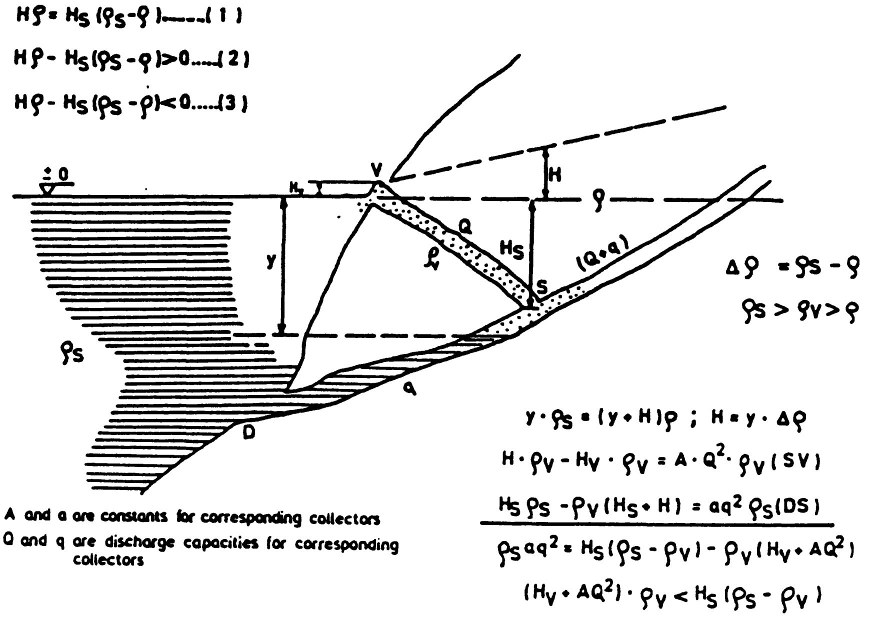

Figure 2. Schematic representation of salting processes in submarine and coastal springs.

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 $(H_V + A\,Q^2)$ ρ_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 avertical 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).

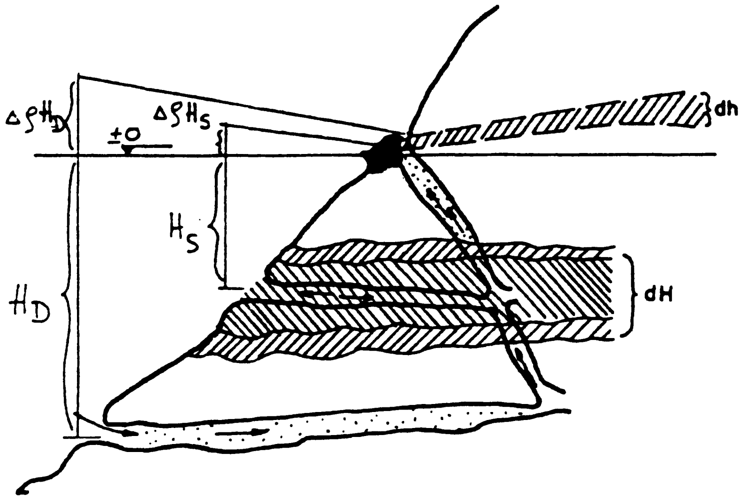

Figure 3. Provocation of the submarine spring by artificial slowing of discharge within the same drainage system.

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.

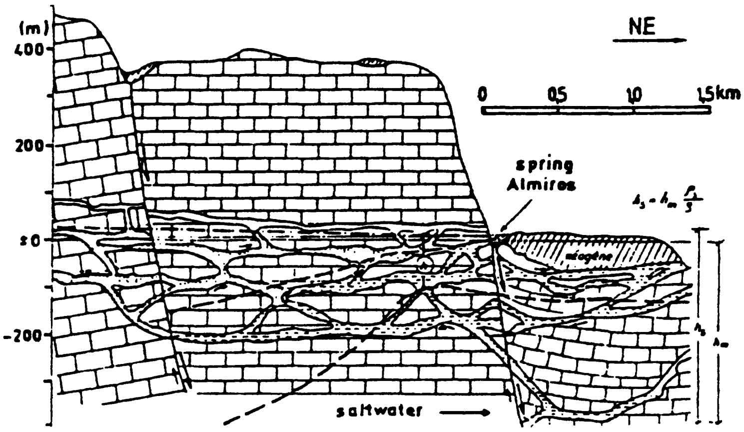

Figure 4. Geological cross-section from carbonate massif of the Keri mountain to the plain of Iraklion and the spring Almiros (Monopolis and Mastopis, 1969).

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 (ρ_S - ρ_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.

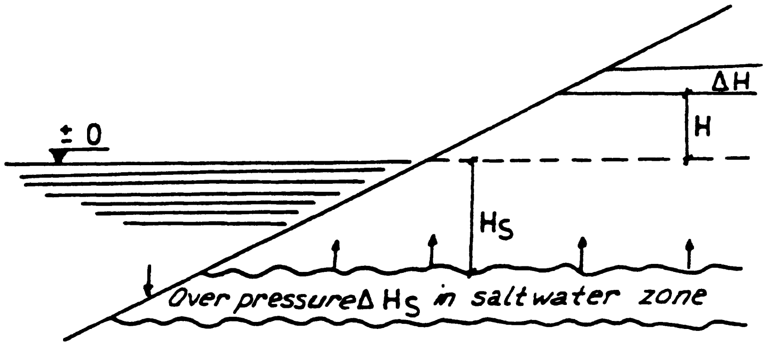

Figure 5. Schematic display of freshwater overpressure, not in balance with the brackish zone.

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.

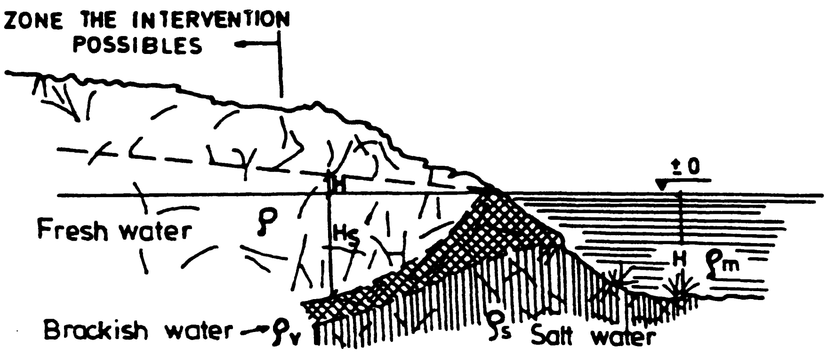

Figure 6. Coastal karst aquifer open to the sea.

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).

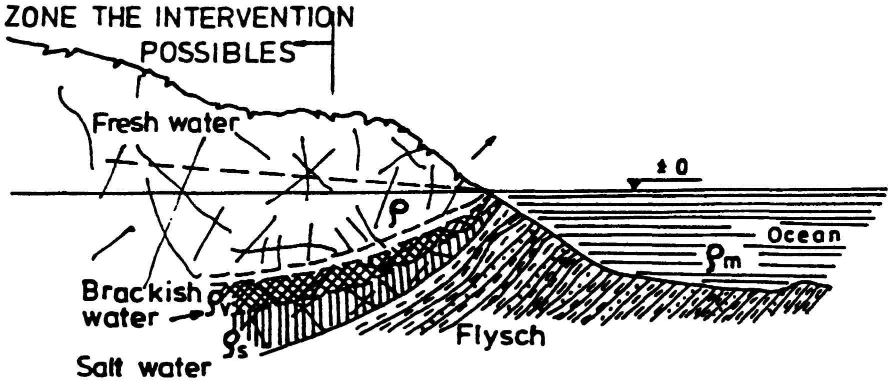

Figure 7. Coastal karst aquifer with incomplete barrier in the sea.

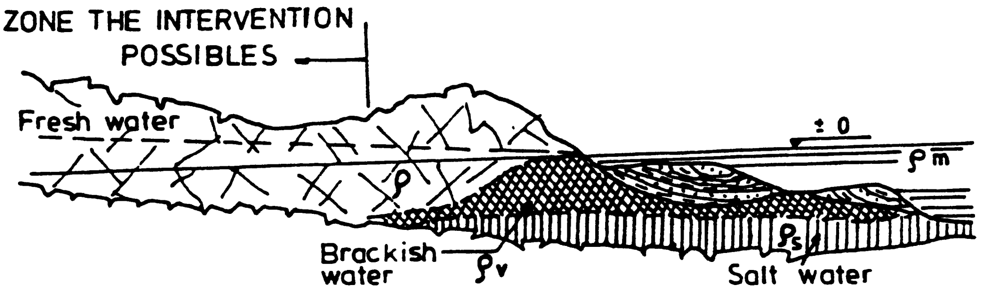

Figure 8. Coastal karst aquifer with hanging barrier.

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 relavant 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 captture 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 depsoites and dune sands.

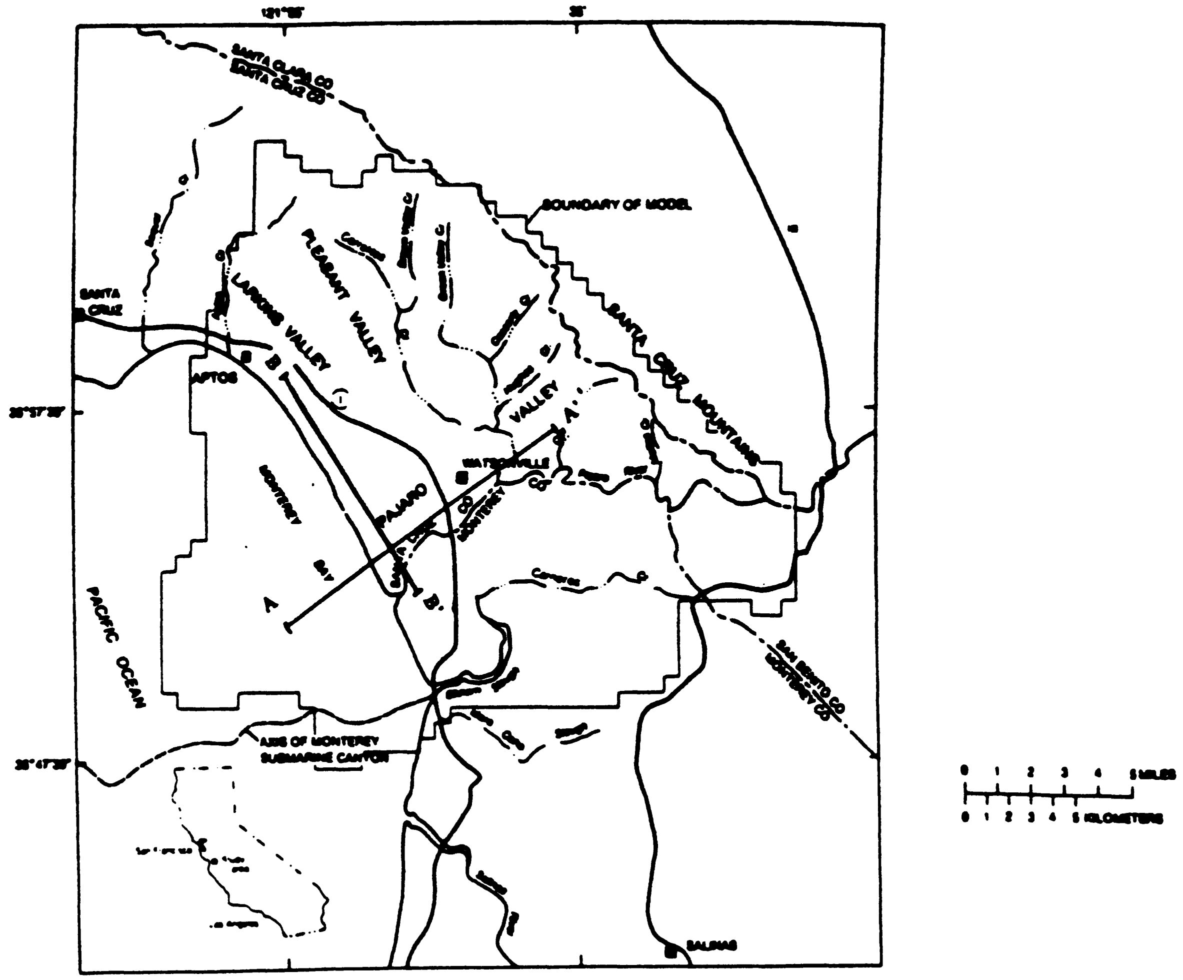

Figure 1. Location map of Pajaro Valley with cross-section locations (after Johnson *et al.*, 1988).

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.

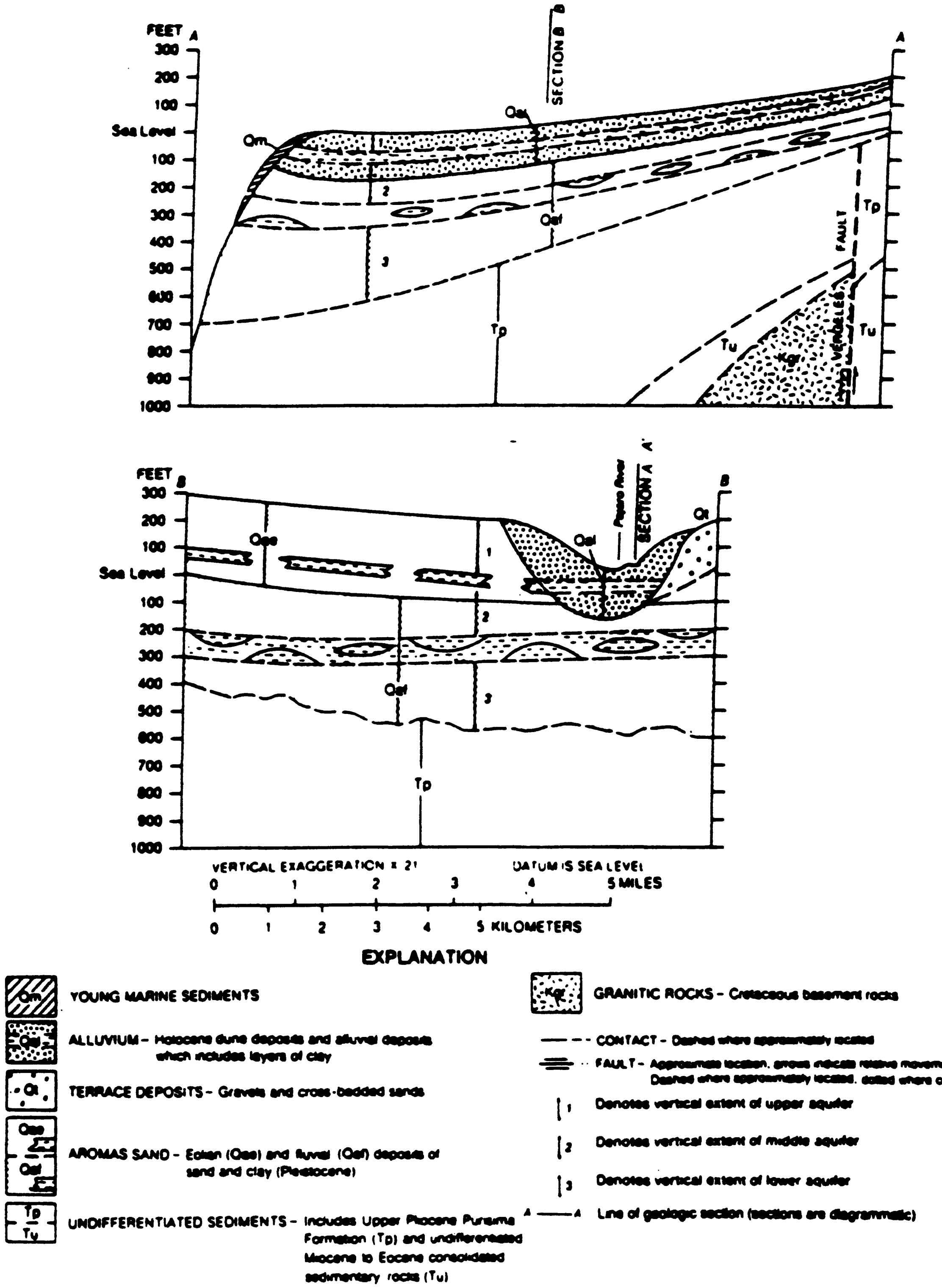

Figure 2. Geologic cross-sections (Johnson *et al.*, 1988).

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 x 10^5 m^3/d.

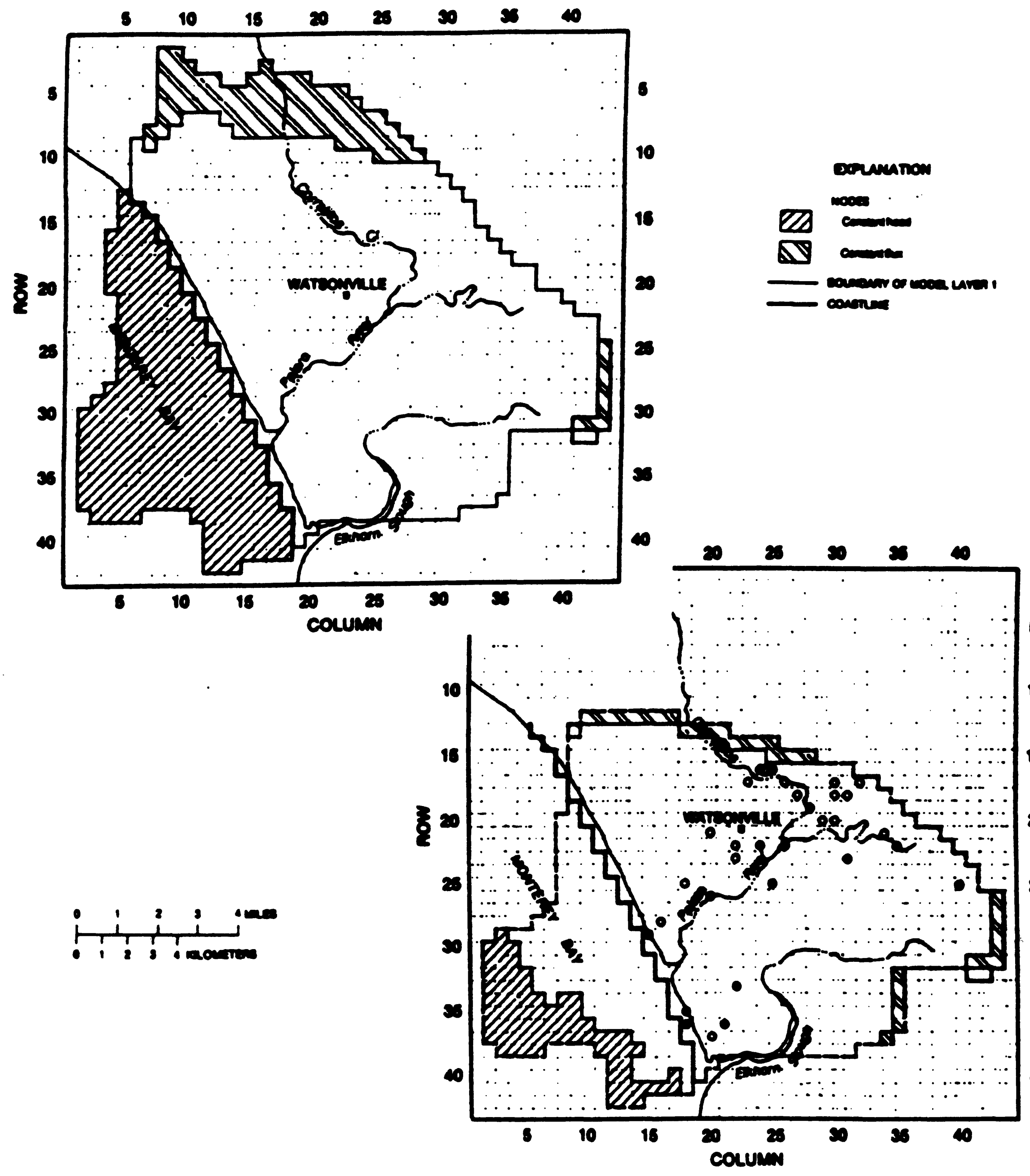

Figure 3. Finite difference grid for Layers 1 and 2; the Layer 3 grid is similar to that for Layer 2 (Johnson *et al.*, 1988).

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.

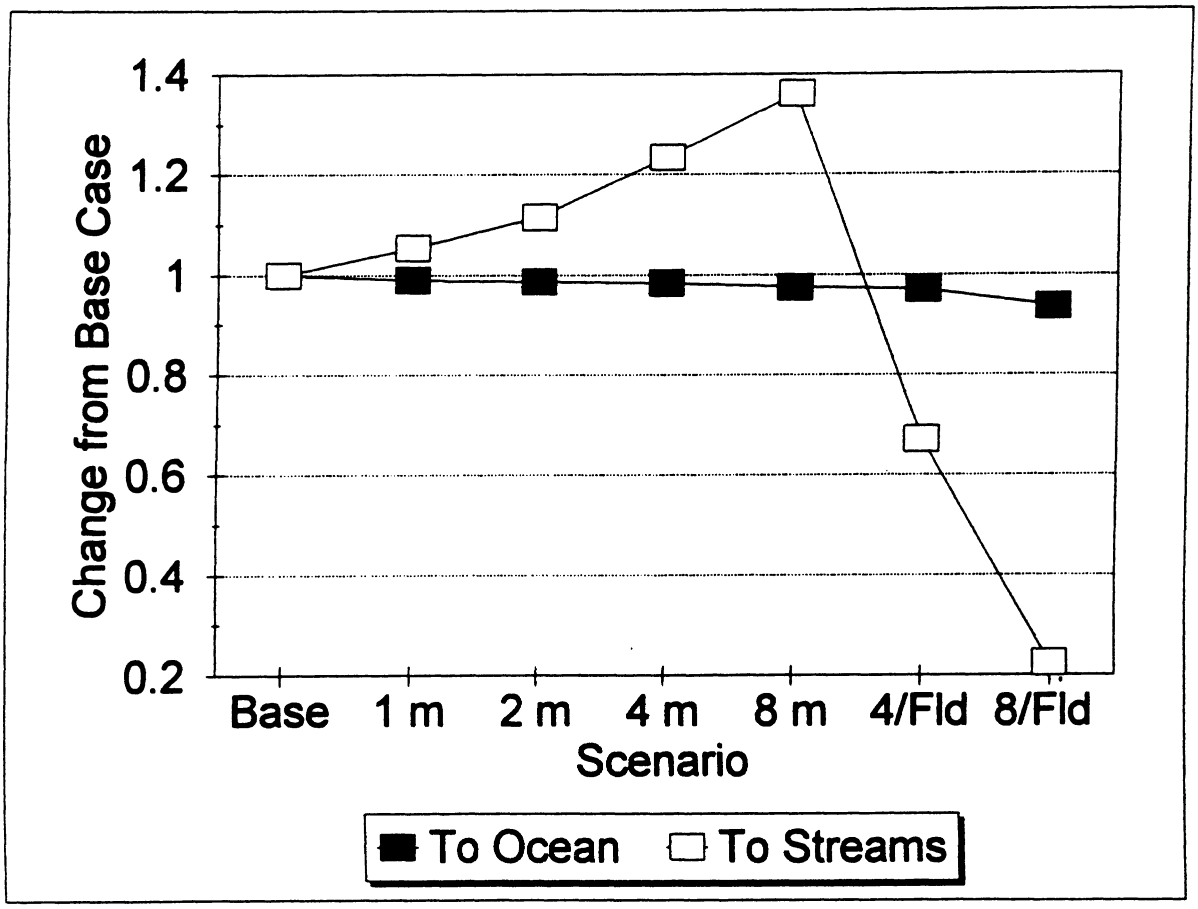

Figure 4. Results for discharge to the ocean of sea level change scenarios (without and with flooding), relative to the base case discharge.

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.

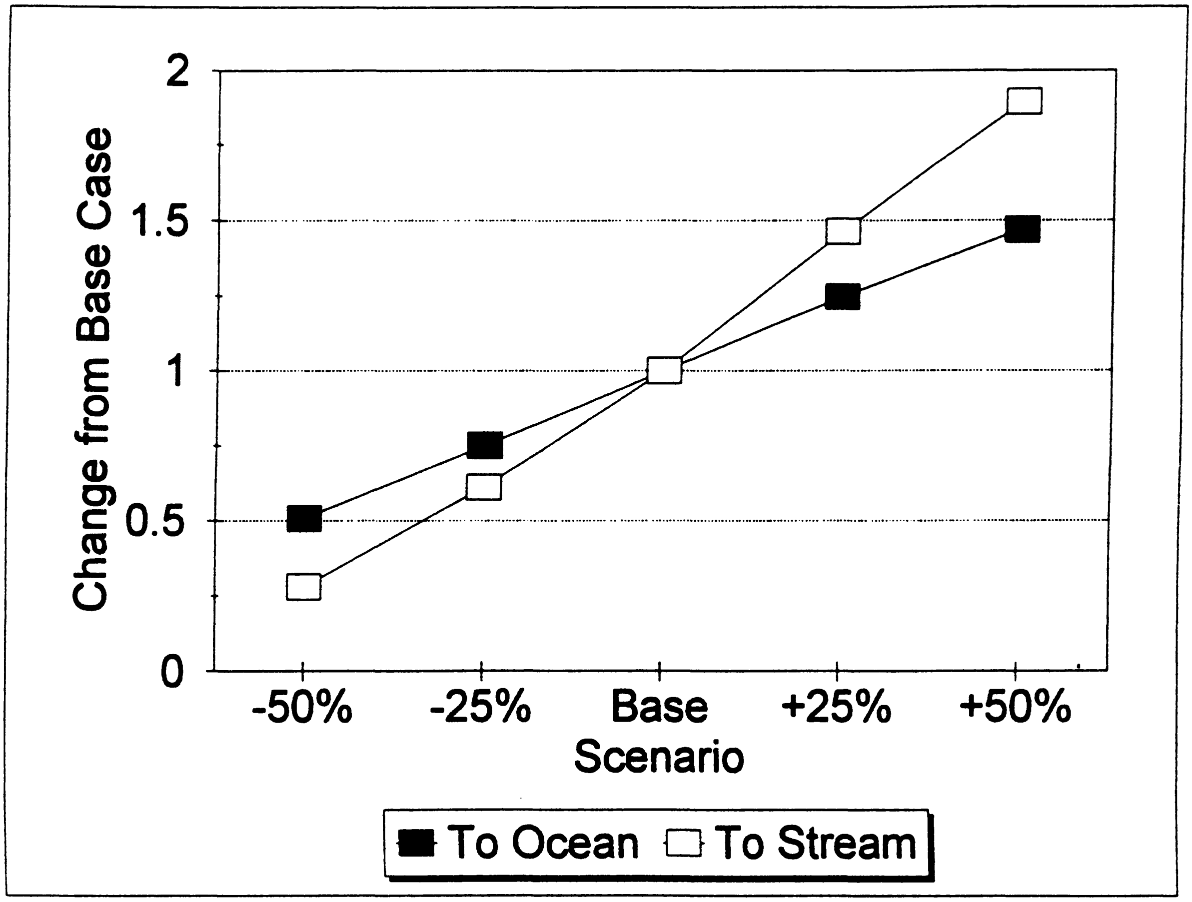

Figure 5. Results for discharge to the ocean of scenarios for changes in recharge, relative to the base case discharge.

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.

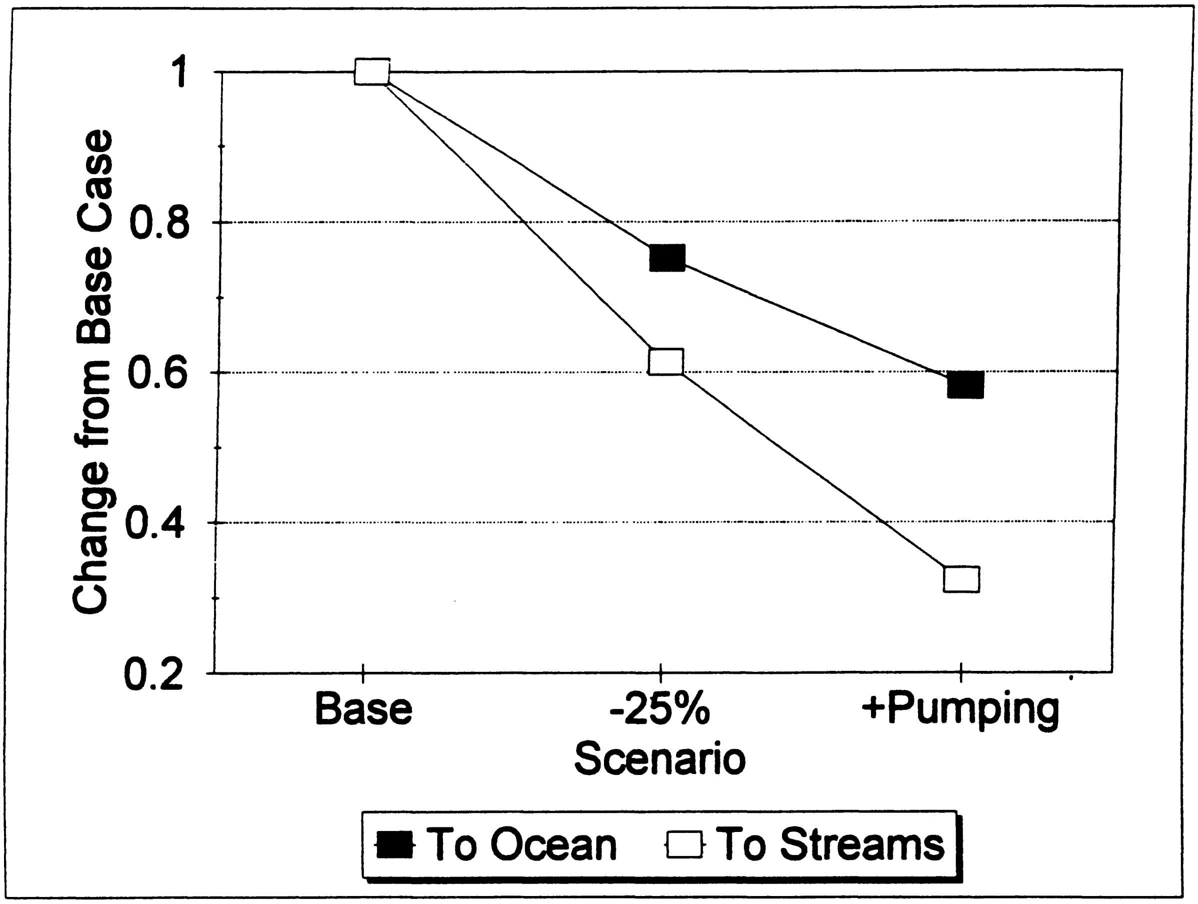

Figure 6. Results for discharge to the ocean of scenarios of 25% decreased recharge (without and with pumping) relative to the base case discharge.

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).

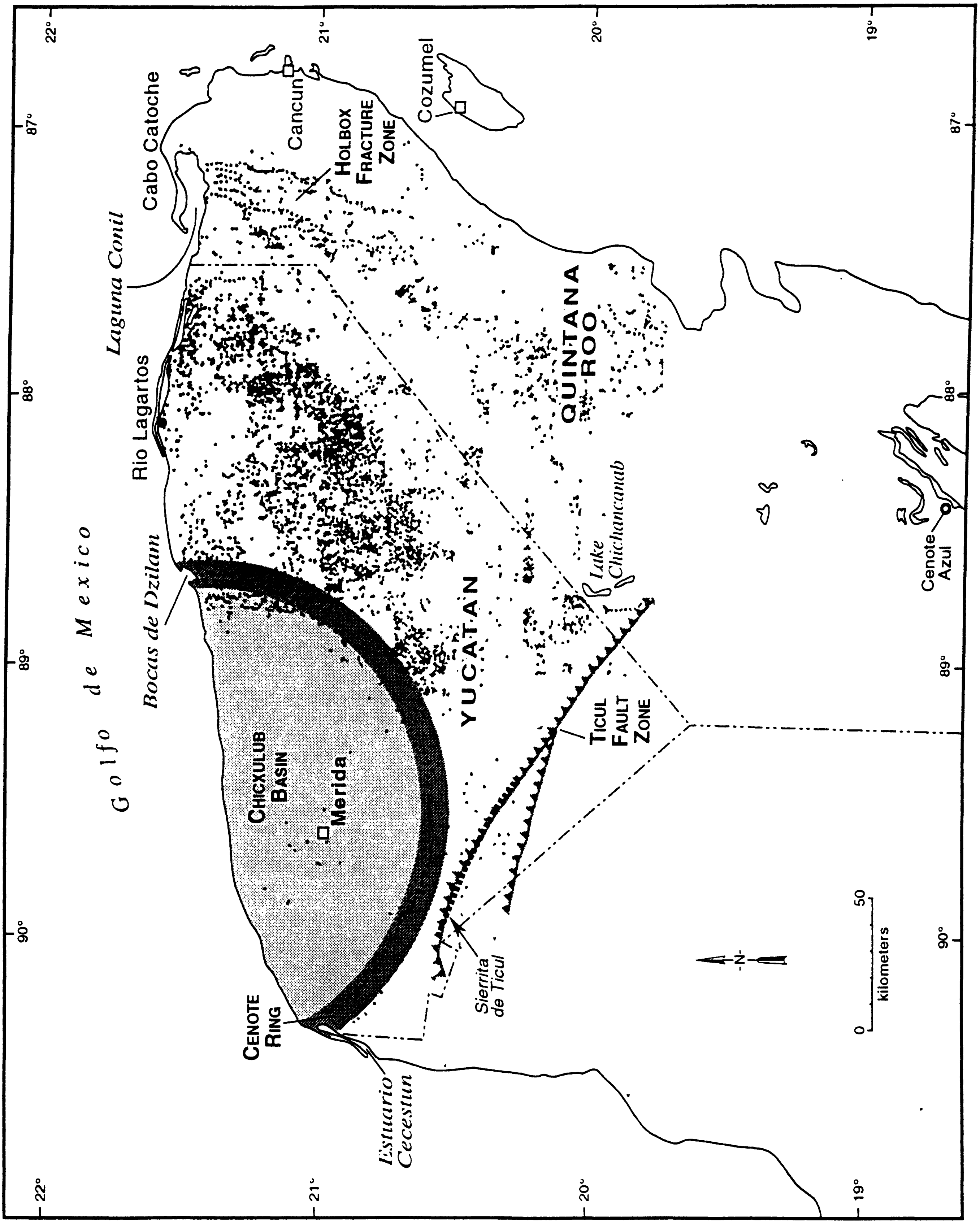

Figure 1. Northern Yucatan Peninsula showing the Cenote Ring, Chicxulub sedimentary basin, Ticul Fault, and Holbox Fracture Zone (as a set of aligned cenotes). Gray dots are cenotes (from Hildebrand *et al.*, 1995). Highest concentration of cenotes (east of Cenote Ring and south of Rio Lagartos) marks 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 agressively 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 CO_2 result in precipitation of $CaCO_3$ 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 sytem that drains a region of evaporite. Its water contains only 1.25 meq/l of Cl but 25.75 meq/l of SO_4 indicating positive flow preventing mixing with seawater. Possibly, groundwater here is moving through a deep, cavernous system.

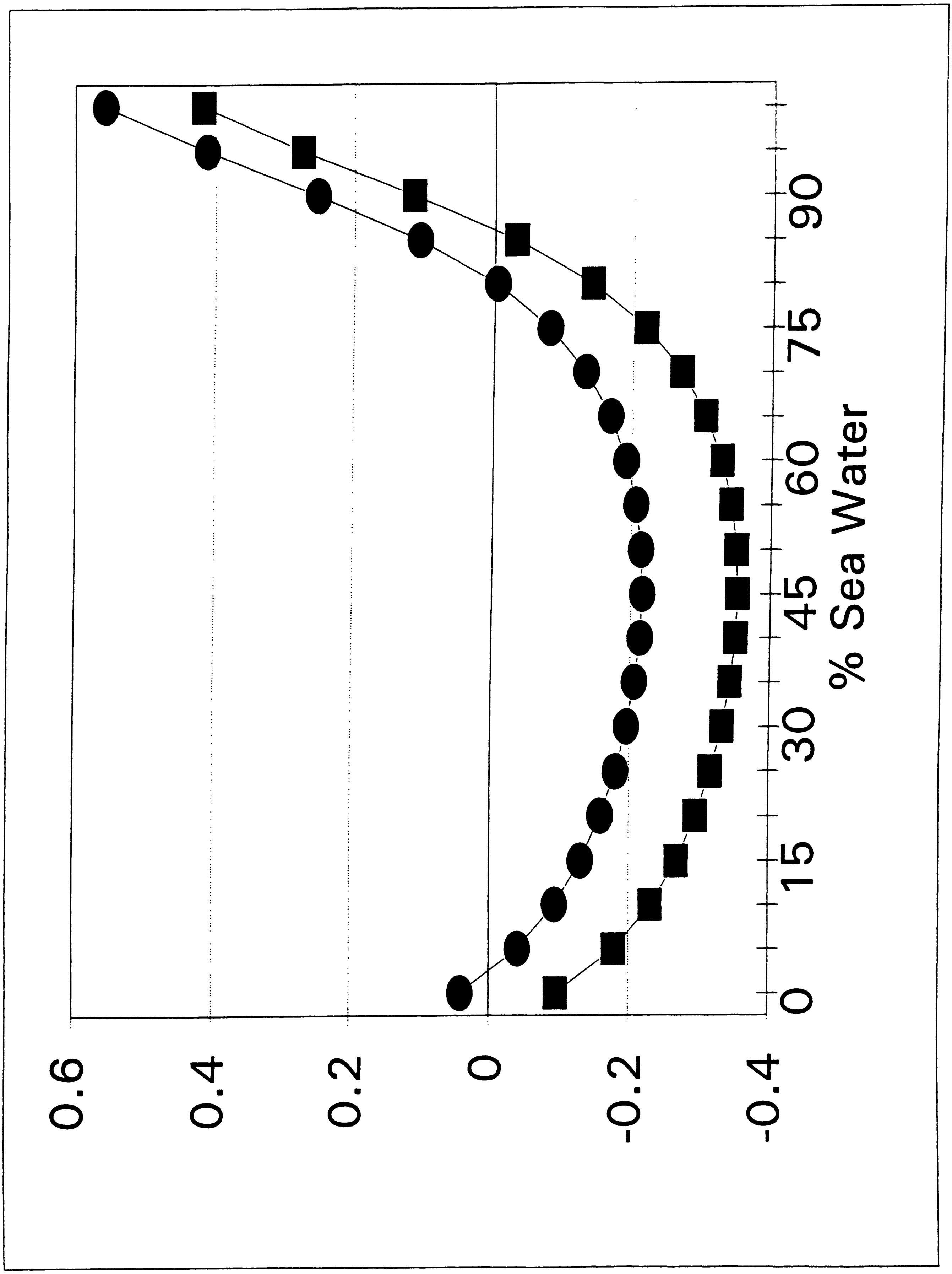

Figure 2. Calculated result (using SOLMIN) of mixing Kopoma groundwater with seawater. Saturation index $=\mathrm{Log}\{[\mathrm{Ca}^{++}]\mathrm{x}[\mathrm{SO}_4^{-}]\}/\mathrm{Ksp}$. Positive values indicate supersaturation; negative values indicate undersaturation.

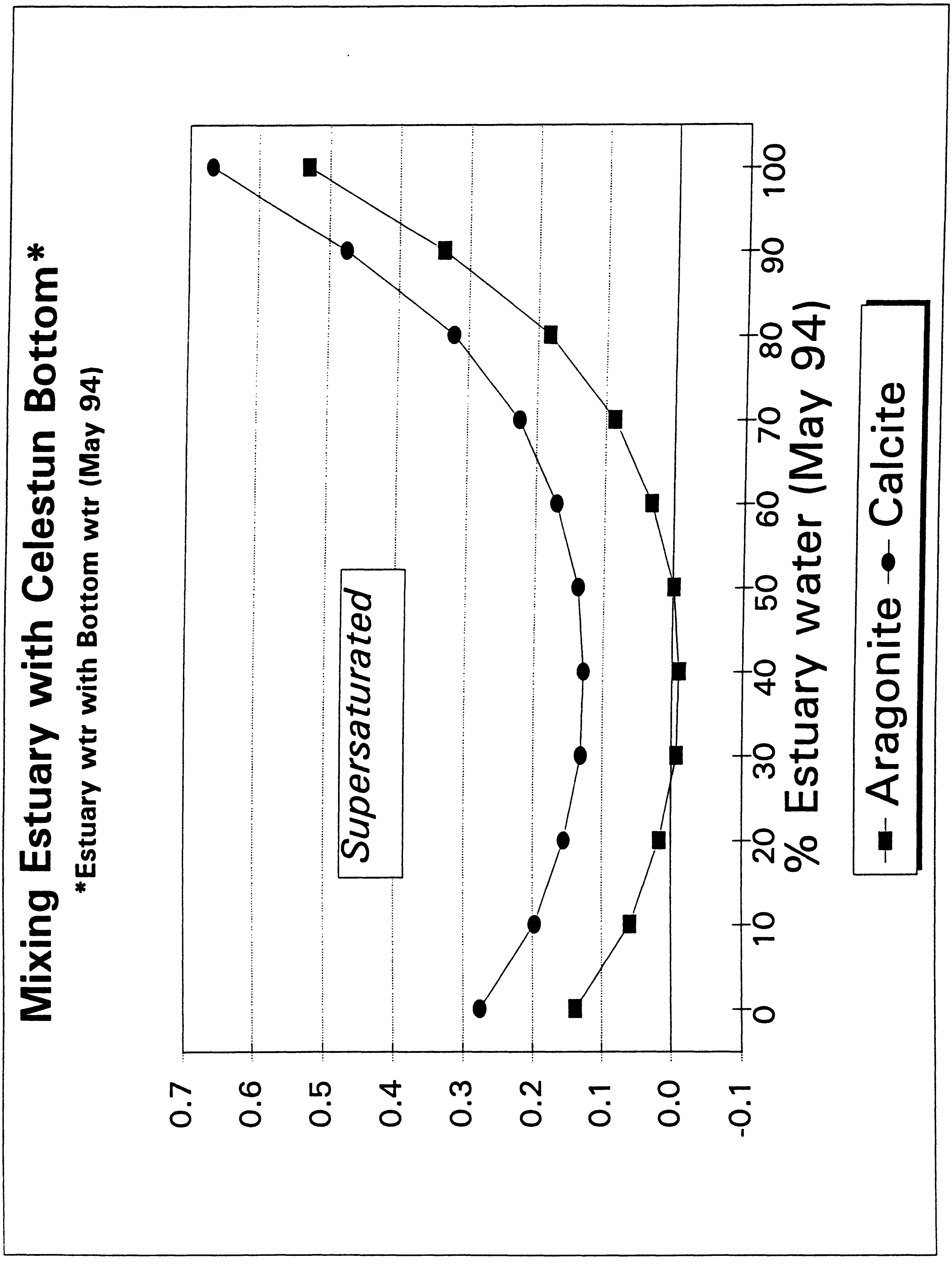

Figure 3. Calculated result of mixing surface water from Esterio Celestun with estuarine groundwater.

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^{222}Rn AS A POWERFUL TOOL FOR SOLVING HYDROGEOLOGICAL PROBLEMS IN KARST AREAS

TADOLINI, T.and M. SPIZZICO

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.

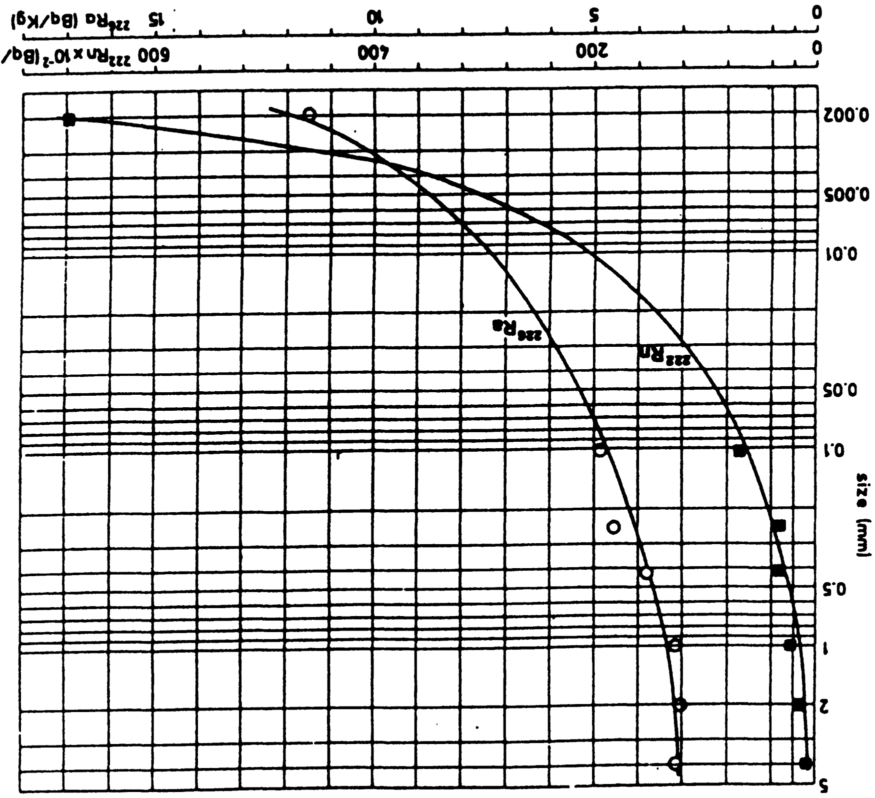

Figure 1. The dimensions of crushed calcareous material as related to ^{226}Ra concentrations in the rock and to ^{222}Rn in water, respectively.

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 (DellÁnna, 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_2S0_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).

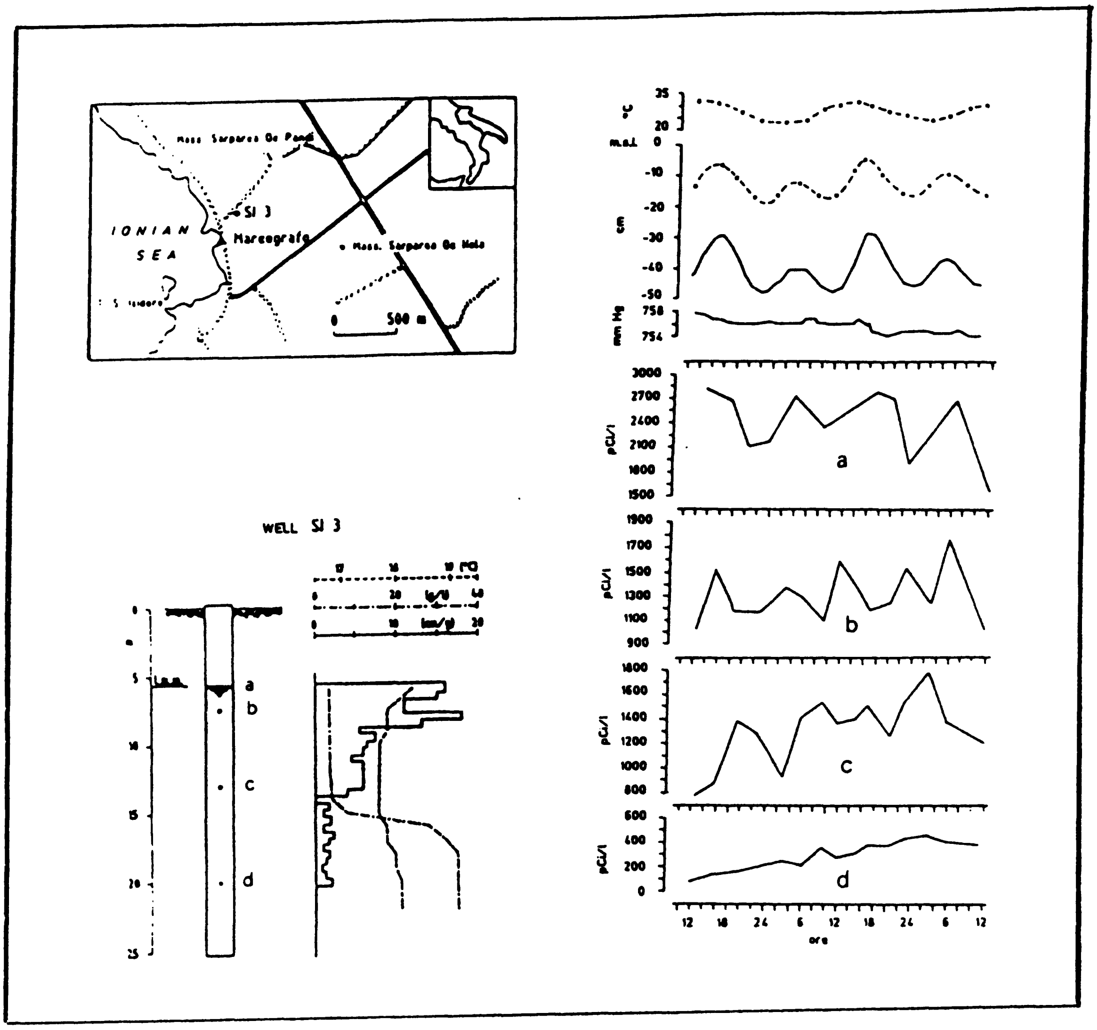

Figure 2. Time course of ^{222}Rn concentrations at different water levels selected on the basis of data obtained from temperature and salt logs and from the distribution of groundwater velocities as measured along the water column inside the borehole; trends of air temperature (Ta), depth of watertable (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.

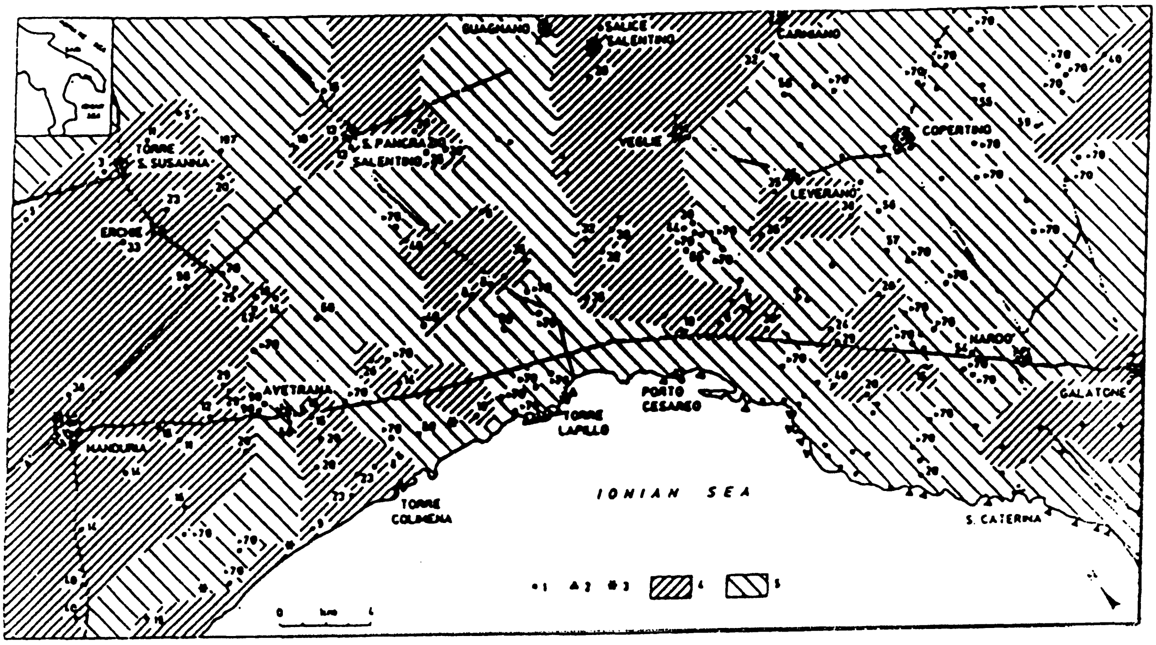

Figure 3a. Distribution of specific yield values (Qsp) providing a good representation of permeability in the aquifer's investigated section (I. borehole; 2. coastal spring; 3. subaerial spring; 4. Qsp < 50 l/s.m; 5. Qsp > 50 l/s.m).

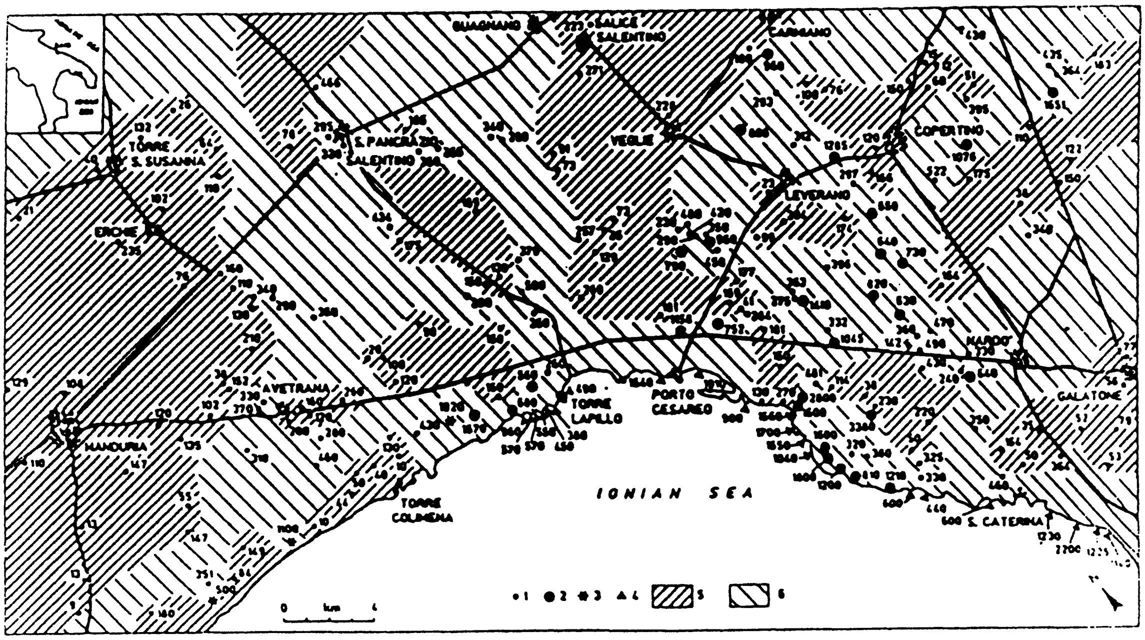

Figure 3b. Distribution of 222Rn concentration levels in groundwater (1. borehole; 2. borehole with 222Rn concentration levels > 600 pCi/l; 3. subaerial springs; 4. coastal springs; 5. areas characterised by the presence of 222Rn at concentrations <270 pCi/l; 6. areas with ^{222}Rn concentrations >270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

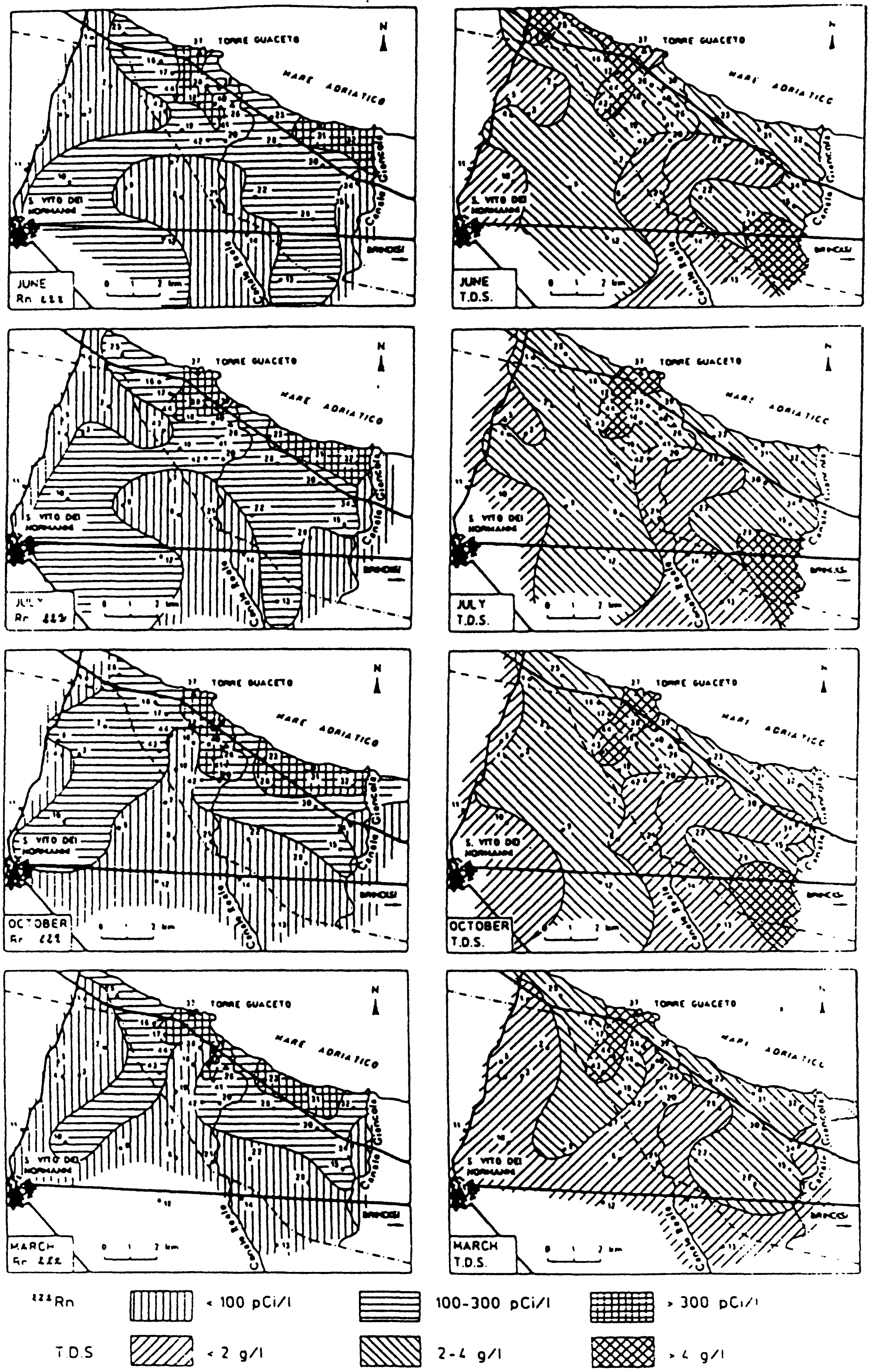

Figure 4. Different distributions of ^{222}Rn and T.D.S. concentrations in the karstic aquifer during the periods of observation, as follows:
* a period of active water withdrawal and low supply from upstream reaches (June);
* a period of peak pumping and of almost complete groundwater depletion (July);
* period roughly coinciding with termination of the pumping season and with lowest level of groundwater depletion (October);
* no pumping and groundwater recharge phase (March).

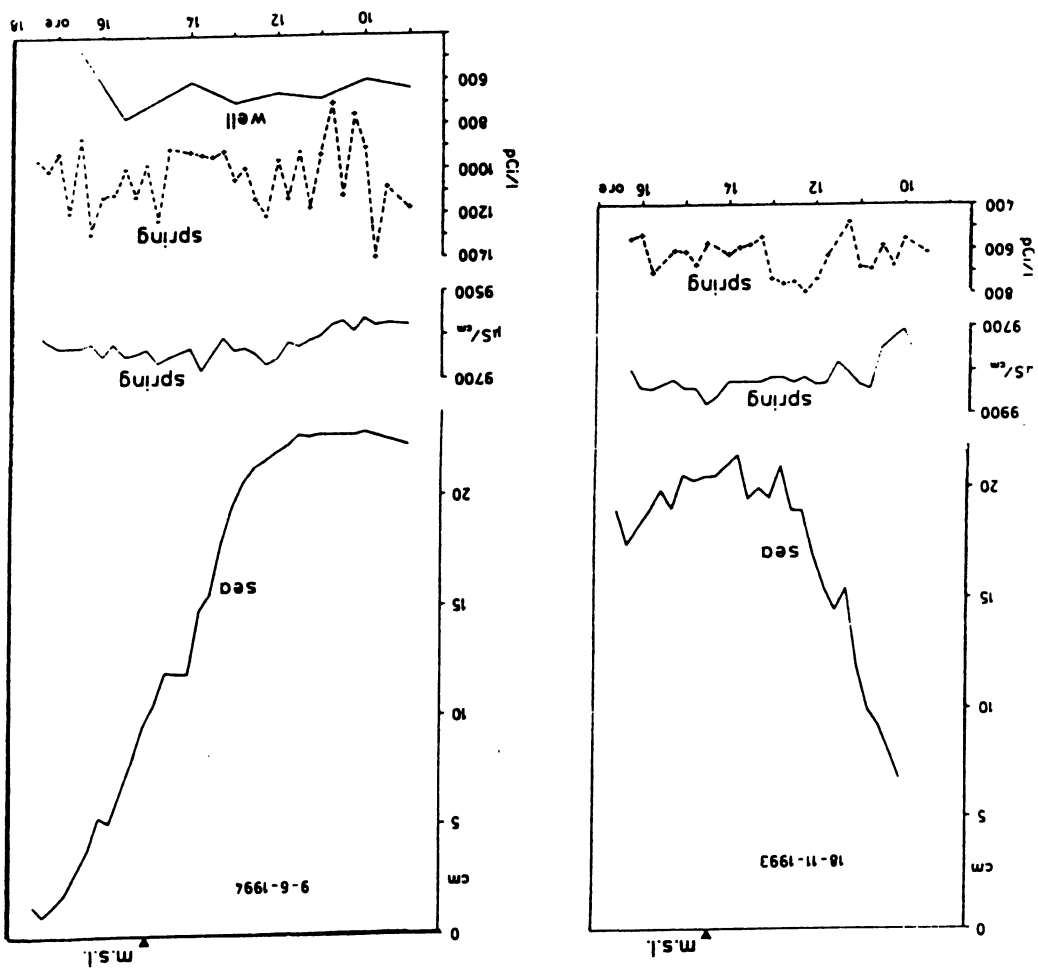

Figure 5. Changes in ^{222}Rn concentrations correlate with changes of sea level and of salt concentrations in the water flowing from a coastal spring and in that withdrawn from a well just inland from the shore. Subsequently lowering sea levels again mobilise the groundwater body resulting into increased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

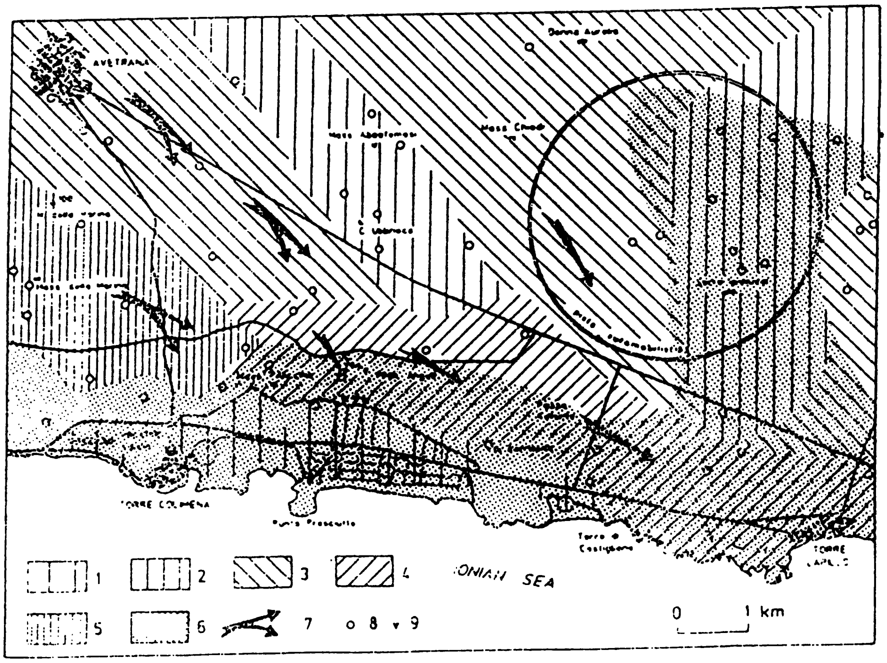

Figure 6a. Map of subterranean water circulation: l. preferential flow areas essentially originating from direct groundwater supply; 2. preferential flow areas mainly developed along large and deep circuits strongly conditioned, among other elements, by the barrier to free seaward outflows imposed by 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.

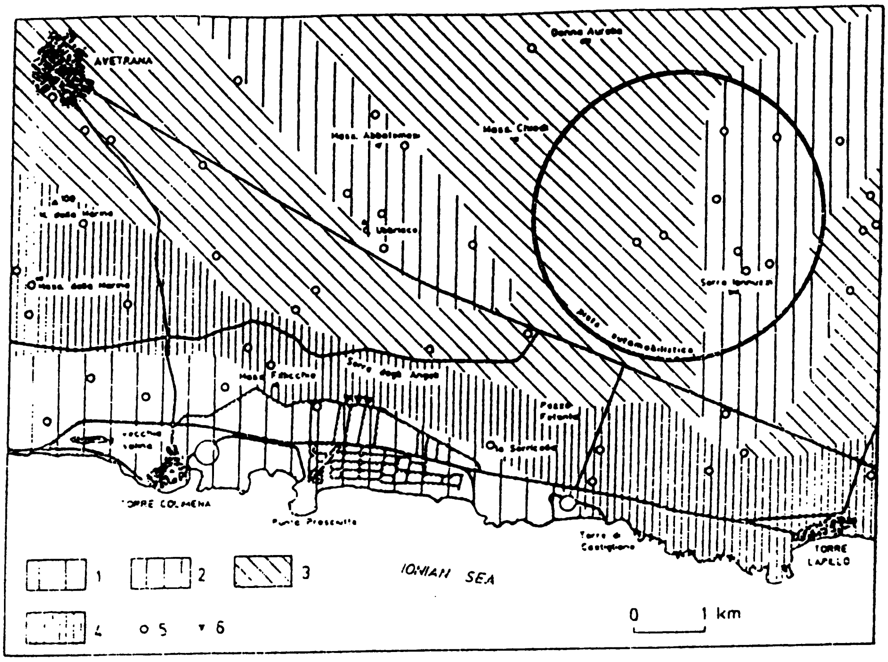

Figure 6b. Map of groundwater mobility as assessed by the radioisotope method. 1. Portion of aquifer where mobility ranges from zero to low owing to the obstruction to free seaward outflow imposed by the clay mass or else to the presence of scarcely permeable rocks (50-400 pCi/l); 2. Portion of aquifer 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.

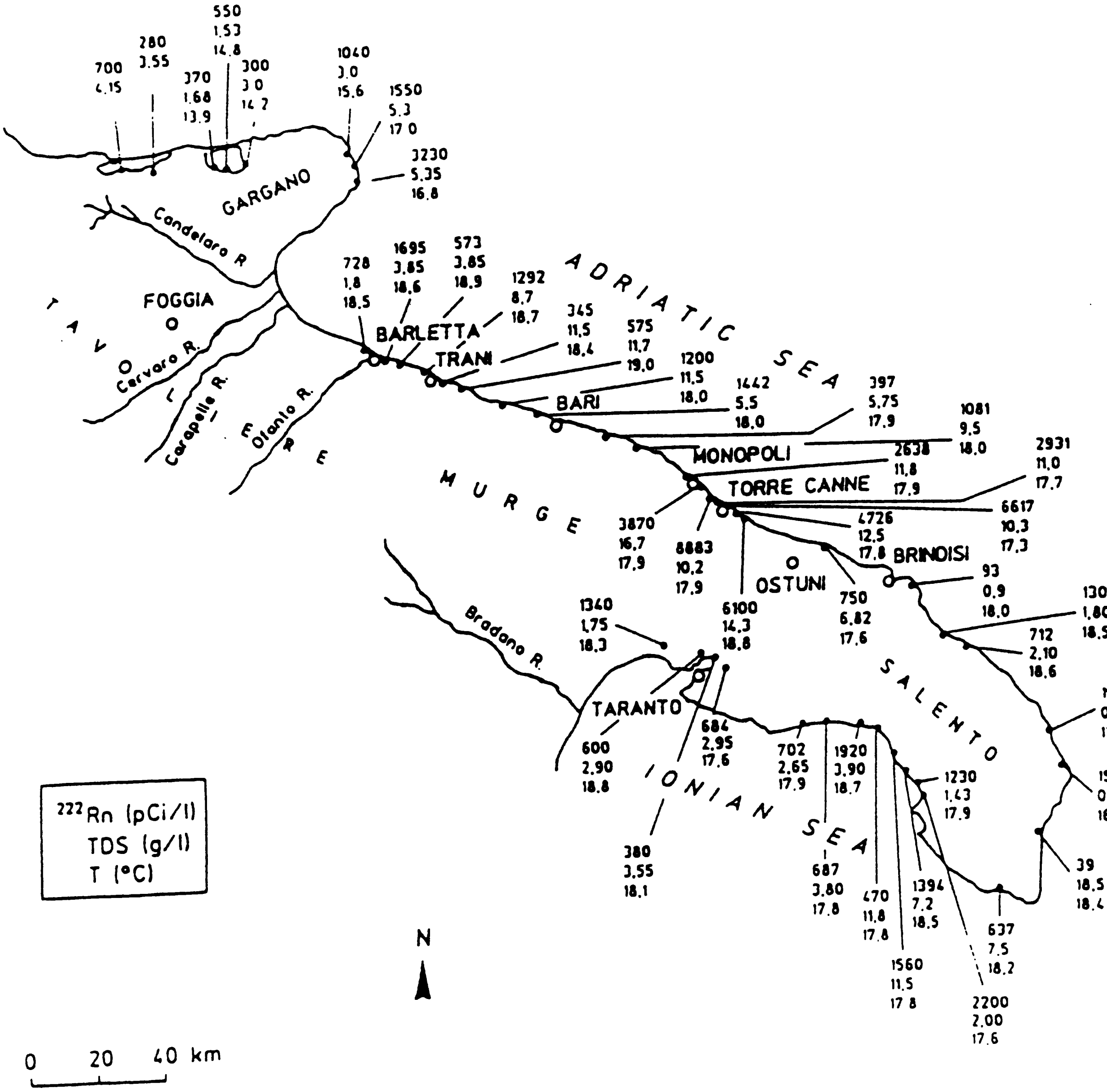

Figure 7. Mean value of ^{222}Rn concentrations in the waters of the main coastal springs fed by karstic groundwater; mean values of T.D.S. (g/l) and temperature (°C) are also indicated.

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

This work was financially supported by MURST (60%-40%) and by CNR CE.R.I.S.T.

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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.

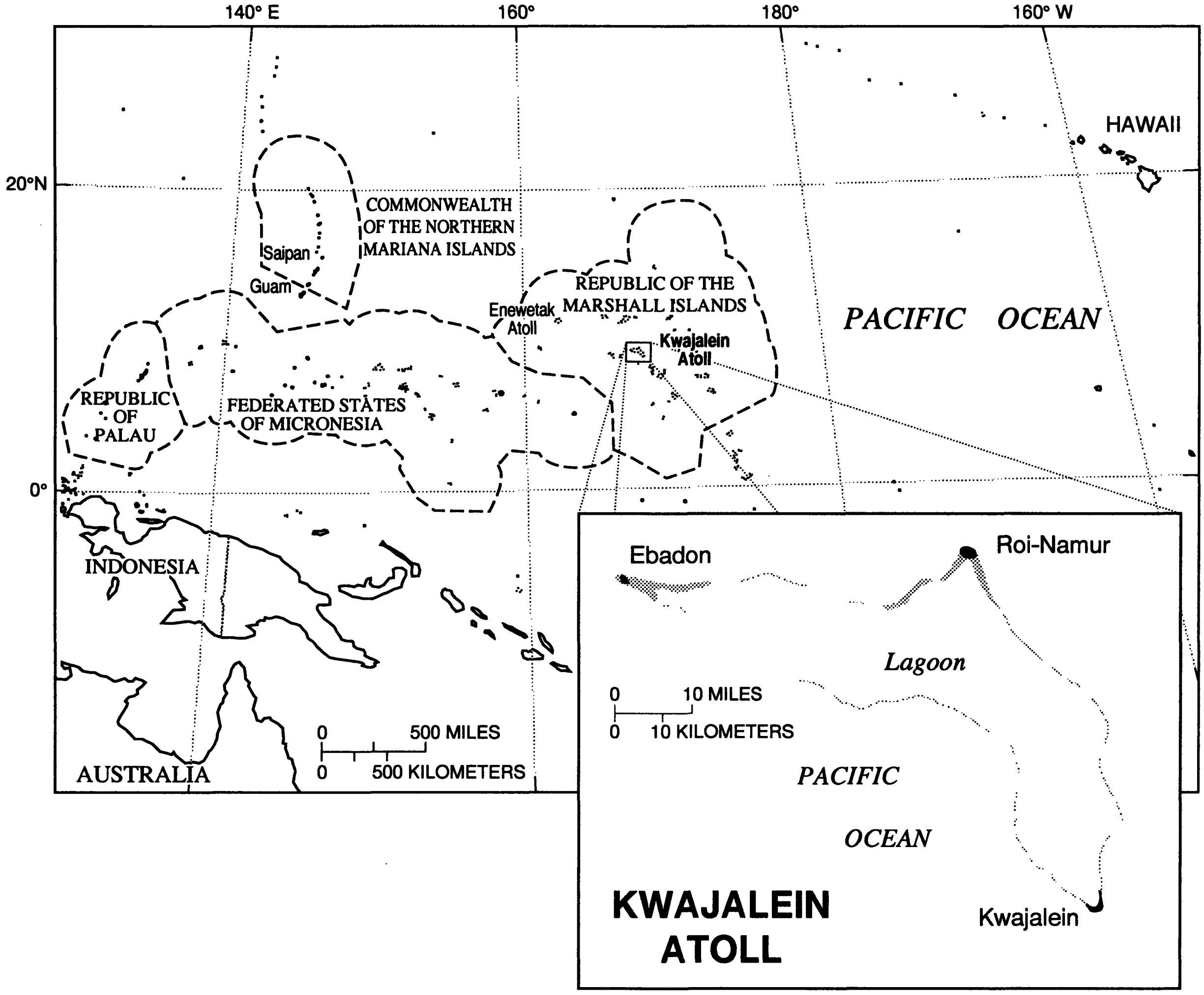

Figure 1. Location of Kwajalein Atoll and Kwajalein Island, Republic of the Marshall Islands.

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 L d^{-1} m^{-1} on the ocean side of the island and 790 L d^{-1} 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 (Cl^-<250 mg/L), with an average concentration of 37 µM, and decreased with increasing salinity. DIP concentrations averaged 0.35 µM in freshwater and rose to 1.0-1.6 µM in waters of intermediate salinity (5,000-15,000 mg/L Cl^-). If groundwater discharging at the shoreline is assumed to be fresh, the fluxes of DIN and DIP are $4x10^4$ and $3x10^2$ µmol d^{-1} m^{-1} on the ocean side of the island and $3x10^4$ and $3x10^2$ µmol d^{-1} 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 $4.8x10^7$ L d^{-1} 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 µM. The wave set-up results in marine nutrient fluxes of $2x10^7$ and $5x10^6$ µmol d^{-1} 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 µm day^{-1} m^{-1} shoreline):		
	Groundwater	Seawater
DIN	$4x10^4$	$2x10^7$
DIP	$3x10^2$	$5x10^6$
Lagoon side (in µmoles per day for the 4500 x 100 x 2 m control volume):		
	Groundwater	Seawater
DIN	$1x10^8$	$9x10^8$
DIP	$1x10^6$	1x108

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 $2.1x10^6$ m^3 d^{-1} of seawater through the control volume, resulting in DIN and DIP fluxes of $9x10^8$ and $1x10^8$ µmol d^{-1}. In contrast, the total groundwater input of $3.5x10^3$ m^3 d^{-1} should result in DIN and DIP fluxes of $1x10^8$ and $1x10^6$ µmol d^{-1}. Thus, for our assumed control volume, the marine fluxes exceed the groundwater fluxes by 1 to 2 orders of magnitude (Table 1).

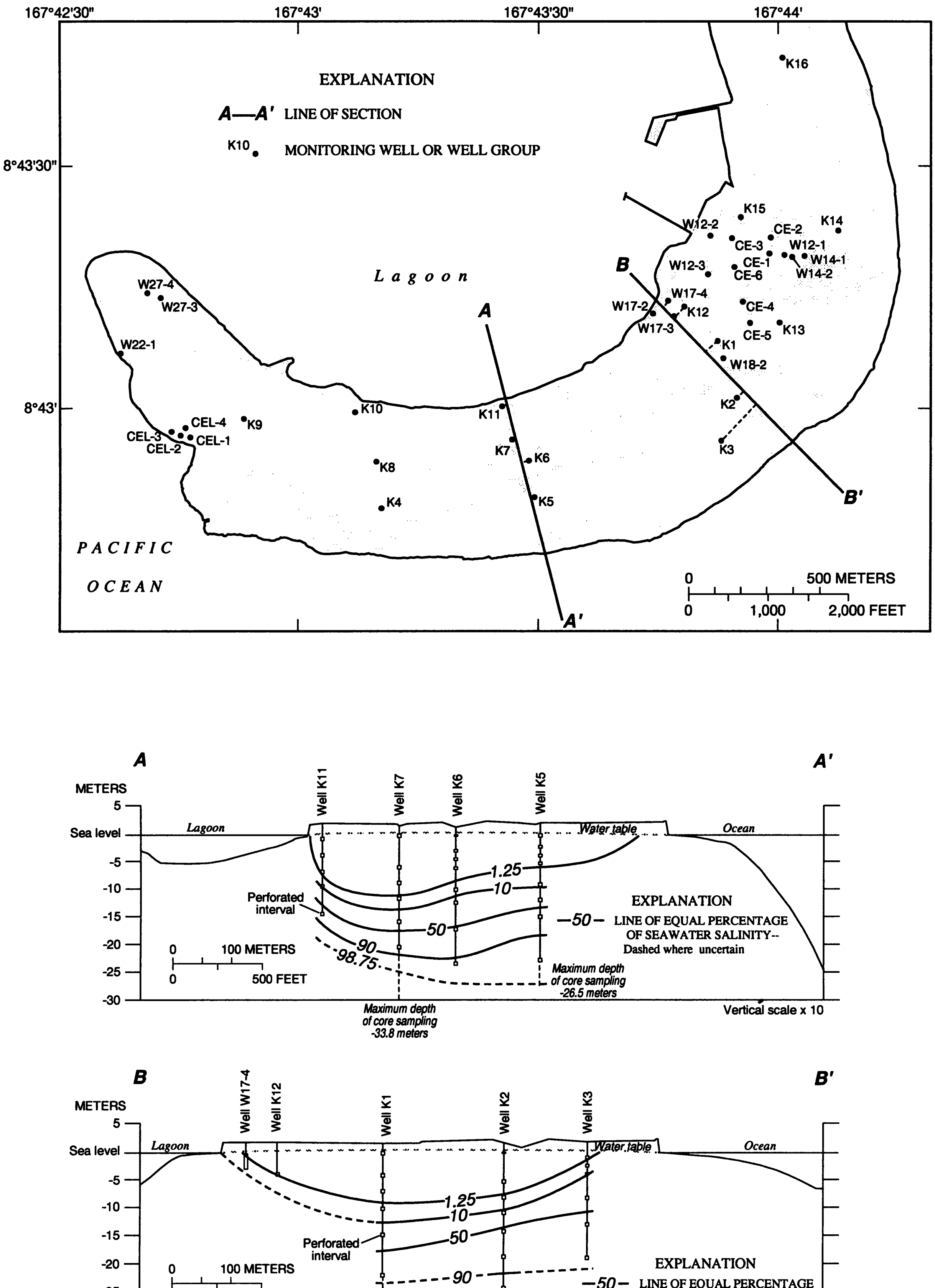

Figure 2. Location of monitoring wells and lines of section (top); and cross sections of chloride concentration as a percentage of seawater salinity (bottom).

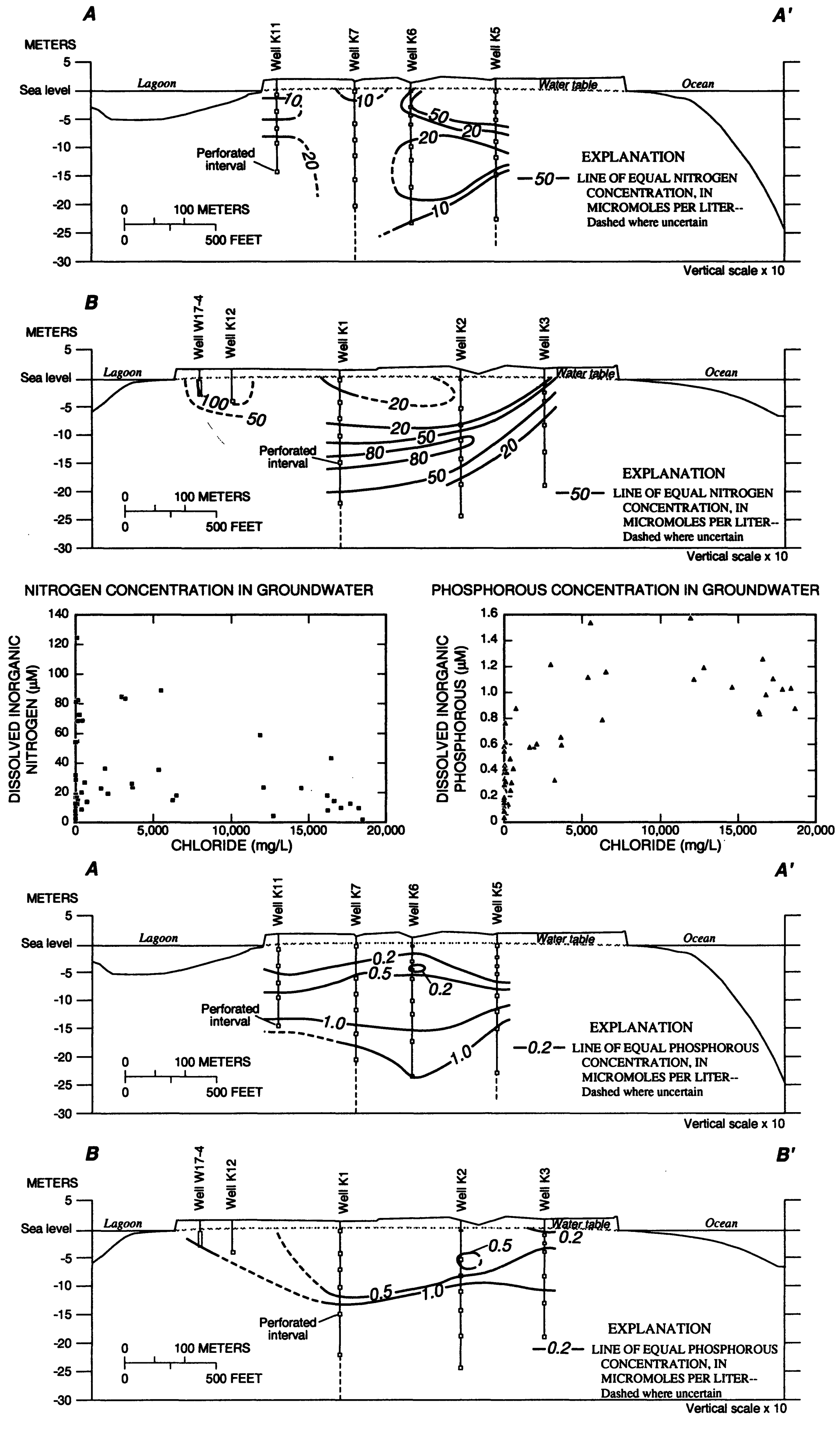

Figure 3. Cross sections of DIN (top) and DIP (bottom) concentration along lines of section *A-A'* and *B-B'*, and graphs of DIN and DIP versus chloride concentration.

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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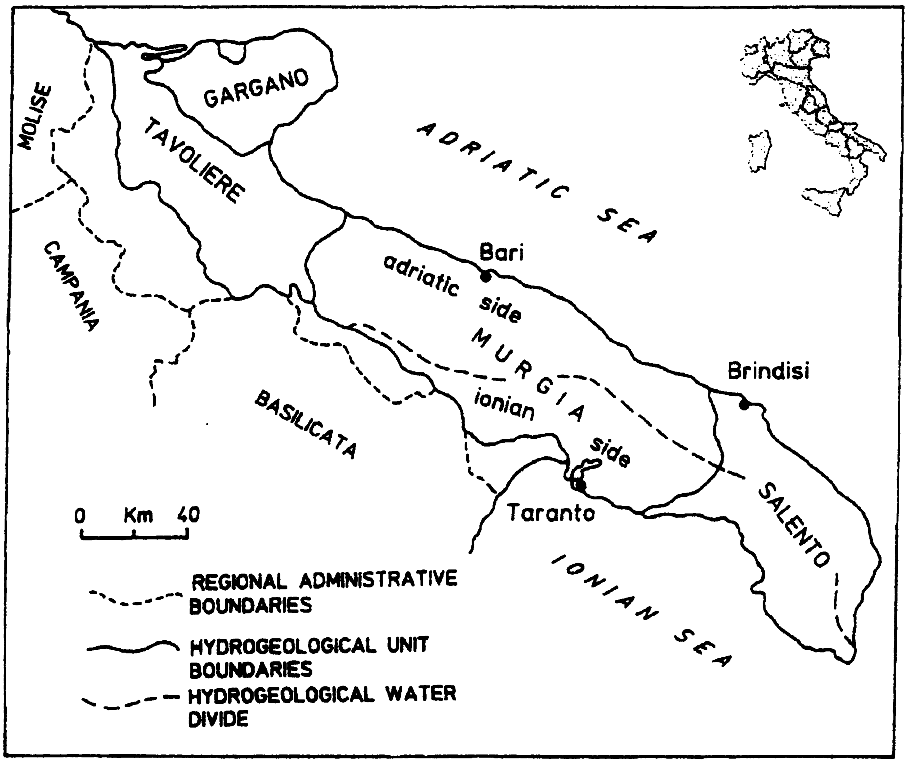
MULTITRACING APPROACH FOR THE IDENTIFICATION OF MAIN HYDROGEOLOGICAL PATHWAYS FEEDING COASTAL SPRINGS OF KARSTIC AQUIFER

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.

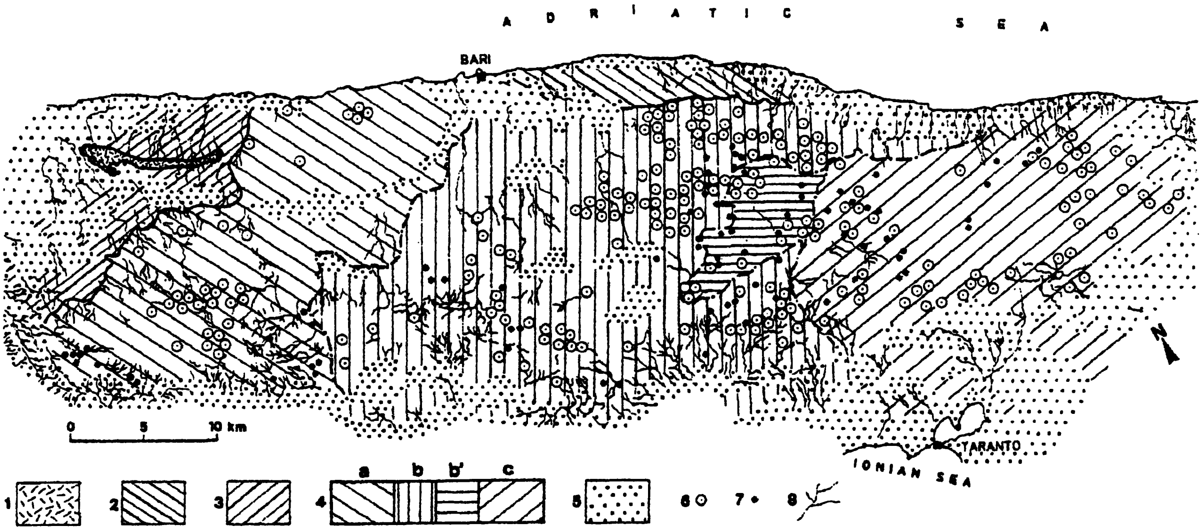
Murgia aquifer supplies most of the groundwater demand of the Apulia region. Groundwater discharges to the sea through coastal springs: composite fluxes of natural constituents and inland released pollutants are conveyed to the coasts.

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

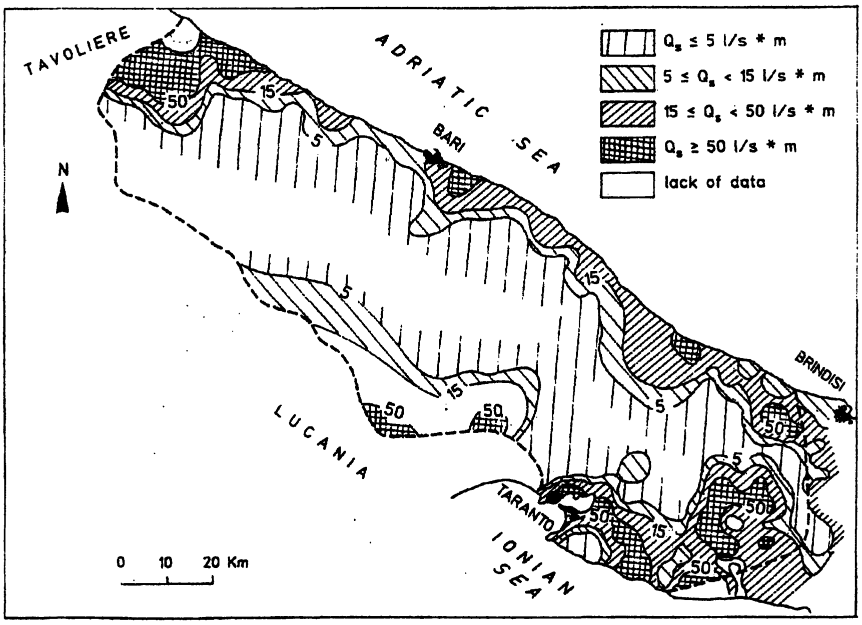
Geological characterisation of the aquifer represents the first step for the definition of the model of groundwater circulation.

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)

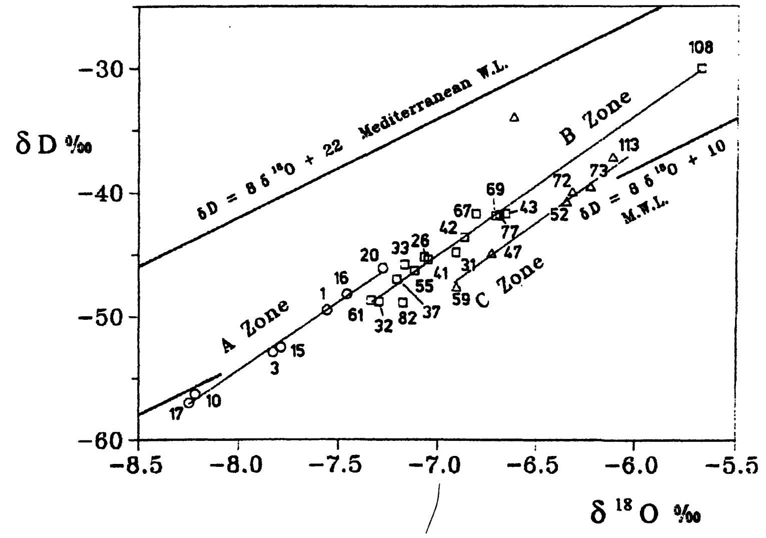
Karst solution is the main process leading to the development of conduits in the form of principal and secondary branches. Groundwater flows at the highest velocity along these branches (preferential pathways). Fissuring contributes to the overall permeability having also the hydraulic function of connecting 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.

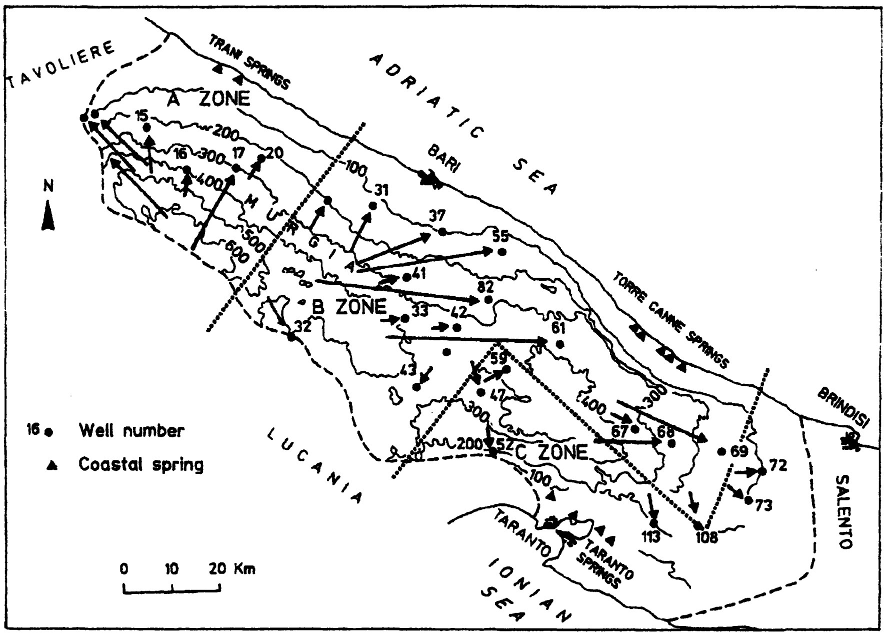
ENVIRONMENTAL TRACERS

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.



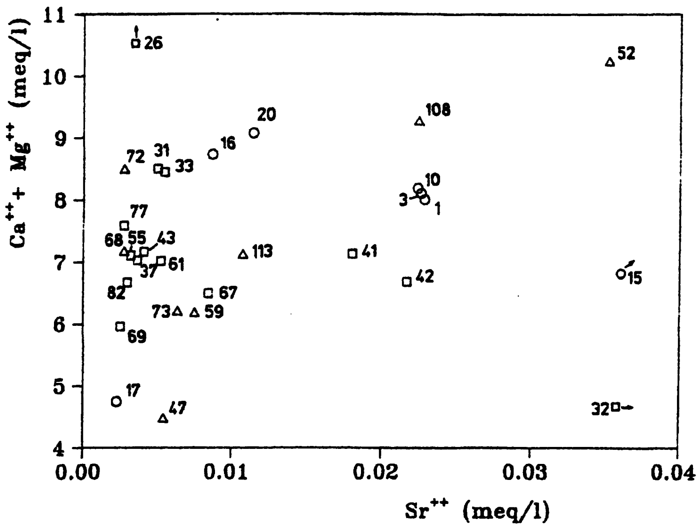
The distribution of the stable isotope data along three parallel lines is due to the climatic differentiation of the entire territory. For each climatic zone (A, B and C) the linear sample distribution is related to the change in altitude of the feeding area.

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.



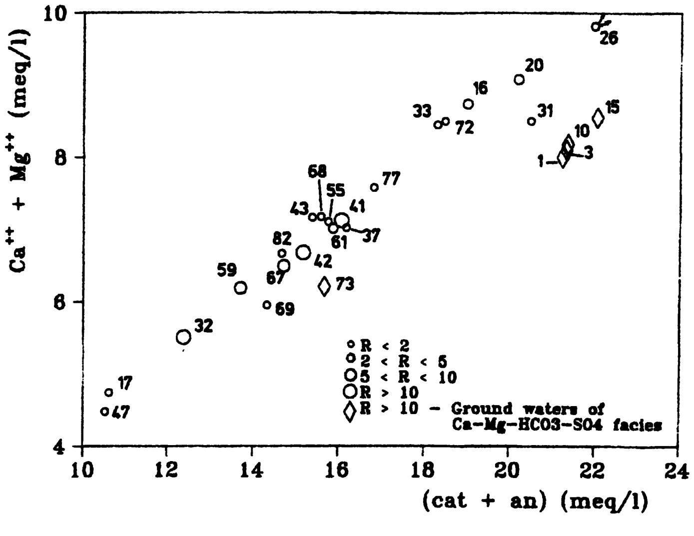
The arrows indicate the connections between each sampling point and the most probable recharge altitude: local characteristics of feeding water are likely to be preserved for long distances within the aquifer, as many of these groundwaters are restricted to preferential flow pathways. The notable differences 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.



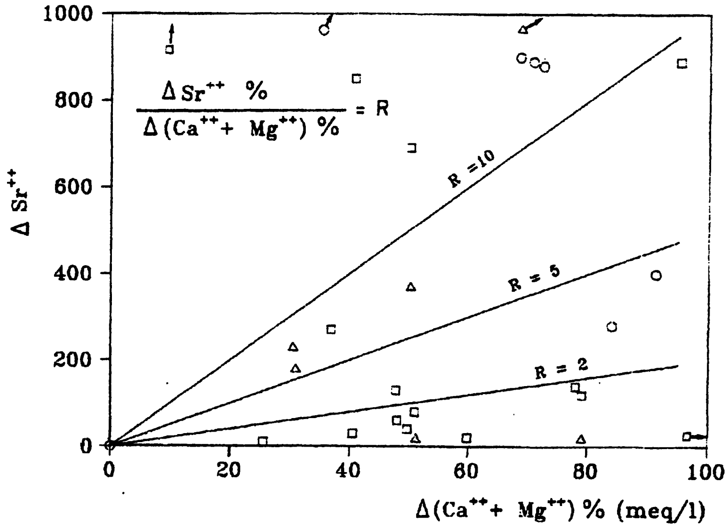
Due to incongruent dissolution of carbonate minerals, while Ca^{++} and Mg^{++} can be removed by precipitation, concentration of Sr^{++} tends always to raise: thus, the occurrence of numerous cycles of dissolution and re-precipitation can be recognised by high Sr^{++} concentrations. Among examined 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.



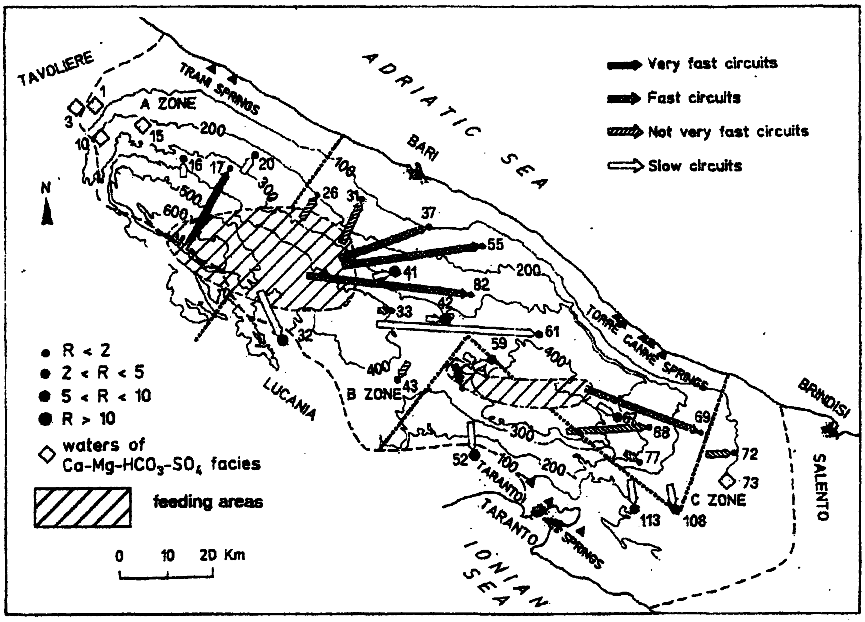
When water-carbonate rock interaction processes are the only processes determining the chemical evolution of ground waters, the increase of total salt content is linearly correlated to the growth of Ca^{++} and Mg^{++}: T.D.S. of samples out of the linear correlation is in fact influenced by evaporite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

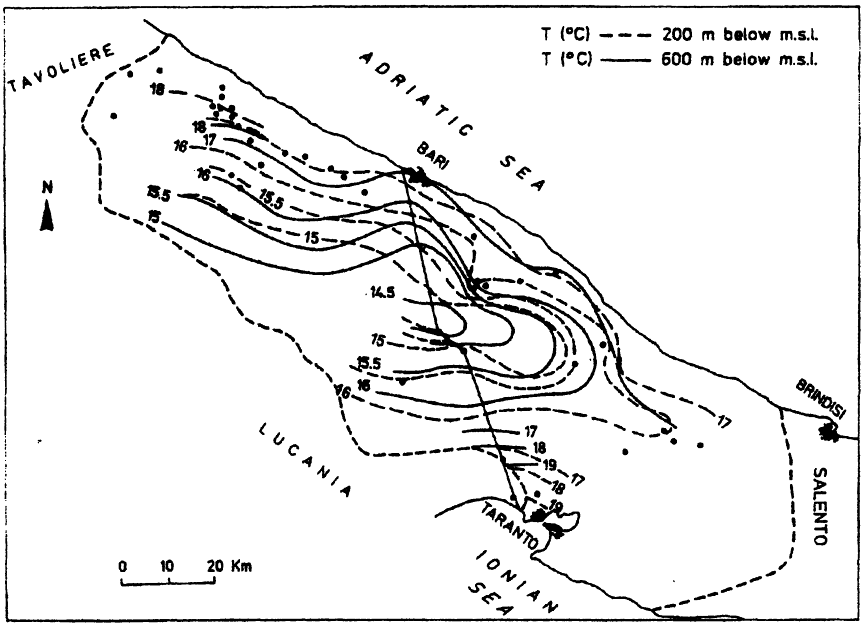


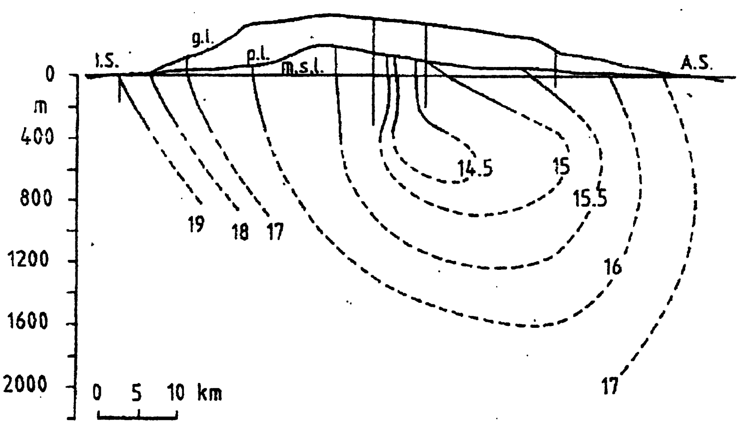
Groundwaters defined as having R > 2 (medium or high chemical maturity degree) belong to slow circuits; groundwaters with R < 2 (low maturity degree) pertain to fast circuits, distinguished in three levels of velocity. Most of the fast circuits originate from the two main feeding areas recognised in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

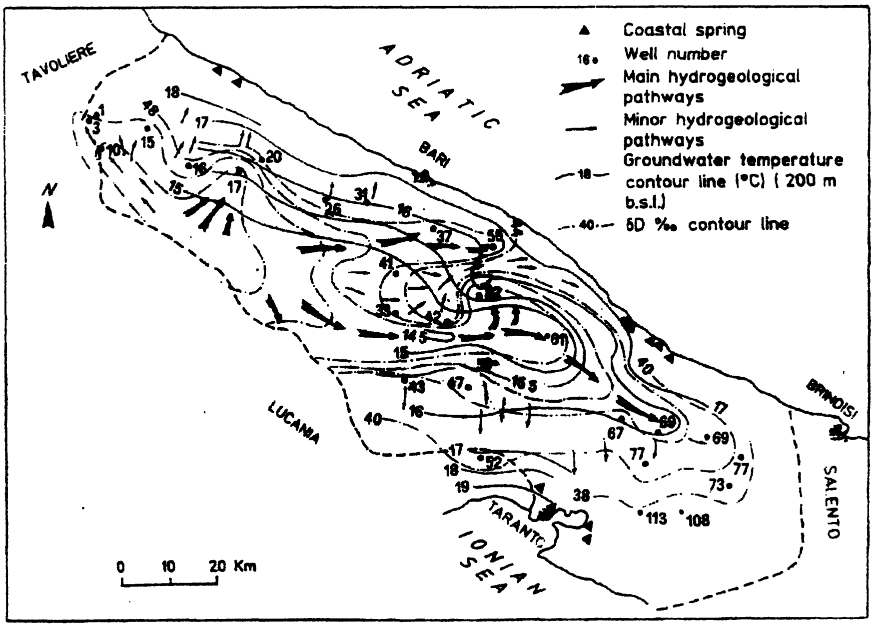
Particularly in an anisotropic aquifer, the reconstruction of iso-geothermal contours allows the main recharge areas and the preferential flow pathways to be recognised. The thermal gradient gives information on flow velocity and residence time of groundwaters: main discharge directions coincide with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

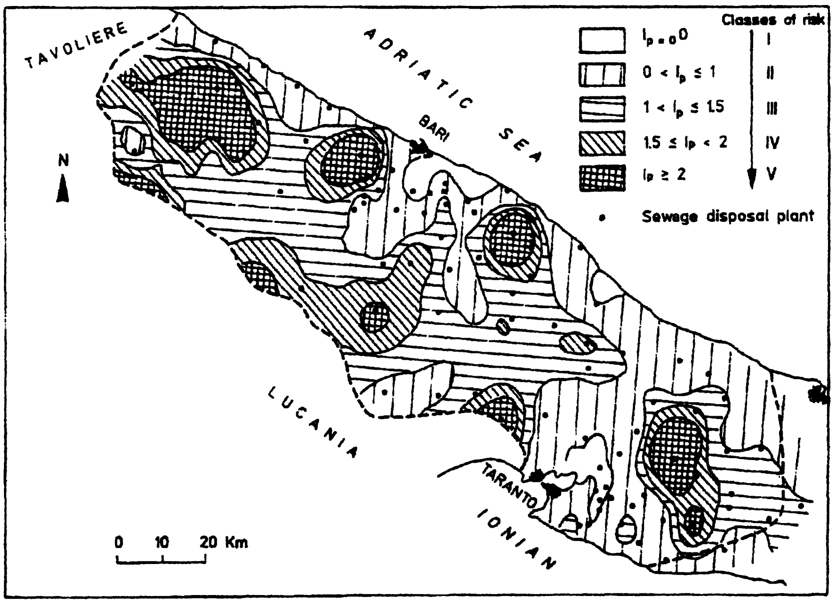
- Two fast groundwater flows, separated by a slow flow of local origin, originate from the recharge area located in the central part of the region, at an altitude ranging from 400 to 500 m. Upon reaching the coast, southward flowing groundwater contributes directly to two large concentrated springs belonging 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.

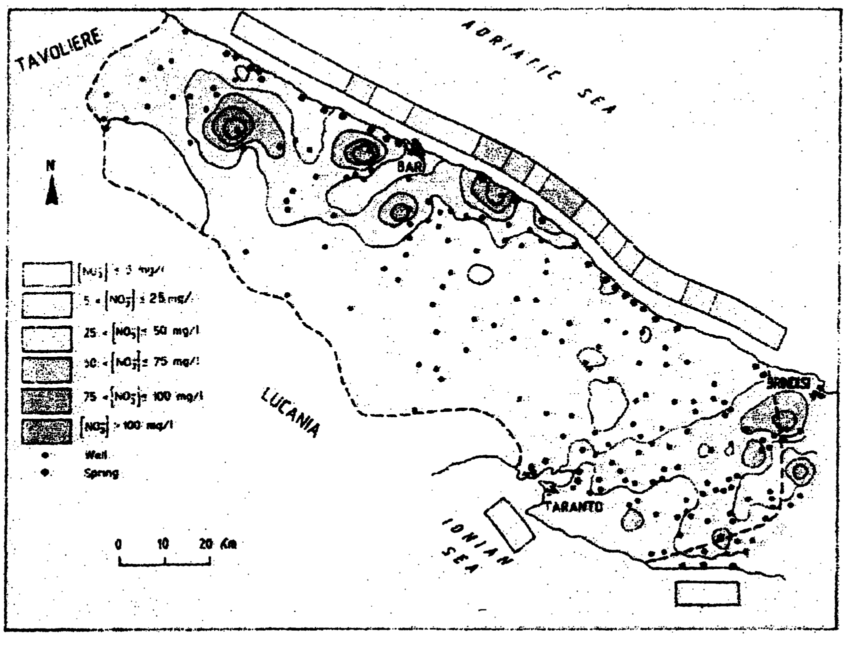
GROUNDWATER POLLUTION AND IMPACT ON COASTAL ENVIRONMENT

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.

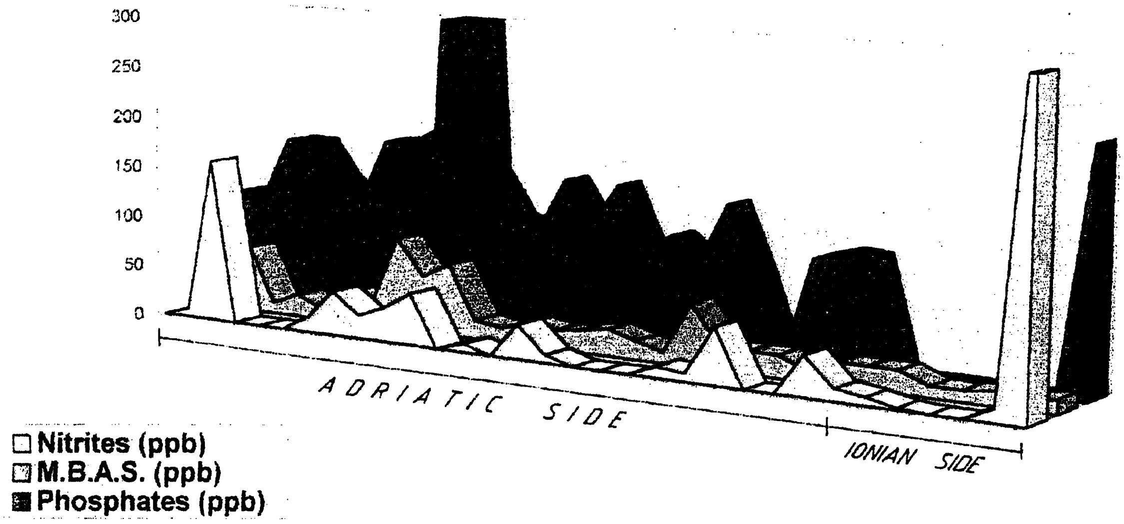
Actual distribution of NO_3^- concentration confirms that urban waste water release is the main factor affecting the quality of groundwaters in the region.



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 every where 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, Yugolavian, 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 km^3/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 m^3 yr^{-1}. The results of easimating 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 m^3 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 responsibly 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 Jacksonsville. 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 physicochemical 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

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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/CO_2 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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A STUDY OF GROUNDWATER CONTAMINATION WITH VARIOUS IONS, METAL AND BACTERIA IN KOREA

KIM, H.S. and RHIE, K.T.

1. Abstract

Regional groundwater contamination with various metals, ions, and bacteria in urban, agricultural, and industrial areas was analysed and compared with Korean criteria for drinking water. Water samples from various groundwater resources were investigated in relation to U.S. EPA guidelines for safe use of groundwater with various parameters. A set of 80 samples from research areas was compared regionally with drinking water criteria for various parameters. The mean concentration of NO_3-N satisfied the Korean standard for drinking quality, which is 10 ppm for all areas. However, the concentration of NO_3-N in 42.31% of groundwater samples from agricultural areas was higher than 10 ppm. The highest concentration of NO_3-N was observed in a water sample from an agricultural area; it was 29.37 ppm, which can cause higher infant mortality by methemoglobinemia. Generally, the mean concentration of various metals was lower than the Korean criteria for drinking water, except in the case of Zinc. The highest concentration of Zn was 1.221 ppm in groundwater from an industrial area; this was the only concentration higher than the Korean standard, which is 1.000 ppm. About 15% and 32.5% of wells were contaminated by general bacteria and *E. coli*, respectively. There were no significant differences among the three areas in the frequency with which wells exceeded the *E. coli* standard. Apparently, there is no adverse effect of acid rain and chemical disposal in the form of pH alteration of groundwater; the mean pH in all areas ranged from 6.5 to 6.7. Generally, industrial groundwater has high concentrations of metals, while agricultural groundwater has high concentrations of NO_3-N in Korea.

Table 1 Comparison of various metals (ppm) in groundwater from urban, agricultural, and industrial areas.

Metals: Area		Fe	Zn	Mn	Cd	Pb	Cu
	Min	0.005	0.000	0.009	0.000	0.003	0.001
Urban	Max	0.021	0.399	0.424	0.002	0.065	0.008
	Mean	0.011	0.069	0.052	0.001	0.035	0.004
	S.D.	0.005	0.101	0.101	0.000	0.017	0.002
	Min	0.003	0.001	0.010	0.001	0.018	0.000
Agri-	Max	0.089	0.118	0.737	0.002	0.072	0.017
cult-	Mean	0.015	0.032	0.145	0.001	0.037	0.004
ural	S.D.	0.024	0.034	0.253	0.001	0.017	0.004
	Min	0.004	0.006	0.010	0.000	0.001	0.001
Indust-	Max	0.077	1.221	5.188	0.002	0.064	0.012
rial	Mean	0.016	0.251	0.522	0.001	0.026	0.004
	S.D.	0.021	0.390	1.478	0.000	0.021	0.003

Table 2. Comparison of pH and $KMnO_4$ consumption (ppm) in groundwater from urban, agricultural, and industrial area.

Parameter: Area		pH	$KMnO_4$ consumption (ppm)
Urban	Min	6.10	0.03
	Max	7.60	4.64
	Mean	6.70	1.34
	S.D.	0.42	1.07
Agricultural	Min	5.60	0.06
	Max	7.90	7.54
	Mean	6.50	1.77
	S.D.	0.65	1.70
Industrial	Min	5.70	0.06
	Max	8.10	3.64
	Mean	6.50	1.35
	S.D.	0.54	0.85

Table 3. Comparison of various cation concentrations (ppm) and hardness in groundwater from urban, agricultural, and industrial areas.

Cation: Area		Na	K	Mg	Ca	NH_4	Hardness
Urban	Min	4.60	0.00	1.00	4.40	0.00	16.03
	Max	17.30	12.90	23.09	106.55	5.97	361.53
	Mean	11.33	3.16	9.98	47.77	0.37	161.30
	S.D.	2.96	3.48	6.93	29.95	1.44	100.91
Agricultural	Min	7.13	1.00	3.22	10.65	0.00	10.32
	Max	17.28	28.05	21.63	94.09	0.78	318.80
	Mean	11.66	5.78	11.61	48.61	0.07	165.80
	S.D.	2.62	7.00	5.29	22.63	0.22	82.36
Industrial	Min	3.04	0.80	2.00	10.06	0.00	33.08
	Max	15.34	16.36	22.03	85.98	0.09	307.21
	Mean	9.77	2.52	8.49	41.34	0.01	134.10
	S.D.	3.51	3.29	6.17	23.17	0.02	85.90

Table 4. Comparison of various anions concentration (ppm) in groundwater from urban, agricultural, and industrial area.

Anion: Area		F	Cl	NO_2	NO_3	Br	SO_4	PO_4
Urban	Min	0.00	3.55	0.00	0.00	0.00	2.12	0.00
	Max	0.61	43.79	1.49	16.65	0.82	155.81	1.22
	Mean	0.16	25.65	0.07	4.73	0.31	40.02	0.03
	S.D.	0.03	11.89	0.30	4.64	0.52	44.22	0.21
Agricultural	Min	0.00	6.31	0.00	0.00	0.00	0.00	0.00
	Max	0.38	65.76	1.80	29.37	0.57	97.50	0.97
	Mean	0.08	29.32	0.06	9.84	0.06	33.57	0.03
	S.D.	0.08	12.65	0.34	9.28	0.11	25.97	0.18
Indus trial	Min	0.00	7.83	0.00	0.00	0.00	3.13	0.00
	Max	0.67	60.04	0.19	22.14	0.22	111.50	0.00
	Mean	0.15	29.03	0.01	4.18	0.09	34.95	0.00
	S.D.	0.18	14.65	0.04	5.29	0.08	36.94	0.00

Table 5. Comparison of frequency (%) of samples that exceeded criteria for general bacteria and the *E. coli* group in groundwater from urban, agricultural, and industrial area.

Parameter: Area	Percentage of samples with concentrations in excess of standards General bacteria (No. in excess/total)	*E. coli* group (No. in excess/total)
Urban	8.82 (3/34)	35.29 (12/34)
Agricultural	15.38 (4/26)	30.76 (8/26)
Industrial	25.00 (5/20)	30.00 (6/20)
Average	15.00 (12/80)	32.50 (26/80)

OFFSHORE MARINE AND GROUND WATERS. THEIR RELATIONSHIP AND ZONATION

KOLDYSHEVA, R Ya.

Ground waters found on land and those found under the floor of oceans, seas, and major lakes differ distinctly in some features of occurrence. This fact has been debated by K.G. Jamalov, I.S. Zektser, A.V. Meskheteli, V.A. Kiryukhin, A.I. Korotkov, A.N. Pavlov, Yu.G. Yukovsky, N.I. Tolstikhin and others.

Based on the mode of occurrence and discharge pattern of ground (submarine) water, its interaction with sea water, and the horizontal and vertical inhomogeneity of seawater itself (vertical stratification by temperature and salinity), three hydrodynamic zones are recognised: shallow, shelf, and deep.

The shallow zone includes the coast with the areas submerged by high tides, the submarine coastal slope, and the extreme nearshore sections of the shelf. The shallow zone averages a few m to 5 m in depth, with the maximum depth being 10-20 m. The shallows are the first to receive polluted surface and ground waters from extensive catchment areas. The regime of the shallow water zone (circulation, orientation, influx of river and ground water) governs the degree of self-purification capacity and the quality of waters moving seaward into the deeper regions.

The shelf zone, with a maximum depth of 200-300 m, occupies the shelf and part of the continental slope. Not only seasonal thermal fluctuations and wind mixing throughout the whole water column, but also an active interaction with ground water are characteristic of this zone. It is the domain of the principal load of submarine water. Seasonal temperature fluctuation, wind mixing, and submarine water discharge (sometimes reaching the oceanic surface) provide for maximal intensity of convective and advective mixing of the water column. Two subzones, a more active (within 50-100 m depths) and a less active (100-200 m depths), are recognised based on the relationships between sea water and ground water within the shelf zone.

Further offshore, in the deep zone where depths exceed 200-300 m, a hydrodynamic equilibrium between ground and marine waters is usually established. There is little or no ground water discharge into the ocean. The ground water flow under the oceanic floor is retarded, and the periods of water exchange are longer. The constant salt exchange between ground water and sea water may bring about similarity in mineralisation and in the salt composition of waters above and below the ocean floor.

REVIEW OF IMPACT BETWEEN SEA WATER AND FRESH WATER ON THE COASTAL ZONE - A CASE STUDY FROM CHINA

LI, C. and ZHAO, L. (Belgium)

1. Abstract

The study was undertaken in the eastern shores of Shangdong Province of China. The region lies in the zone of continental monsoon climate and is in the semi-humid warm temperate zone. The annual precipitation is between 500 and 900 mm. However, because of the effects of typical monsoon climate, the seasonal distribution within a year is quite uneven; 50-70% of annual rainfall is concentrated in the period from June to September, frequently causing droughts in spring and wet autumns. The rainfall also varies greatly among the years. All those coastal areas consist mainly of continental deposits. The aquifer has the potential ability to yield large and reliable quantities of water and has been the main water source for domestic, industrial and agricultural utilisation.

There are some important cities in the region. Since 1980s, with rises in people's living standard and rapid economic development, water demand has exceeded water yield in the region. Over-exploitation of groundwater has occurred, especially during series of dry years and dry seasons when the river flow was cut off. Over-exploitation resulted in some area groundwater tables much lower than sea level; sea water as well as coastal salt water intrudes and endangers the fresh water aquifer of the Quaternary system. The intruded area has increased year by year at a high rate and the concentration of chloride ions has reached a high level. The water supply field has become useless.

Sea water intrusion and salt water diffusion not only cause a great danger to industry and agriculture, but also cause problems for the people, worsen the ecosystem in the coastal zone, and change the hydrologic cycle. The occurrence and further development of sea water intrusion have already caused attention by the affected cities and counties in the coastal areas. Some prevention measures have been adopted: water transfer project from outside basins, drilling infiltration wells in the river and canal courses, water resource management, water saving measures, etc. Among the measures, diversion of surface water for groundwater recharge is an effective and economical measure to ease water shortages and to raise water tables to prevent further sea water intrusion.

In spite of many efforts, sea water intrusion and its problems still exist. Understanding of the hydrological regime of coastal aquifers and reasonably planned exploitation of groundwater are essential for the social and economic development and for our living environment.

2. Study Area

The study area is bounded by the Yellow River on its west side and by the seas on the other sides, with an area of 64186 km^2, and is located in Shangdong Province (Figure 1). The region lies in the zone of continental monsoon climate and belongs to the semi-humid warm temperate zone. The annual precipitation is between 500 and 900 mm, with 50 - 70% of the annual precipitation concentrated in the summer season, from July to September. The potential annual evaporation is 1200 - 1400 mm, frequently causing droughts in spring and wet autumns. The rainfall also varies greatly among the years. The coastal areas consist mainly of continental deposits. The aquifer has the potential ability to yield large and reliable quantities of water and has been the main water source for domestic, industrial and agricultural utilisation.

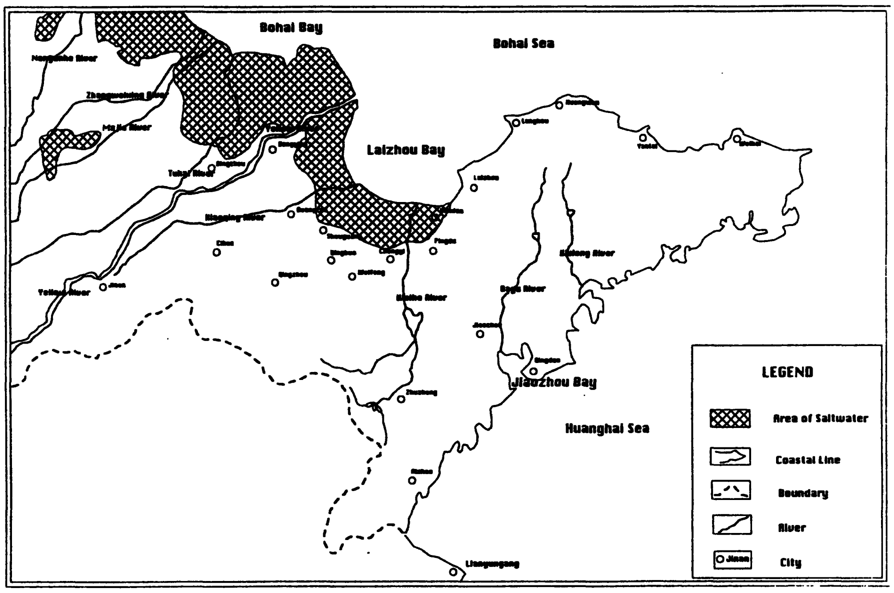


Figure 1 Geographic Location Of the Study Area

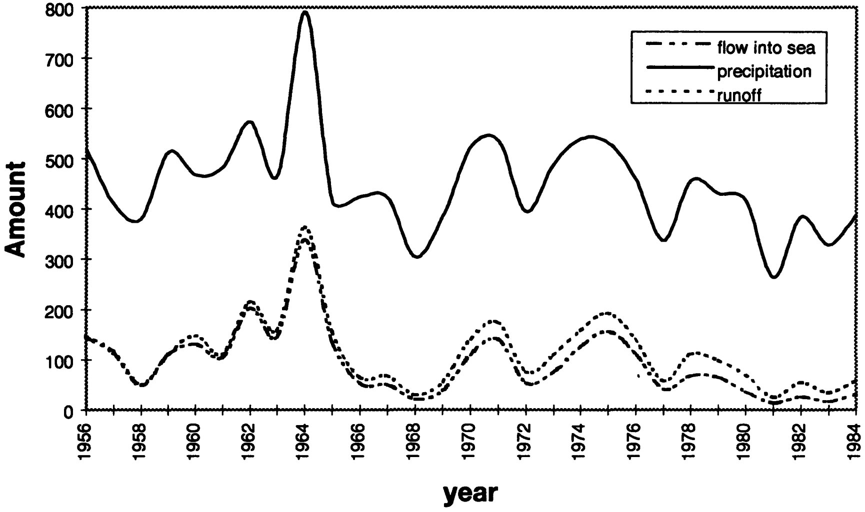
3. Description of Sea Water Intrusion and Reduction of Available Water

With the expansion of industry, agriculture and urbanisation, as well as the rising in people's living standard, the amount of water use has increased year by year.

Since 1970s, lack of good management, groundwater recharge reduction, a series of dry years, reduction of runoff into the seas (Figure 2), and over-exploitation of groundwater, have resulted in the phenomenon of sea water intrusion into the aquifer of the Quaternary system. Salt-water diffusion to different degrees has affected the counties and urban districts in the study area. The total area of sea water intrusion into fresh aquifer reached 397 km^2 in June 1984, with a concentration of chloride ions of more than 250 mg/L (the highest concentration is up to 6900 mg/L). In Hanting, Shouguang, Changyi and Guangrao counties, the area of sea water intrusion is 137 km^2, with an intrusion rate of 100 m annually.

Upstream of this area is piedmont alluvial plain. There is a sharp boundary between fresh and salt water in the coastal areas of Pingdu, Changyi, Shouguang, and Guangrao Counties. South of boundary region, there is fresh water whose mineralisation is less than 1 - 2 g/L. In the northern boundary region, salt water with mineralisation greater than 2 - 5 g/L is found. During the continuously dry years, the amount of water consumption increased (Figure 2), and groundwater over-exploitation caused different degrees of coastal salt water diffusion, intruding toward the south and polluting the fresh water aquifer. It appears that there is a sharp fresh - salt interface in the mentioned areas. According to incomplete statistics, the affected area is up to 100 km^2.

Fig.2 Precipitation and Runoff Series(unit: *10^8 cu.m)



Due to the long-term over-exploitation of groundwater in the study area, there was not only sea water intrusion in coastal areas, but also larger areas with a water- table cone of depression. To June 1986, the total area of depression was up to 9600 km^2 in the coastal zone. The groundwater table is generally 10 meters lower than sea level. The motor-pumped wells and equipment to lift water were almost unusable in the area of water-table depression, so the wells and machine-pumps had to be replaced, which greatly increased the cost of irrigation. Taking Yentai as an example, there existed an area of 40 km^2, where the water table was lower than sea level. The deepest water table reached 13 meters below sea level. It caused springs to dry up, rivers to stop flowing, and even sewage water permeation polluted the groundwater. The water source field was becoming useless.

As a result of over-exploitation of groundwater, the speed of surface water seeping into the ground is accelerated and surface water levels declined; some rivers, lakes and ponds have dried up in dry years or dry seasons. The regional environment and ecosystem was been damaged;. some aquatic plants and animals could not live, some fish and birds disappeared, and biodiversity has been reduced. Drawing down the groundwater table changed the condition of horizontal and vertical infiltration, and led to shallow water pollution.

4. Problems

It is not an exaggeration to say that water supply is the most critical local problem. The sea water intrusion, salt water diffusion, and groundwater depletion has limited the local economic development and threatened the environment where people live.

4.1. Restriction of Industrial Development

Due to the groundwater reduction and sea water intrusion, water supply has been sharply reduced, so industrial water use has been affected. Some factories, construction, and projects have had to stop or partially to stop production due to the lack of water supply. In 1979, the industrial output was reduced by about 90 million Yuan in Yie County.

4.2. Hindrance of Agricultural Production Development

Due to the shortage of irrigation water, the effective irrigation area decreased year by year. In Yenta, effective irrigation area decreased to 1896 million mu in 1989, which was 62% of the cultivated area. From 1980 to 1989, there were 910 million mu per year suffering water shortage due to sea water intrusion and drought, and the food oil production was reduced 1675 million tons. Yie County lost 250 million kilograms compared with 1979. Moreover, 34 villages with a total population of 44900 persons lacked adequate drinkable water. Due to the salinity of groundwater the vegetation of the coastal region is diminishing, which also affects future life in the coastal zone.

4.3. Problems for People's Normal Living

Water is part of everyday human life. Freshwater shortage greatly troubles people's normal living, making it difficult to supply water for both urban and rural people. In Yie County, for example, based on statistics of early 1985, the water quality of 1078 wells in 12 villages and towns became salt because of sea water intrusion.

In some cities during the dry period, water supplies are often managed by putting a limit on quantity time of use. In 1989, for example, in Yenta City, the limit on water quantity use per person was 50 L per day. This not only affected the people's normal living, but also obstructed the development of the tourist industry.

5. Counter-measures

The occurrence and further development of sea water intrusion have already caused attention by affected cities and counties to the need for defining water problems and working out equitable solutions in coastal areas. Some prevention measures have been adopted and good results have been achieved.

Water transfer projects from outside river basins and tide-control gates have been built. This was done to regulate the runoff in the flood period and to divert runoff for groundwater recharge in the groundwater depression cone areas near coastal areas. The purpose was also to build up some projects of diverting water from water source areas to solve the difficulty of water supply for the area near the towns, and to reduce the rate of sea water intrusion.

In Huang county, infiltration wells were drilled in the river and canal courses for increase the amount of groundwater recharge. Water resources management was strengthened. Industrial and agricultural water saving measures widely were taken. In this way, conditions were improved to some degree.

However, the river systems in the study area belong to the same climatic region, so that the wet and drought cycle occurs synchronously in all of the river basins. So, there is no excess water available to be diverted from one river to another. Therefore, the measures taken are still unable to fully solve the problems. In addition, groundwater abstraction is still not strictly controlled, and the water saving measures and regulation on the plantation structure have not been carried out everywhere. So, the sea water intrusion is still not under control.

Diversion of surface water for groundwater recharge is an important measure to solve the water shortage. Along the coastal zone, some water recharge measures have been adopted. For example, building some gates across rivers and excavating water transmission canals; transferring flood water to water shortage areas for recharging groundwater sources; drilling wells in river course and canal bottom and filling them with sand to make the flood water permeate downward; excavating canals and ponds to save surface water for water recharge.

Generally, irrigation is one of the measures for recharge. The methods of over irrigation as well as infiltration of ditches and ponds are used to recharge the groundwater. The results are satisfactory, with the water levels in the cone area raised rapidly. In Huang County, 5000 infiltration wells were drilled and filled with sand along the canal and river bank (each one with a diameter of 1 meter, and a depth of 5 meters) in the western part. The amount of infiltration increase in rainy season is quite obvious, the water table rose rapidly. The results show that diversion of water to recharge groundwater will have a high efficiency if the basins do not have the same wet and drought cycles. However, diverting water or retarding floods in the flood season to recharge the cone of depression areas in the neighbouring basins, has poor results when the wet and drought cycles occur synchronously, especially in long continuous droughts. The problem of the cone of depression in such areas is still not solved.

The types of water recharge projects are well-recharge, ditches, canals, puddle and pond infiltration, field surface irrigation instead of recharge, etc. According to experimental data for the silt and fine sand aquifer, well recharge would require much more investment, while yielding poor results. Usually, the amount of recharge in a well is less than 5 - 10 m^3/h and decreases with duration of the recharge. But by utilising ditches, canals and puddles for recharge, good results were achieved. The daily infiltration depth from the water surface of ditches and canals is 0.05 to 0.1 meter or so. The daily infiltration depth from puddles and ponds is 0.02 to 0.07 meter or so. The effect of recharge is better in new puddles and ponds than that in old ones. In the area where the stream water was used as the source of irrigation water, the recharge effect was better, since the rate of infiltration that can be reached is 25% to 35% of the total diverted water. In addition, by using canals instead of wells, the amount of pumped groundwater will be reduced. So if there is a high probability of water sources in such area, then groundwater level can raised rapidly.

Moreover, when carrying out groundwater recharge, clean water should be used in order to protect the groundwater from pollution.

6. Conclusion

Although many efforts have been made, sea water intrusion problems still exist. A good understanding of the hydrologic regime in the coastal zone is essential for social and economic development, and for preservation of our living environment.

GROUNDWATER DEVELOPMENT AND SIDE EFFECTS IN MAIN CITIES ALONG THE COASTAL ZONE OF CHINA

LIN, X. and LIAO, Z.

1. Abstract

China has a coast line of about 18000 km. Along the coast, there are more than 20 metropolitan areas and cities, such as Tianjin, Shanghai, Xiamen, Guangzhou, Zhanjiang, Zhuhai, and Shenzhen, which are the developed areas in China. As a result of rapid economic development, construction, and of population increase, agricultural, industrial, and domestic water usage are speedily increasing. The conflict between water demand and water supply becomes more prominent day by day in the above cities.

2. The Situation of groundwater development in typical cities along the coastal zone

(1) Shanghai is the biggest economic center in China. The total area is 6200 km^2 with 12 million population (P=1141 mm, E=1427 mm, T=13-16 °C).

In Shanghai, the main source of water supply is surface water with a small amount of groundwater coming from deep aquifers.

In 1980 (a rainy year), more than 80 hundred million m^3 of total water was used; 58 per cent for industries, 36% for agriculture, and 6% for domestic.

The total surface water is about 120 hundred million m^3. Because the local runoff and the water from upper reaches are small, per capita quantity of water resources is 1000 m^3, only 1/2 of that in the country.

However, Shanghai has plentiful tide water resources (about 470 hundred million m^3) that makes up the deficit of local runoff and water from upper reaches.

The allowable withdrawal of groundwater is 10 hundred million m^3 (including 4.3 hundred million m^3 water from the unconfined aquifer and 5.7 hundred million m^3 water from the deep confined aquifer), which is insufficient for water demands of the city because of the small permeability of aquifer, poor water recharge, waste water disposal, and sea water intrusion. According to statistical data for the year 1987, waste water disposal was 5 million tons per day, which was mostly drained directly into the Huangpu river and its branches without waste water treatment. The pollution of surface water and groundwater makes the quantity of water available much smaller.

There is a need to pay more attention to water exploitation and utilisation due to the flat landform, frequent typhoons, rainstorms, and water body contamination. The calamities of flooding, tides, and soil salinization are still not effected with a radical cure in the city.

(2) Tianjin is an another typical example of a water-importing city among cities of Dalian, Xiamen, Shenzhen and Qingdao etc..

Tianjin is the third biggest city in China with 11300 km^2 and 7.5 million populations. It is in a semi-moist to semi-arid area (P=550-800 mm, E=1000-1200 mm, T=11.7 °C). It is located in the Hai River and Ruan River Basins, where it is one of rainfall-shortage cities along the east of the coastal zone.

In the past, surface runoff mostly passed Tianjin into the sea even during the successive dry years of 1980-1985. The average water flow to the sea was 144 hundred million m^3 in the 1950s and 4.66 hundred million m^3 during the dry years 1980-1985, and the water quantity could satisfy the demands of agriculture, industrial and domestic use before 1980. Since the end of 1950s, a water crisis has emerged because of large quantities of diversion works constructed in the upper reaches of Hai River, waste disposal, and successive dry years. The water crisis was only alleviated by importing water from the Ruan River into Tianjin city for use after 1983.

In Tianjin, the hydrogeological conditions are similar to Shanghai. The shallow aquifer is the main exploitation aquifer due to high salinity water in deep aquifer. The allowable yield of groundwater is 0.1 hundred million m^3 within the downtown of the city. Because of groundwater overpumping (1.1-1.2 hundred million m^3/year), land subsidence and sea water intrusion have occurred.

For solving the problems of water shortage, water has been imported from Ruan River. Works for importing water from the Yellow River and the Yangzi River are being planned.

(3) Qinhuangdao city is more than 3000 years old. The area is about 7790 km^2 with 124 km coast line and more than 2 million population (P=690 m, T=10.1°C).

It has a continental climate, in the semi-moist monsoon region of the warm temperate zone.

There are more than 100 rivers passing through the city. The precipitation is mostly concentrated in the flooding season that makes up 1/3 of total annual rainfall. In January, the precipitation only accounts for 2% of the total.

The rivers along the coast have short courses and rapid flow with poor water regulation because 70-80% of the annual water flow occurs during the flood season.

The main reservoirs (such as Shihe reservoir) are small for water supply to the city in a dry season. In rainy years, a large quantity of water is drained away directly into the sea.

The total groundwater quantity is about 6.1 hundred million m^3 that is mainly distributed in the plain of alluvial fans of the Ruan River and the Yang River. The aquifer is thinner (depth of bed rock is 10-20 metres), so the allowable withdrawal of groundwater is only 0.12-0.18 hundred million m^3. As a result of lack of surface water, sea water has invaded inland due to groundwater overpumping, which has made water quality worse along the coast area.

The city is one of the water-deficient cities in China, where water-importation works and conservation constructions are urgently needed to meet the water demands of Qinhuangdao city.

(4) Guangzhou is the biggest city in the south part of China with 16631.7 km^2 area and more than 7.1 million population in 1987. It is in the tropical monsoon climate of south Asia, (P=1600-2000 mm, T=21°C). It is situated in the south-central plain of Guangzhou province, where the Zhu River delta is the north boundary, near Hong kong and Macao in the confluence of the East River, West River and North River. The Zhu River passes through the city.

Guangzhou is rich in shallow groundwater. The annual quantity of groundwater was 54.45 hundred million m^3, accounting for 26.7% of surface runoff in 1987. The natural water quality is good with the exception of the river mouth area where the total dissolved solids and hardness are high due to tidal influence. At present, groundwater is mainly supplied for sanitary use.

The surface water is abundant including transit water (about 500 hundred million m^3) and flood tide water (4.6 hundred million m^3 and good quality in flooding season). The average river flow per year is 203.6 hundred million m^3 (Per capita quantity of water is 2866 m^3), 70-80% of which occurs in the flooding season that is the same as maximum rainfall distribution.

Even so, people are still facing a future water crisis in Guangzhou city because of the areal expansion of the city, rapid development of industries, deforestation and decrease in grass land, water pollution, waste disposal and low rate of waste water treatment, etc..

For solving the problem of lack of water, importing water from the North River and West River into Guangzhou city is essential.

3. The side effects induced by groundwater overdevelopment

When water resources bring benefit to mankind, they also give various ecological and environmental problems as side effects in the process of development and utilisation.

Especially because the cities along the coastal area of China are economically developed areas, the water demands there are much bigger. Groundwater is one of main sources in these cities. Many environmental side effects have taken place and are taking place due to groundwater overpumping.

The main side effects can be described as follows:

(a) Sea water intrusion
Since 1970s, because of overpumping of karst water, the groundwater level dropped by 10-40 metres in comparison with that in 1964, which led to sea water intrusion and chloride ion increase to 1.3 g/l in the wells of some water works along the coastal area of Dalian City of Liaoning province.

The area of sea water intrusion was 360 km^2 and involved 10 counties of this city. The groundwater level was 10 metres lower than sea level, causing 2000 wells to be abandoned and 266.4 km^2 of farmland to become saline in Longkou and Laizhou cities of Shandong province in 1981.

Since the 1950s, because of groundwater overpumping in some water works of Beidaihe City, the sea water intrusion has invaded inland with a speed of 8 m/year which caused water deterioration and drops in crop production.

At present, with rapid economic development, similar incidents have occurred along almost the whole coastal area of China, from Dalian, Yinkou, Beidaihe of Laizhou bay in the North, to Shanghai, Ningbo, Dongshan island of Fujian province in the East, and to Zhangjiang, and Beihai in the South. The distance of sea water intrusion inland has been more than 10 km along coastal area of Bohai Bay.

(b) The problems of environmental geology
Groundwater in one important factor for maintaining the natural stress balance of strata. Large-scale abstraction of groundwater will lower water head pressure in the aquifer and destroy the stress balance of strata, which will cause some geological problems, such as land subsidence, ground fissures and collapse, etc.

Land subsidence has occurred in the cities of Shanghai, Tanjin, and Suzhou along the coastal area. The biggest depth of land subsidence is 2.37 and 2.70 metres in Shanghai and Tianjin respectively, which has destroyed building foundations and caused disastrous sea tides.

Moreover, in Tianjin city, the flood control dike on banks of Hai River has subsided 1-2 metres. The capacity of flood discharge of Hai River was decreased from 1200 m^3/s to 400 m^3/s. Many sluice gates of the river were damaged due to land subsidence.

Now, the altitude of the land surface is less than 2 metres higher than sea level along coastal areas of Tanggu, Hangu, Dagang and the downtown of Tianjin, which will be inundated with sea water if the land surface continues to subside.

Land collapse is the greatest problem of environmental geology in buried karst pumping areas. Usually, the fillings and water escape from karst caves, and latent corrosive action is aggravated due to groundwater pumping; then land collapse occurs as a result of disruption of the stratum.

Generally speaking, the land collapse often happens so suddenly in karst areas that control measures are usually very difficult to adopt in time. For example, when a 50000 m^3/d water supply work was built in Liujiang basin of Qinhuandao city of Hebei province, after a half year, 1700 buildings in 16 villages were damaged because of 286 land subsidence and collapse **occurrences within an area of 28.32x10^4 m^2.**

Similar incidents occurred in Guanghua basin on the north of the Zhu River Delta. It is a syncline basin of carbonate rock covered by Quaternary loose deposits where more than 100 wells were distributed with 75000 m^3/d of total pumping quantity in 1987. Because of overpumping, 140 land collapses and ground fissures have happened in the basin and 73 buildings have cracked to various degrees.

(c) Water quality deterioration and human health
Some important environmental side effects insidiously emerged due to unreasonable groundwater development. For instance, the regional groundwater level continuously dropping down has resulted in a percentage decrement of total surface water cover from 27.8% in the 1950s to 7.7% in the 1980s which made land desertification and salinization increase, while the precipitation and moisture were decreasing and temperature rising slowly (The average temperature increase was 1°C in the 1970s and 0.4-0.6°C in the 1980s).

The incidence of fluorosis and liver cancer has risen in the past few years along the coastal area, which has a close relationship with the bad quality of drinking water. Because of lack of fresh surface water and shallow groundwater, some residents have endemic disease of fluorosis and goitre resulting from drinking water with high fluoride or iodine content from the deep aquifer.

Along the coastal area, Guangxi, Guangdong, Jiangdshu, Fujian, Zhejiang, Yangzi Delta and the Zhu River Delta are areas of high incidence of liver cancer because of bad drinking water quality.

According to the statistical data at the end of 1980s, waste disposal was 340 hundred million m^3/year, more than 75% of which came from industrial waste in China.

The Yangzi River Delta and the Zhu River Delta are the main industrial developed areas where a large quantity of waste disposal without waste water treatment is the primary cause of water pollution. This area is the heavy endemic disease area.

In sum, groundwater resources are precious for mankind, but they also give many kinds of ecological and environmental problems under unreasonable groundwater exploitation.

Making full use of water resources while controlling the side effects is the pressing task for hydrogeologists. Some measures, such as water resource regulation, water level control under optimal condition, artificial recharge and comprehensive development of groundwater and surface water must be adopted under different conditions in different places.

The prefect water management organisation and water law are also required for solving the problems mentioned above.

*QUANTIFICATION OF GROUNDWATER INPUTS TO THE COASTAL OCEAN AND RESIDENCE TIMES OF COASTAL WATER USING RADIUM ISOTOPES

MOORE, W.S.

Submarine discharge of groundwater may be as important as river discharge for the supply of some elements to the ocean. Because of the diffuse nature of this source and the difficulty in recognising and quantifying its importance, few investigators have attempted to assess the impact of **s**ubmarine **g**roundwater **d**ischarge (SGWD) on ocean chemistry. Evidence is mounting that SGWD must be considered in the mass balance equation for the supply of some elements to the ocean (Moore 1996; Moore and Church 1996, Rama and Moore, in press). New methods are needed to assess the magnitude and impact of this process.

To assess the impact of SGWD, it is critical to know the total dissolved flux of components of interest from coastal regions to the ocean. Short lived Ra isotopes, ^{223}Ra (half life = 11.3 days) and ^{224}Ra (half life = 3.6 days), constrain the mixing time across the coastal ocean. Therefore, offshore gradients of dissolved components in coastal waters coupled with these exchange rates provide an estimate of fluxes to the ocean. These fluxes must be sustained by input from rivers, SGWD, or other sources.

Submarine groundwater is a mixture of fresh groundwater and sea water; chemically, it is very different from either component because of reactions with aquifer solids. For example submarine groundwater entering the Bay of Bengal during low river discharge is at least a factor of 3 supersaturated with respect to barite, and more likely a factor of 10 supersaturated (Moore, submitted). Groundwater entering the South Atlantic Bight contains at least 100 times more ^{226}Ra and 10 times more Ba than local rivers (Moore 1996; Shaw *et al.* submitted).

Estuarine processes sequester many of the trace elements and nutrients delivered by rivers through processes such as flocculation, adsorption and intense biological productivity. Consequently, estuarine processes (rather than river water chemistry) determine the net flux of many elements to the coastal ocean. Because SGWD largely bypasses the estuary filter, the elements delivered by this route are more likely to be mixed into the ocean interior rather than removed into estuarine and coastal sediments. Thus groundwaters represent an input flux of trace elements and nutrients for which the magnitudes and the chemical processes are virtually unknown. New methods are needed to assess this input.

Ra based mixing rates coupled with solute concentrations yield a transport flux for dissolved constituents from the coastal zone into the ocean. In order to understand the process that control these fluxes, the transport studies must be coupled with a detailed evaluation of groundwater input processes. Groundwaters are distinctly different from river waters and as such contribute a very different chemical flux to the ocean.

Most of our work has been along the southeastern coast of the US. Here we find ^{226}Ra activities greatly exceeding the amount that can be supported by river input (Moore 1996). The source of this extra ^{226}Ra must be the discharge of salty groundwater. Intrusion of salt water into coastal aquifers facilitates the desorption of Ra from the sediments. Flushing of this chemically altered groundwater into the ocean explains the high ^{226}Ra activities. Sizeable contributions of Ba, P and N are also provided by the groundwater discharge.

This paper explores the use of short-lived Ra isotopes, ^{223}Ra and ^{224}Ra, to establish residence times of coastal waters and uses the residence times to estimate fluxes of elements to the ocean. I apply these concepts to evaluate the importance of groundwater as a source of ^{226}Ra and Ba to near-shore waters.

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ASSESSMENT OF SALTS DISCHARGE WITH GROUNDWATER TO SEAS

SAFRONOVA, T. I

1. Abstract

The submarine groundwater runoff is often the main cause of formation of large geochemical anomalies in the bottom and sea sediments. In turn, anomalies in geochemical fields at sea bottom are indicators of submarine groundwater discharge. Subsurface dissolved solids discharge to seas is governed by the rate of submarine groundwater discharge, washing of water-bearing rocks, paleohydrogeological and present conditions of groundwater formation, as well as human activities in the coastal zones. The total discharge of salts with groundwater to oceans amounts to 52% of salt discharge with river inflow. Therefore, the estimates show that submarine discharge of groundwater can have substantial effect on the salt and hydrobiological regime of seas and oceans, biogenic sedimentation, and formation of mineral deposits in bottom sediments.

2. Introduction

Oceans, marginal and inland seas are the main base of drainage of surface and groundwater runoff. In this connection, their salt balance is generated under the influence of salt transport by river and ground waters. Of these two main sources of dissolved solids supply to seas, river dissolved solids transport has been studied sufficiently. Estimation of the contribution of groundwater runoff to dissolved solids transport has been complicated until recently by lack of data on regional groundwater discharge directly to seas.

As result of studies carried out in separate regions show, direct groundwater discharge to sea bypassing the river network in respect of the total river runoff is usually expressed by a small value. At the same time, the contribution of subsurface dissolved solids discharge to the salt balance of inland seas is appreciable and accounts for tens of per cent of the surface dissolved solids transport by rivers. For example, the transport of salt by groundwater to the Caspian Sea accounts for 27% of dissolved solids transport by rivers, while the groundwater discharge to the sea does not exceed 1% of river inflow (Dzhamalov *et al*., 1977).

In the distribution of the groundwater and subsurface dissolved solids discharge to seas, the general vertical hydrodynamic and hydrochemical zonality for the groundwater is observed; this zonality governs the increase in the total transport of salts with depth despite the general reduction in groundwater discharge. This general law is sometimes disrupted by the effect of local hydrogeological conditions (wide occurrence of karst, presence of salt-bearing rocks, and processes of continental salinization). For instance, the largest values of subsurface dissolved solids discharge to the Baltic Sea (48.5 t yr^{-1} km^{-2}) are characteristic for the coastal portion of the Silurian-Ordovician plateau, where submarine groundwater flow is mainly generated in aquifer systems composed of karstified limestones and dolomites.

3. Main results and discussion

It should be noticed that the contribution of subsurface dissolved solids discharge to generation of the salt regime of seas may appreciably increase with a decrease in total river runoff under the action of natural factors and the human impact. Salinization of the deep portion of the sea would occur more intensively since there water-exchange periods are longer. The salinization of some deep hollows in inland seas, being observed at present, may be caused in addition to other factors, by the increasing influence of subsurface dissolved solids discharge from deep aquifers. Apart from the effect of groundwater runoff on the total salt balance of seas, it is often the main cause of formation of large geochemical anomalies in the bottom water layer and sea sediments. In turn, anomalies in geochemical fields at sea bottom are indicators of submarine groundwater discharge.

The salt transport by groundwater to the Atlantic Ocean amounts to 470 million t/yr, and to the Arctic Ocean (from estimated drainage areas) 7 million t/yr The total supply of salts with groundwater to oceans amounts to 1300 million t/yr that is 52% of salt supply by river runoff amounting to 2480 million t/yr (this last figure does not include the dissolved solids transport by river from major islands). The proportion between surface and subsurface dissolved solids discharge amounts for continents is presented in the following Table 1.

Table 1. Estimated continental surface and subsurface dissolved solids discharge.

Continent	Surface dissolved solids discharge (Mt/yr)	Average salinity of river water (g/l)	Subsurface dissolved solids discharge (Mt/yr)	Average total groundwater dissolved solids content (g/l)
Europe	240	0.077	60	0.4
Asia	850	0.065	296	0.9
Africa	310	0.072	288	1.0
North America	410	0.069	149	0.4
South America	550	0.053	113	0.3
Australia (including Tasmania, New Guinea, New Zealand)	120	0.060	199	0.5
World's total	2480	0.063	1045	0.6

Note: Data on surface dissolved solids discharge and average river water salinity are taken from the book by M.I. Lvovich (1974). The value 1045 Mt/yr does not include discharge from major islands.

Subsurface dissolved solids discharge to seas is governed by the rate of submarine groundwater discharge, washing of water-bearing rocks, paleohydrogeological and present conditions of formation of groundwater dissolved solids content and composition, presence of evaporites and development of continental salinization processes in arid regions.

The tabulated data show that the average total dissolved solids content of groundwater discharging directly to oceans from the area of Asia is equal to 0.9 g/l. However, in arid and semi-arid regions, a decrease in submarine groundwater discharge is attended by an increase in total and specific values of subsurface dissolved solids discharge.

An anomalously high salt evacuation by groundwater is observed in areas with evaporite deposits where they contact water-bearing rocks (the Red Sea and the Persian Gulf). It is a determining azonal factor of dissolved solids discharge formation.

The Red Sea basin is noted for very peculiar groundwater runoff conditions. As to tectonics, the region is located in a rift zone whose sites are a system of grabens of different age. The grabens are filled mainly with sedimentary rocks with large inclusions of evaporites. In this connection, discharge sites of thermal water having a high dissolved solids content are observed largely in the deeps of the Red Sea. Unfavourable recharge conditions are responsible for very insignificant regional submarine groundwater discharge values commonly not exceeding 0.1 l s^{-1} km^{-2}. At the same time, the high dissolved solids content of groundwater is the cause of a substantial salt discharge to the sea (its total amount equals 22.2 million t/yr and the discharge rate is up to 150 t yr^{-1} km^{-2}).

The values of specific submarine groundwater discharge to the Mediterranean Sea from the area of the Near East and Asia Minor are usually no more than 3 l s^{-1} km^{-2}. The groundwater dissolved solids content is diverse and commonly increases southward (up to 12 g/l) where gypsums, limestones, and terrigeneous deposits occur among other rocks. The higher salinity of groundwater is responsible for the fairly appreciable subsurface dissolved solids discharge to the Mediterranean Sea from the Asian continent, the specific discharge rates gradually rise from north to south from 46 to 140 t yr^{-1} km^{-2}.

The broad development of karstified carbonate rocks and fissured sandstone on the Florida Peninsula results in an azonally high submarine groundwater discharge whose specific rates sometimes exceed 6 l/s per sq. km. A tongue of fresh and brackish groundwater, formed inland in Paleogene and Cretaceous limestones, is traced under the floor of the Atlantic Ocean 120 km off shore down to a depth of over 600 m. Submarine groundwater is commonly freshened in the influence zone of coastal artesian basins. At the same time, the existence of submarine water with a salinity of over 35 g/l is indicative of the occurrence of salt-bearing rocks at some depths in the majority of cases.

On the whole, the wide distribution of fresh groundwater all over the Atlantic coast of the USA is responsible for the insignificant subsurface dissolved solids discharge here, its specific discharge rates gradually increase from 10 to 40 t yr^{-1} km^{-2} in the direction of the Florida Peninsula.

The Eucla basin is a typical example of artesian basin of arid desert regions in Australia. In this artesian basin, water-bearing Paleogene cavernous limestones are not practically recharged now because annual precipitation here does not exceed 180 mm. In this connection, the groundwater discharge to the oceans from the Eucla basin is as small as 0.1 l s^{-1} km^{-2}, while the subsurface dissolved solids discharge amounts to 75 t yr^{-1} km^{-2} is due to the high salinity of groundwater.

In the distribution of submarine dissolved solids discharge values, their dependence on latitudinal physiographic zonality may be observed since salt transport with groundwater primarily depends on submarine groundwater discharge (Zektser *et al.*, 1984). Fresh and weakly mineralised groundwater flows to seas largely from the upper hydrodynamic zone. The dissolved solids content of groundwater increases largely due to the presence of salt-bearing rocks, processes of continental salinization, stagnant flow regimes, or weak flushing of aquifers. These conditions of formation of the chemical composition of groundwater are often encountered within African and Australian coasts, which leads to azonally high values of submarine dissolved solids discharge in some areas there. The complicated character of dissolved solids discharge distribution indicates that this natural process is greatly governed by paleo- and recent geological and hydrogeological conditions of groundwater discharge generation. In other words, the regional effect of the latitudinal physiographic zonality on the distribution of principle runoff-forming factors is levelled or complicated in separate coastal areas by local conditions of the generation of the chemical groundwater composition.

4. Conclusion

Thus, submarine groundwater discharge may exert a considerable influence on the salt and hydrobiological regimes of seas and oceans, on processes of biogenic sedimentation and on formation of mineral deposits on sea floor. The significant role established for salt transport by groundwater discharging to seas (52% of surface dissolved solids transport) should drastically modify existing concepts in which the primary biological products of seas and the scale of biogenic sedimentation are considered to be limited only by the amount of salt transported by rivers to the seas (Zektser *et al.*, 1984).

5. Acknowledgements: This research has been carried out with support of Russian Foundation for Fundamental Investigations (Project 95-05-64107).

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NORDIC-BALTIC GROUNDWATER MONITORING; CONTRIBUTION TO POLLUTION OF THE BALTIC SEA

SOVERI, J.

All Nordic countries have operative national groundwater observation networks, which were established during the International Hydrological Decade (1965-1974). The networks provide several types of data to be utilized both in research projects and as reference material. It should also be performed to provide good information for integrated management of environmental sectors. A better understanding the complex interaction between groundwater, terrestial and coastal systems requires more detailed studies on chemical and physical processes in catchment areas and long-term monitoring of groundwater quality and quantity.

This presentation is an outline of a joint project proposal including participants from Denmark, Estonia, Finland, Latvia, Lithuania, Norway and Sweden. The main aim of the project is to develope a compatible groundwater monitoring system in the Nordic and Baltic Countries, i.e. to establish joint databases, exchange information for the regional planning of groundwater abstraction, evaluate the changes and trends in groundwater quality and prepare and implement common groundwater protection measures. The overall objective of the project is to establish the necessary basis for a common, comparable groundwater monitoring programme in the Baltic Drainage Basin as a part of the entire monitoring of the Baltic Region.

The Baltic Sea is a semi-enclosed sea of about 370 000 km2 of brackish water, and its volume about 21,000 km3. The watershed is more than four times as large, inhabited by 80 million people. From the watershed area with all ongoing human activities, waste production, leaching of agricultural chemicals etc., the fresh water is discharged into the sea from hundreds of rivers and water courses. The annual fresh water imput totals is estimated to be approximately 450 km3.

The part of groundwater runoff to the Baltic Sea is not well known. In order to assess the impact of groundwater quality and quantity on the Baltic Sea environment, and the ecological conditions of the Baltic Region it will obviously be of great importance to establish and operate a coordinated groundwater monitoring programme, including comparable methods and standards.

Fig.1. The Baltic Sea drainage area touches upon 14 countries.

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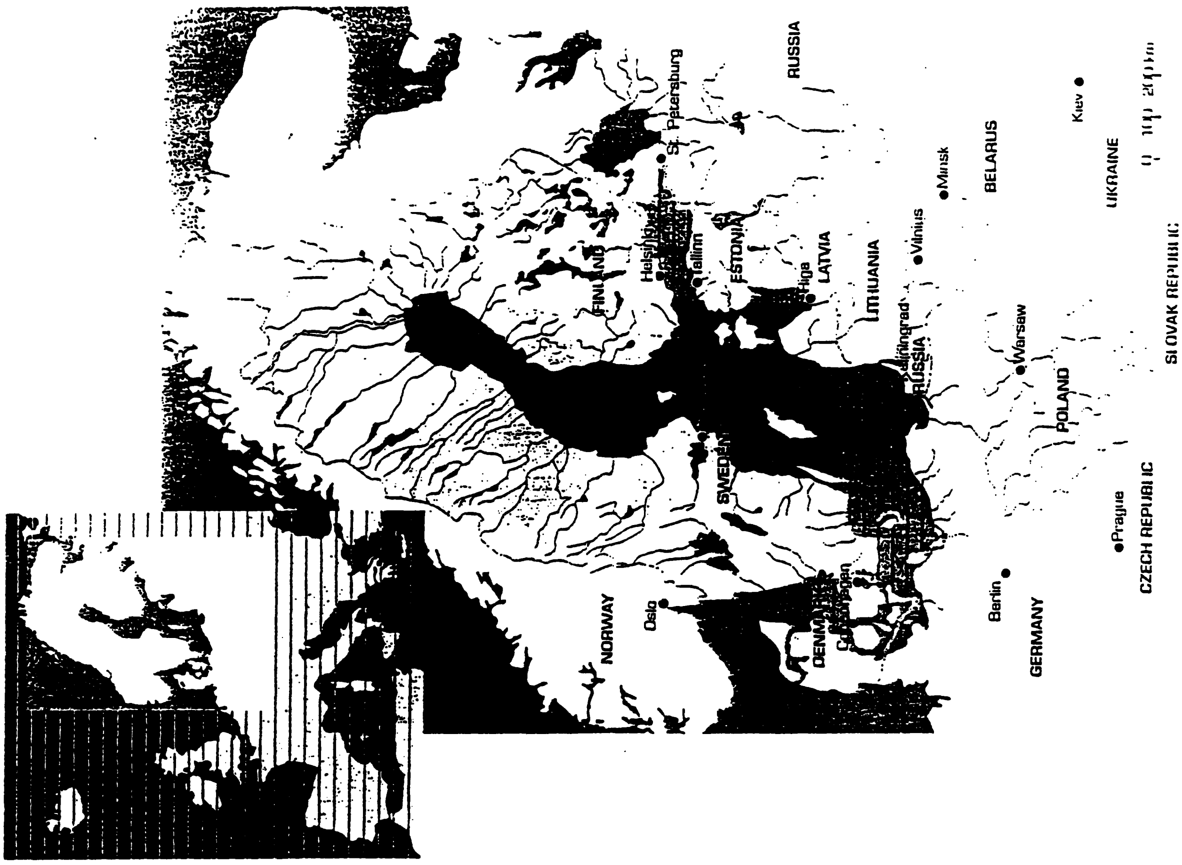
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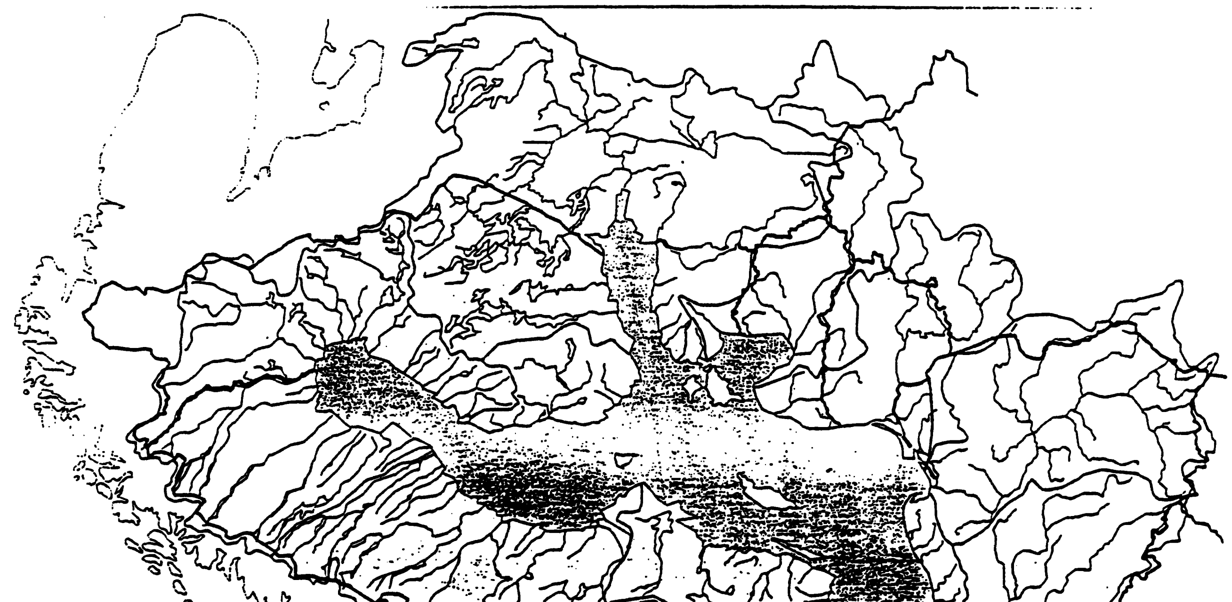

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GROUNDWATER DISCHARGE CONTAMINATION TO THE BALTIC SEA AND PLAN OF ITS STUDY

VORONOV, A.N., O.V. KUZMITSKAYA and A.A. SHVARTS

The groundwater discharge pollution is very dangerous for inland seas that have limited links with the ocean. The Baltic sea is one of such seas. Twelve industrial developed countries where more than 65 million people live are situated within the Baltic sea basin. A large number of industrial centres -- St. Petersburg, Riga, Tallinn, Helsinki, Kaliningrad, Gdansk, Kiel, Copenhagen, Stockholm -- are all round the sea. Despite the large sea surface area (above 415000 km^2), total water volume is not great.

There is no question that the sea gets a major part of pollution with surface discharge; however, the contamination received by way of groundwater discharge is also considerable. There is a sluggishness of the groundwater changes in bottom sediments that are the most vulnerable part of ecosystem. There are also difficulties in the study of the process. It should be specially noted that although the generalised coast line has 7000 km length, it's length including gulfs and islands is about 22000 km. One should not underestimate the influence of groundwater discharge contamination upon ecosystem; oceanography papers and reports often do not take into consideration underground water flow.

However, not long ago (June 1993) this problem was discussed at the International congress "Ecological Hydrogeology of the Baltic Area" in St. Petersburg. This congress was organised by St. Petersburg and Wroclaw Universities and was sponsored by the International Association of Hydrogeologists, the International Association of Hydrological Sciences, and the Russian Academy of Science. There were more than 200 representatives from 22 countries. The results of study of groundwater discharge to the Baltic sea in different countries were reported. The great pollution of Baltic groundwater due to anthropogenic influence had been pointed out.

The concrete example of influence of underground water flow on the Baltic sea were considered in some reports. Large numbers of contamination types changing the sea water quality were mentioned. This contamination worsens ecological conditions of the waterside zone. However, reports on groundwater pollution influence on biological organisms, geological environments, water-supply quality, and its social and economic results have not yet been submitted.

In the nearest future scientists must focus their attention on following questions:

- estimation of the pollution carried by underground water flow;
- chemical processes of the interaction between bottom deposits and groundwater in the seaside zone;
- new methods of ecological estimates of coastal zone and water state.

For these reasons the Department of Hydrogeology of St. Petersburg University began a systematic investigation of pollution groundwater flow within the Russian part of the coast of the Baltic sea. The coast line of the Finnish Gulf is about 300 km. The depth of the gulf is less than 50-100 m. The hydrological condition of this part of Baltic sea is controlled by the Neva river. The average water flow of the Neva river consists of 3500 km^3, and area of its basin is 202000 km^2. The new dam that separated the most shallow part of gulf from the sea changes the hydrological regime of the gulf.

The underground flow to the Finnish Gulf consists of two parts: immediate discharge of groundwater, and underground flow to rivers and lakes which are connected to the sea. There are two largest fresh water lakes, Ladoga and Onega, within the basin of the Neva river. The Neva river transports Ladoga water to the Finnish Gulf.

The immediate discharge of groundwater in turn can be divided into flow of water from the upper hydrodynamic zone and discharge of deep aquifers that contain unconfined water. The discharge of shallow groundwater occurs all along the coast. On the north part of the gulf it is discharged from fissure zones of crystalline rocks of Archaic basement and from aquifers of glacial layers of the Carelian isthmus. On the south coast of the Finnish Gulf it is discharged from an aquifer of Ordovician limestone which contains large water systems. It is possible that the Gdov aquifer on the Carelian isthmus discharges immediately into the Finnish Gulf. However, because of reduction of water level it is possible that the process has reversed.

The Hydrogeological Department of St. Petersburg University has been carrying out ecological and hydrogeological mapping of subsurface water discharge to eastern part of the Baltic Sea (Finnish Gulf). The methodological principals of such mapping has been worked out. The set of four maps shows pollution of the aquifers.

The first map shows the economic view of the territory, and potential sources and types of water pollution. There are agricultural lands, stock-breeding farms, roads, railways, industrial enterprises, etc.

The second map characterises the degree of aquifer vulnerability. This map is based on the information which makes it possible to estimate the protection of the aquifer from surface pollution and the speed of movement of the front of polluted groundwater.

The third map shows water quality and pollution of the upper aquifer by toxic and bioactive substances.

The fourth map shows the main recipients of pollution, mainly the existing and planned water protection zones, showing area in which the water flows to the water intakes.

The zones of water recharge and discharge, surface water courses, pollution control wells and others are also shown on the map. The maps are not overloaded and can be easily read. The number of maps can be increased according to concrete tasks.

The most contaminated part of the underground flow is the water discharge from urbanised territories. The groundwater of St. Petersburg and its vicinity is very polluted. The degree of contamination increases from residential districts to the central part of city. Heavy metals, organic substances, sulphates, and radioactive elements are founded in the upper horizon of subsurface water. Total mineralisation has increased to 3-4 g/l. The acidity of water also increases in some cases. The water has high agressivity. The groundwater is discharged into the Finnish gulf directly and into a number of flows and rivers.

The Karstic water of the Izhorskoe plateau which is discharged immediately to the Finnish Gulf in the Estonian part of the Baltic coast and by small rivers on the south part of Baltic coast of Russia is very contaminated. The basic type of contamination is agricultural. Nitrate, pesticide, organic substances, and others are found here. The nitrogen contamination is widespread within the region. The main part of this contamination is nitrates. It reaches 50-100 mg/l to the northwest. The main pesticide is Lindan. Industrial and chemical contamination have local characteristics. Oil contamination have also found in some places.

The groundwater of the Carelian isthmus is cleaner. One encounters local contamination only in the places where clays have been removed.

In the course of the Ecobalt congress it was noted that contamination of the Baltic Sea was wide spread and study of the shelf and shore was necessary. It must be a joint project. The international programme of study of contamination water flow was accepted.

Among the main problems to be solved are:
- working out and improvement of methods of ecological and hydrogeological mapping;
- improving of the chemical-analytical base of ecological study;
- working out of complex methods of quality evaluation of water resources and the geological environment;
- elaboration of monitoring principles and creation of effective measures against groundwater flow pollution;
- creation of a data bank on groundwater and creation of a package of ecological hydrological maps for the basin of the Baltic Sea.

3.3 Original Program Abstracts (presentations not represented by a full paper or extended abstract)

METHODS FOR EVALUATING GROUNDWATER DISCHARGE AS APPLIED IN SOUTHERN ITALY

AURELI, A.

The study group within the Geology Institute of the Catania University, under the scientific direction of prof.A.Aureli, for more than 20 years has been interested in the problems concerning the exchanges that take place in coastal aquifers between fresh and sea water.

The study has been led by clearly distinguishing diffused exchanges from concentrated ones.

The first ones originate exchanges that are difficult to measure.

The second ones originate submarine or coastal springs.

The most recent techniques such as thermoscopy, salinometers and remote sensing have been used to evaluate their possible utilisation in analysing water exchanges along the coasts.

These methods have been tried along the coasts of Sicily and Calabria, allowing us to identify and study in a particular way the main submarine springs that we have spotted. We have also led sea campaigns to study the behaviour of some of these springs.

In a special case we have identified the paths of ground feeding of some submarine springs through the colorimetric method.

An extreme economical and practical importance have also revealed the studies concerning the sea intrusion phenomena along the coasts.

The editing of detailed Hydrogeological Maps to a scale of 1:50.000 of some of the coastal zones of Sicily has pointed out the entity of the phenomenon of the increasing salinity of coastal aquifers due to primary permeability as well as their path along the tectonic dislocations in aquifers with a secondary permeability.

We have also been able to follow and analyse the link between tectonic structures and the formation and development of karst phenomena in a coastal setting.

In general we have detailedly studied 936 km of coasts in Sicily and 593km of coasts in Calabria.

We have identified 134 submarine springs in Sicily and 61 in Calabria.

We have reckoned that, altogether, the coastal aquifer losses into the sea, in Sicily, amount to an average 284×10^6 cubic meter a year. For Calabria this figure has come out to correspond to 104×10^6 cubic meters.

The vulnerability maps of the south-east coastal region of Sicily, which are to be seen on posters, give an idea of the researches carried out and of the obtained results.

ESTIMATING SUBSEA GROUNDWATER SEEPAGE FROM A COASTAL PLAIN

BOKUNIEWICZ, H.

ABSTRACT

Coastal plains cover about 5.7 million square kilometers of the earth's surface. The coastal plain of the United States has an area of 940,000 square kilometers. It is one of nine major coastal plains worldwide. The others are along the Caribbean coast of Mexico, in Venezuela and French Guinea, at the Amazon delta, in northern Europe, Mozambique, southeast Asia and Siberia. The hydrology of the U.S. coastal plain has been studied extensively and modeled by the U.S. Geological Survey under its Regional Aquifer Systems Analysis Program between 1979 and 1987. Although specifically focused on the emergent coastal plain, model results showed a diffuse seepage across the shelf corresponding to subsea discharges of up to several thousand liters per day per meter of shoreline. High rates appeared off the coasts of New York and the Carolinas. Seepage of the Long Island coast had been measured; seepage rates have also recently been confirmed at least 37 km off the Carolina coast amounting to 40% of the river flow (Moore, 1996, Nature 380:612). The concentration of subsea seepage near the shore was unresolved by the regional model. Even with this attention, estimates of the magnitude and distribution of the direct seepage of groundwater are difficult to obtain and estimates of less well studied coastal zones are uncertain. A simple, cross-sectional analytical expression may be used to guide professional judgment in making estimates especially where numerical solutions are lacking.

Along the New York coast, the observed rate of seepage decreased rapidly offshore, as expected. For a homogeneous, anisotropic coastal aquifer, the outflow gap is expected to be approximately 4l/k where l is the thickness of the aquifer and k is the square root of the ratio of vertical hydraulic conductivity (K) to the horizontal hydraulic conductivity. The total discharge per unit length of shoreline is $\pi Kil/2k^2$ where i is the hydraulic gradient at the coast. The expression is an upper limit because it does not take into account a substantial recirculation of salt water which can be driven by the same hydraulic potential. Even simple aquifers may not be well-characterized by singled valued parameters and systems of confined aquifers can only be qualitatively described. Observed seepage magnitudes and distributions off the shore of Long Island, NY were fairly well described by the analytical impression, within the range of parameters, very near shore where the surficial aquifers are expected to control the flow. Empirically, the seepage amounted to almost 9000 liters per day per meter of shoreline or 20 to 35% of the total freshwatrer supply. An outflow gap of at least 8 kilometers was forecast but deep, confined aquifers add an anisotropy which forces low seepage rates far offshore.

STUDY OF THE DISCHARGE OF GROUNDWATER CONTAMINATED BY OIL PRODUCTS IN THE COASTAL ZONE OF SEAS

BOREVSKY, B.V., BOREVSKY, L.V. and SHCHIPANSKY, A.A.

Actually the contamination of sea areas presents a real ecological hazardous problem in the worldwide. One of the most contamination sources is the groundwater discharge to the sea in the coastal zones where are concentrated a number of industrial and civil objects. Ground water contamination by hydrocarbons is the most dangerous and complicated problem for studying. So, were formed two contaminated phases, such as contaminated ground water and free oil products floating on the ground water surface. The last one, moving towards to the sea, creates a visual environmental contamination of the sea on large areas, and the extent of contamination widespreads not only over the sea water but also in bottom sediments, beach deposits, and sea biota. On the other hand, the saturation of clayey rocks by hydrocarbons decrease their structural associations resulting in increasing the rate abrasion seashores.

The studying the ground water mass transport in these conditions is a complex and multi-purpose problem. The difficulties of its solving are aggravated by the fact that the theorie of two-phases flow in unconfined aquifers and interaction in the system shore/ sea in conditions of the adverse contamination by hydrocarbons is not aqequately developed. Moreover, the evaluation of quantitative characteristics of contaminated ground water and oil products as well as forecasts changes in time and space needs important financial and material expenses.

The investigations results of large technogenious oil products in the coastal zones of the Sea of Azov (town of Eysk) and Black Sea (town of Tuapse) are taken as examples. The above sites are essentially differed one from another by complex hydrogeoecological conditions. If in the first case (Eysk) the ground water flow is confined to semipermeable loess-like loams taking into account the fact that the value of permeability for hydrocarbons is greatly more than that for water, in the second case (Tuapse) the groundwater flow is associated with alluvion deposits having high permiability and variable hydrogeological conditions which are typical for mountain rivers in the Caucasus.

In this paper are considered the concepts and methods of ground water investigations under conditions of geoenvironmental contamination by hydrocarbons in the sea coastal zone as well as forecasts methods of contamination evolution processes.

GEOCHEMICAL APPROACH TO THE EXAMINATION OF SUBMARINE DISCHARGE OF GROUNDWATER IN THE COAST AREA

BROUSSILOVSKI, S. A.

In the wide complex of hidrodinamic, hidrochemical, geophysical, balance, aerospace and other methods of examining submarine discharge of ground water employment of geochemical methods is perspektive as well. Display of submarine discharge as geochemical or temperature anomaly in bottom and especially surface sea water can be seen very seldom, only in case of concentrated spring discharge and ladge expenditure, as bottom currents, turbulent mixing process lead tu concentration and temperature equalization, that limits the use of many methods.

The most common features of submarine ground water discharge are interstitial water, anomalous in composition, and chemisedimentation processes of a number components of ground water on oxidation-reduction, hydrogen sulfide and sorbtion barriers in sea sediments. Almost all iron and manganese as well as a big group of microelements accumulate in discharge areas, making steady complex geochemical anomalies.

Water and ion underground discharge to the sea is estimated by the content of iron in in ground water, its ion composition, general quantity of iron excess in bottom sediments of anomalious area and age of iron area.

Identification of water of the discharge area with separate water-bearing formation is being made on the base of comprasion of chemical and isotop composition date, taking into consideration possible changes in diagenetic reactions. Geochemical inert chloride ion is a good indicator. This method was tested while studying submarine discharge in the Caspian, Black and Red Sea.

DIFFERENT TYPES OF SUBMARINE DISCHARGE FROM THE GEORGIAN COAST TO THE BLACK SEA

BUACHIDZE, G. and MESKHETELI, A.

General geotectonic structure predetermines, besides other processes, the ground water discharge as well. The coastal part of Georgia involves the Great Caucasus Southern Slope fold system (carbonaceous rocks); Georgian Block with thick Quaternary deposits and Adjara-Trialety fold zone of the Minor Caucasus (volcanogenic rocks). Accordingly are distinguished the types of submarine discharge: the northern one peculiar for prevailing karstic discharge; then southwards comes the type specific for direct seepage from phreatic aquifers and shallow subtidal zone; the southmost one with deep offshore discharge from volcanic rocks.

The first zone features high pressures of karstic waters (recharge areas are located at the elevation of 2 to 2.5 km), this predetermining intense discharge both of concentrated (with springs yielding over hundred litres per second, Gagra) and areal (Leselidze) pattern.

The second zone presents an area of discharge of shallow ground water flows - Kolkhety.

The waters of the third zone develop a deep penetrating system of pressure fracture waters, investigation of which happens to be the most difficult one. It coincides with Adjara seacoast.

The researches, that have been conducted herein lately, have revealed that the change in hydrogen sulphide surface in sea water on the shelf is due to the pollution of the coast and the adjoining water area (increased discharge of the organic material). The effect of rising of this surface is very clear - accounting in some places for above 50 m just in 10 years. With this one has a universal criterion of seashore ecological condition.

RIVER PROTECTION ZONES AND ITS ROLE IN OUTFLOW OF POLLUTANTS INTO SEA WATER

CHERNOGAEVA, G.M. and ORLOV, M.S.

Problems connecting with outflow of pollutants from the river systems into the sea waters are analysed. Calculations using monitoring data show that yearly thousands tons of pollutants are flew out by the big rivers in Russia. The main part of the total outflow is oil outflow (near 100 thousand tones). Pollution of the river flow is along the whole of hydrographic system. It being known that near half of the whole mass of pollutants flows diffuse way from the watershed area.

The principles of choose of the river protection zones are formulated in the paper from the systematic ecological point of view. The natural (including hydrogeology) and technogenic conditions are also taken into account. The main idea of river protection zones is management of water quality in the river system taken as a whole.

MAJOR ENVIRONMENTAL ISSUES ASSOCIATED WITH COASTAL GROUNDWATER SYSTEMS IN AUSTRALIA

JACOBSON, G., BIEWIRTH, P. and GRAHAM, T.

Major environmental issues are emerging as a result of the intensified urbanisation of the Australian coastal zone, as well as agricultural development in the hinterland catchments. These issues include:

. Eutrophication of coastal waters in southwest Australia owing to the discharge of nutrients from sewage, fertilisers and industrial effluent. This problem contains a substantial groundwater component, as the Perth coastal plain is underlain by Quaternary sediments containing permeable and productive aquifers. Remedial strategies are being developed, including reduction of fertiliser use.

. Acidic drainage from acid sulphate soils on Holocene coastal plains along the eastern Australian coastline. Drainage of these soils for urban and other development has resulted in the oxidation of pyrite and consequently the acidification of groundwater and estuarine water. This problem of ecosystem degradation affects the fastest growing region in Australia and is regarded as a major constraint on economic deveklopment.

. Significant degradation of the Great Barrier Reef has occurred through the export of nutrients from North Queensland catchments to the coastal zone. The nutrients are mainly derived from fertilisers used in sugar cane and other farming. This problem is under intensive study.

. Seawater intrusion is a problem in several important regional aquifers along the east and south coasts of Australia. Management strategies include the conjunctive use of surface water for irrigation, and artificial recharge.

An annotated bibliography of recent Australian research on these problems will be made available to participants.

NORTH CHINA PLAIN: THE NEED AND PLAN TO JOIN THE LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE PROJECT

JIN, F.

In China, such work like studying on Land-ocean interaction with the view point of groundwater discharge into ocean and its impact on global climate change, has not yet carried out. However, in order to explore and utilize groundwater, quite a lot of hydrogeological studies have been done throughout the country for more than 40 years, and abundant data as well as work experience have been accumulated. For recent years, along with China's rapid economy development, arises problem of groundwater resource sustainable utilization. In order to solve the problem, Chinese hydrogeologists realize that it is essential to solve the problem of mid and long term regional climate changes and their impact on groundwater resources. On the other hand, Chinese hydrogeologists are more and more concerned about the impact of groundwater change itself on climate changes. Among other problems, the role of groundwater discharge that could reflect the functioning of the Earth System and its consequence is a very interesting and important problem to study. Now a 4 year key project has already been set up for this purpose. The selected area for this project is the North China Plain -- the coastal area of Bohai sea, with the following considerations:

- Total area -- 320,000 km^2, population -- more than 100,000,000.
- This is the most important economic area in China.
- The area is highly dependent on groundwater water supply, more than 80% of the total water supply.

- Due to the long time and large scale overexploitation, as well as pollution problems, groundwater and river water in this plain have greatly changed both in quantity and quality, for example, in some places of Tangshan area, close to Bohai Bay, the NO_3 and NO_2 contents in groundwater are observed as high as 275 mg/l, while it was less than 0.05 mg/l 30 years ago.
- There is a big gap between water demand and water resources. It is urgently needed to solve the problem of groundwater resource mid or long term prediction and the problem of interaction between groundwater overexploitation and climate change (at least, regional change).
- Abundant hydrogeolgical data. There are hundreds of monitoring wells' of more than 20 years observation history on groundwater level (head) change and change in chemical components of Ca, Mg, K, Na, HCO_3, SO_4, Cl. Other necessary data are available too.

The project was approved in May, 1996 by the Ministry of Geology and Mineral Resources of China P.R.. The title of the project is "The evolution process of regional groundwater and its interaction with neighboring spheres". Under this project, there is a topic of "The Evolution of Regional Groundwater and its Interaction with Ocean". The preliminary idea to carry out the topic is as follows:

- Collect all necessary data.
- Establish a data base and hope to set up data exchange with relevant institutions or persons of common interest.
- Select a typical profile to study changes of groundwater discharge and chemical component carried by groundwater into ocean.
- Study the changes of nitrogen content in groundwater and its circulation in bio-rock-water spheres.

About furthermore study on land-ocean interaction problems, Chinese hydrogeologists are still looking for cooperation from oceanologists.

Existing problems:

- Need to establish an international network to strengthen data exchange.
- It is hopeful that the LOICZ Core Project office would promote the progress of relevant studies throughout the would by activities such as publicizing progresses of certain case studies, holding workshops to exchange experiences, strengthening discussions via emails etc..

MAIN PRINCIPLES OF COMPLEX MONITORING IN THE "COASTAL-SEA" SYSTEM

KOCHETKOV, M.V. and KOMAROV, A.V.

Current deterioration of quality and productivity of natural environment in the system "Coast-Shore" is connected mainly with economic activity of Man. First of all this is contamination of air, soil and water. It caused by industrial wastes disposal, outwash of nutrients and chemicals from arable lands, damping of raw materials and industrial wastes in the sea, underwater disposal of municipal wastes, ports activity etc. This leads to contamination of the environment by biogenic elements and organic matter, by toxic compouns and heavy metals, oil and aromatic hydrocarbons etc. Taking into consideration all components quality deterioration (air, soil, river and sea water as well as bottom sediments) to controle the state and improve environment it is necessary systematic measurement of environment components to see their changes, i.e. to carry out complex monitoring.

Main tasks of complex monitoring are the following:

- finding sources of pollution on land and in the sea;
- finding factors of influence (or contamination) which may be subdevided by chemical, physical and biological;
- definition of character and intencity of the environment responce on these impacts.

Complex monitoring includes:

- meteorological monitoring;
- monitoring of geological environment;
- hydromonitoring;

- geochemical monitoring;
- biomonitoring.

Monitoring of geological environment solves the folloving problems: ways of transportation, places of erosion and accumulation of sediments; concentration and movement of suspended materials and connected with them toxic contaminants; composition of bottom sediments, suspended matter and investigation of geochemical associations of elements and compounds; geological- geochemical transformation of current sedimentation conditions, the role endogenous, exogenous and biogenic material in the flux of the matter; estimation of submarine ground water discharge and bottom sediments contamination as well as appearing of geochemical anomalies; distribution and dynamics of contaminants brought by suface run-off and disposal of untreated municipal and industrial wastes.

The basis of monitoring is the model-oriented network of obsrvation sites in the system " coast-sea" located using the same metodological and organisational principle and containing obervation points and regime polygons. Programmes of observations are different for various types of monitoring and depend on intencity and changebility of components being observed.

Results of monitoring in different media which is carried out by different organisations are stored in data bases permitting interchange of data and usage of the same GIS. Usage of GIS in management decisions will permit sufficiently improve their quality and efficiency.

EXPERIMENTAL STUDY OF THE BOTTOM BOUNDARY LAYER IN THE DYNAMICS OF COASTAL ZONES

KONTAR, E.A.

The horizontal components of the flow velocity and the temperature of the bottom boundary layer (BBL) in the coastal zones of the Black and Mediterranean Seas and the Atlantic Ocean (in the vicinity of Coastal Canary Upwelling Zone) were measured 2.5 m above the bottom. The measurements were made continuously over the 6-day period. The Potok meters were incorporated into the self-recovering (pop-up) self-contained bottom stations. In the Black and Mediterranean Seas our study includes the discavery of bottom (benthic) storms in the coastal zone. These storms contain clear evidence of deposits, termed 'turbidites', which result from episodic down slope gravity transport of a dense suspension of water and sediment in a 'turbidity current'. Our data thus suggests a strong unsteadly mass transport in the coastal zone. The coastal zone BBL dynamics are complicated by variety of physical phenomena that show up as bottom storms, sometimes correlating with temperature variations in the bottom water. This latter fact has not been previously observed. In the Atlantic Ocean our measurements indicated that the BBL in the area of the Coastal Canary Upwelling Zone has highly variable dinamics. The complex interaction of the counter-flowing strong geostrophic currents, with flow velocities of 22 and 26 cm/sec, that was identified in the BBL by our measurements inevitably give rise to energy-consuming processes, which may influence the development of the upwelling in the coastal zone. For example the recorded speeds of the bottom currents undoubtedly produce erosion of bottom sediments, increasing the turbidity of the water in the BBL. The boundary region between the counter-flowing currents exhibits high levels of turbulence and a high degree of vortex generation, and these factors cause efficient transport of momentum and of substance in the coastal zone. The pronounced tidal phenomena in the measurement area increase the size of the zone in which the currents interact vigorously, and thus intensify eddy generation, which may follow the sea-floor relief to subsurface level or even emerge at the sea surface, forming the tongues and patches of relatively cold water typical of the upwelling.

CRITICAL REVIEW OF ANALYSIS OF GROUNDWATER DISCHARGE IN THE COASTAL ZONES OF THE GREAT LAKES AND INTERNAL SEAS - CASE STUDIES IN THE UNITED STATES AND POLAND

KRYZA, J.

Abstract

During 1970 -1996 a lot of research were done for groundwater inflow estimation from aquifers to Great Lakes in the USA and to Baltic sea and some lakes in Poland . From 1994-1998 thisa joint US- Poland research supported by a scientific Russian expert. In the first phase, of analysis an evaluation of applied methods and next selection of the best approach to solve the problem in the case study were done. An extended data base on hydrogeological conditions and parameters for four experimental catchments in shore zones in both countries have been prepared. At the present moment, numerical models and fields studies are begining in order to verify in the best way the interaction and water exchange between aquifer and surface water reservoirs. Up to this moment published results stated only calculation of groundwater contribution by rivers flowing to the lakes and sea. The present research attempt to evaluate direct groundwater inflow to the lakes by bottom sediments.

The weak point of this research is a lack or insuficient data about the hydrodynamic field around or/and underlaying formation of the resevoir. This situation creates problem not only for boundary condition of inflowing groundwater but also, in some cases for precise calculations. The only inland sea and gigantic lakes are the cases where stable hydrodynamic fields exist and udergoing small seasonal fluctuation considering shallow groundwater. Stability of these fields are confirmed by regional observation and monitoring of chemical and isotopic composition which allows analitical calculation. As a results preliminary average value of discharge is available. The local and partly regional flow system of Great Lakes are not stable and sesonal as well as long term variation can be observed. This makes it sometimes impossible to apply analitical methods for the budget calculation. Results obtained from different studies show groundwater budgets, for the same region, differ by more than one-hundred percent. In my opinion the most problematic issue for detail calculation of inflow is a lack of sufficient recognation of hydrodynamic field in the lake vicinity . On the coastal zone of the Baltic Sea and Lake Michigan there exist rivers which act as parallel barriers to the regional flow to these bodies. In some cases the barrier continue along tens of kilometers in distance few hundred meters. None of authors publishing on problem under consideration attempted to design boundary q=0 under the lake bottom. For the Great Lakes its extention is important issue for modelling. In most cases, this determines quantitative budget evaluation around reservoir and under the bottom of lakes. The other critical issue is regional evaluation of parameters. Collected data should be the base for regional modell construction. Parameters distribution can be based on numerous geological cross-section across costal zone using the 2D flow net model. It has been confirmed during model construction of Lake Michigan and selected lakes in Poland. Models are prepeared for Modflow and Flownet computer programs and could be basis for 3D model applied in Visualmodflow used in the Polish study. Model validation should be supported with field research, infiltration measurements, geophysical sounding, thermal and chemical monitoring, and isotopic and microbiological study of seeping water. Comprehensive research and method verification of direct inflow with predominant of modelling method can provide detail recognation of groundwater inflow to the lakes.

PREDICTION OF INFLUENCE OF BIG INDUSTRIAL COMPLEXES ON QUALITY OF GROUNDWATER AND SURFACE WATER AS CASPIAN SEA-LEVEL ELEVATES

PITIEVA, K.E. and GOLOVANOVA, O.V.

Fluctuation in sea-level leads to variation in water-level of rivers. Variation of water-level being also a possible result.

Under industrial, agricultural influence, etc. quality of ground water and surface water often degradates. It's expressed as variation in redox and other conditions, concentration of pollutants and others.

Deterioration is supposed to be a result of either upward or downward fluctuation in sea-level. It depends, on the one hand, on the contribution of polluted groundwater flow discharge to the total river runoff. On the other hand, it's conditioned by variation in concentrations of pollutants in the discharge from the fact that the contribution of polluted groundwater to the total one is variable.

As the sea-level elevates, the elevation of rivers water-levels is expacted. It causes decrease of a groundwater flow discharge. In the same time, share of polluted discharge increases. In the case of sea-level lowering the opposite tendency is expacted.

So, resulting changes in the surface water quality are not similar. That's why they must be estimated quantitatively in the each case. In so doing, the changes of components concentrations caused by complexed physical and chemical processes (including mechanisms of increase and decrease of components concentration) must also be estimated.

In the context of the elevation of Caspian sea-levelthe increase of the surface water level is predicted to the area affected by Astrachan Gas-Condensate (AGS) industrial complex. A special identificated groundwater flow and mass transport model is used to estimate pollutants and other species concentrations (boron, total dissolved concentration, etc.) In the rivers, under the most dangerous conditions of the lowest rivers discharge. The identificated model structure makes it possible to estimate the concentrations exactly at given conditions of sewage infiltration rates and concentrations of pollutants in: infiltrated sewage,and given levels of the rivers.

The decrease of the groundwater flow discharge from $7,81 \cdot 10^{-3}$ to $6,08 \cdot 10^{-3}$ m^3/d, the decrease of the total dissolved concentration from 13,9 to 10,9 g/L, but the increase of boron concentration from 1,877 to 2,053 mg/L have been calculated withrespect to the polluted groundwater flow discharge. The decreaseof the resulting total dissolved concentration and boron concentration in the rivers from 1,16 to 0,85 g/L and from 0,164 to 0,152 mg/L respectively has been obtained. All the changes have been predicted as the given levels of modelled rivers elevate by 0,5 - 1,0 m asa whole. So,the influence of the polluted groundwater flow on the quality of the rivers is reduced as the level of Caspian sea elevates.

GIS MAPPING OF NITRATE LEACHING IN VEJLE COUNTY

SKOP, E.

Abstract

A method to couple agricultural data with a soil map in a Geographic Information System (GIS) to predict the spatial distribution of nitrate leaching in a Danish County is proposed. The agricultural farm structure in Vejle County, Denmark, is described using a set of seven farm types distributed on three soil types to give 21 different combinations of farm types and soil types. The spatial distribution of the farms is derived from General Agricultural Register (GAR), Danish Institute of Agricultural and Fisheries Economics (DIAFE) statistics, an address-coordinate register and CORINE Landcover map (Larsen and Soerensen, 1996) using a heuristic spatial allocation procedure in GIS. The allocation procedure consist of the following seven steps, 1) classification of the farms in GAR according to the seven farm classes 2) generation of a point coverage with the location of the addresses of the farms in GAR, 3) rasterisation of the point coverage, 4) overlaying rasterised point coverage with CORINE Landcover map and soil map and reclassifying pixels with agricultural land use (according to GAR) located on non agricultural areas (according to CORINE Landcover) and/or on special soil types to non agricultural land use, 5) creating weighted Thiessen polygons around the pixels located on farm addresses, 6) overlaying weighted Thiessen polygons with a landcover-map to determine areas available for agricultural production, and 7) overlaying with a soil map to derive the soil distributed farm structure.

Nitrate leaching from Vejle County is calculated for each combination of farm classes and soil types by means of a statistical regression model (Simmelsgaard 1991; Skop, 1995), and GIS is used to generate the spatial distribution of the nitrate leaching. Directional trends caused by soil and farm type distributions are easily identified. Large differences between the farm classes can be seen. N-leaching per ha is largest on sandy soils and least on loamy soils. Small differences in N-leaching can be identified as a result of farm sizes, whereas large differences can be seen between pig, cattle, plant and part time farms. Part time and plant cultivation farms have less N-leaching than the cattle and pig production farms, primarily as a result of fewer livestock units per ha and application of small amounts of organic fertilizers. The leaching model does not encompass effects of variations, e.g. in climate. Therefore, the results only show what the nitrate leaching would be, ceteris paribus, i.e. the results are static-comparative.

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GEOHYDROCHEMICAL AND HYDROGEOLOGICAL STUDIES TO DELINEATE GROUNDWATER DISCHARGE ZONES IN EASTERN GHATS REGION OF INDIA

SWAMY, A.N.

The Eastern Ghats of India are disconnected hill ranges running almost parallel to the east coast of India adjoining the sea known as Bay of Bengal. The northern part of eastern Ghats run NE-SW closely with a narrow strip of coastal plain area. The hills are steep sloping in nature and are studded with a number of peaks. Average elevation is 750 meters, though individual peaks rise to heights of 1500 meters above sea level. Hydroclimatological investigations indicated the region to be semi-arid. Geologically the northern eastern Ghats are mostly uniform in nature with dominant rock types known as Khondalites which are highly metamorphosed sediments of Archaean age. Several smaller rivers having their origin in the eastern Ghats have well developed basins in their watersheds and groundwater from these basins and adjoining coastal plains discharges into the sea. In the present study the nature of hydrogeochemical and hydrogeological variations associated with groundwater as it travels from recharge to discharge zone has been investigated in a representative topographic basin located in the middle of northern part of eastern Ghats. The study area known as Visakhapatnam basin is surrounded by hill ranges and extends to an area of 148 square kilometres with mean monthly temperatures ranging from 23.3°C in January to 30.4°C in May. The sea enters to the mud and marsh located at the central part of the basin from the south-eastern flank where a natural harbour is formed and thus may exert influence on groundwater discharge zones of the basin. Water table data was collected from a network of observation wells and groundwater samples were collected. Chemical analyses has been carried out for conductivity, total hardness, chloride, bicarbonate, sulphate, calcium, magnesium and sodium plus potassium ion concentrations. In addition vertical geoelectrical soundings were made to study the hydrogeological nature of the aquifer. Stiff, Piper, Schoeller and Chebotarev methods of classification has been adopted for geohydrochemical analyses and used in conjunction with the hydrogeological data to study the groundwater chemistry as it travels from the recharge areas to the discharge zones where groundwater enters the sea. The results are presented in the paper.

SIGNIFICANCE OF GROUNDWATER DISCHARGE OF NITRATE FROM RESORT ISLANDS OF THE GREAT BARRIER REEF, AUSTRALIA

VOLKER, R.E. and GALLAGHER, M.R.

The influence of water-borne chemicals, especially nutrients such as phosphorus and nitrogen, on the water quality of the Great Barrier Reef Lagoon is assuming greater importance as pressures for development, both on the adjacent mainland and on islands in the lagoon, increase. Maintenance of acceptable water quality is vital to the main reef structure itself but there are also numerous fringing reefs associated with islands scattered throughout the region and the local marine environment around these fringing reefs is likely to be susceptible to discharges from the islands. Evidence suggests that coral reef ecology is sensitive to relatively small elevations of nitrate above natural background levels. The management of water and waste-water in resorts on the islands around which the reefs occur must, therefore, take proper account of the associated nutrient loadings and will rely on accurate predictions of the eventual fate of those nutrients.

Data collection and analysis has concentrated to date on two islands which have been instrumented with soil moisture samplers. One island disposes of its waste-water by irrigation of secondary treated effluent on lawns, golf courses and gardens. The other island pipes its discharge to the sea but is in the process of implementing an effluent irrigation program with most of it to go on the golf course.

On the first island, water supply is from surface sources although some groundwater sources have been identified. The consequences of land based effluent irrigation on the subsurface water quality has been assessed by sampling of soil moisture at monthly intervals over a 6 month period. From these samples the time averaged nitrate-N concentrations vary spatially from 0.1 to 3.0 mg/L.

The resort on the second island draws its water supply from groundwater in the Holocene/Pleistocene dune sands. Average total daily water use by the resort is approximately 294 kilolitres (kL). Of this, approximately 50 kL per day was used for golf course irrigation. Wastewater is generated at the rate of about 183 kL per day with a nitrate-NO_3 average concentration of 8.5 mg/L. The range of nitrate concentrations was from about 1.0 to 19 mg/L. On this second island, monitoring of soil and groundwater has commenced and will continue over the time during which effluent irrigation is introduced and thereafter. The groundwater was sampled from several supply wells and found to have nitrate-N concentrations in the range 0.7 to 1.2 mg/L. The aquifer has a relatively high hydraulic conductivity and is well connected hydraulically to the sea since sea-water intrusion has been detected in bores close to the beach areas in the dry season. Soil moisture samplers at 1.0 metre depth in the vadose zone have returned samples with nitrate-N concentrations in the range 0.7 to 1.5 mg/L over a 3 month period. Even though effluent irrigation is not yet practiced on this island, fertilising of the golf course does occur and the higher nitrate concentrations were measured under the golf course.

While the nitrate levels so far detected in soil or groundwater on both islands are relatively low by drinking water limits, it should be noted that fertilising of lawns and irrigation of treated effluent has been practiced for only a relatively short period, and continued monitoring and associated numerical modelling is warranted to predict longer term consequences.

The best estimates of nutrient output of major rivers from the mainland shows that the potential contributions from resort islands are minimal by comparison in terms of the overall nutrient budget of the Great Barrier Reef Lagoon. Based on loadings from effluent produced on the islands and assuming output to the marine environment in the immediate vicinity, calculations have shown that rises in nitrate concentrations sufficient to be detrimental to the marine ecology are possible. These calculations involve assumptions about residence times around the coast of the islands before transport away by currents and tides. Work on this aspect is being undertaken in conjunction with physical oceanographers modelling currents in the Lagoon under different meteorological conditions.

ANNEX 1 CONCLUSIONS AND RECOMMENDATIONS OF THE INTERNATIONAL SYMPOSIUM

[The following material is an edited excerpt from LOICZ Meeting Report No. 16, which also contains reports of the Symposium Working Groups and discussion rapporteurs.]

At the final session of the Symposium, the chairs presented a list of draft conclusions and recommendations derived from the discussion sessions and working group reports. These were discussed in plenary, following which a recess was taken to allow for revisions and additions based on the plenary discussions. The final plenary session then reconvened and adopted the following statements and recommendations:

A1.1 Conclusions

1. Groundwater flux to the coastal marine environment is an important biogeochemical and environmental factor in many coastal regions.
2. The physical and chemical processes involved in groundwater flux to the coastal marine environment are complex, and highly variable in space and time.
3. In view of the general scientific significance of the subject and to ensure that groundwater fluxes are properly accounted for in the LOICZ Programme, it is necessary to expand our understanding of coastal groundwater flux, and to improve the methods available for its assessment.

A1.2 Recommendations

To address item #3 (Conclusions, above), the following general objectives are identified:

- Elaborate and improve methods, approaches, and field/analytical equipment;
- Study and assess the significance and mechanisms of submarine groundwater flux;
- Investigate contributions of groundwater to biogeochemical regimes in the coastal zone; and,
- Assess potential changes in groundwater flow to the coastal zone connected with global change and human activities.

As initial steps toward achieving these objectives, the Symposium participants recommend the specific actions listed in the following categories:

A1.2.1 Information exchange, distribution, and general co-ordination:

- Prepare, distribute and maintain
    - A directory of researchers and agencies.
    - A bibliography of relevant publications.
    - A catalogue of data sources and access information.
- Publish and distribute
    - Symposium meeting report.
    - Symposium proceedings volume.
    - An overview report summarising and reviewing relevant concepts and methods.
- Establish an international working group to co-ordinate and advise on the further development of the field.

A1.2.2 Research and research co-ordination: The Symposium participants recommend the establishment and co-operative use of test sites and case study areas that will provide integrated investigations and opportunities for methods development and comparison. The characteristics of such sites and studies should include some or all of the following:

- Application to areas of potentially significant groundwater flux and/or changes in flux;
- Application of multiple methods; and,
- Links to LOICZ research activities such as biogeochemical modelling.

Although other sites will be identified in the future, participants constructed a preliminary list of possible test or case study sites that included:

- The Baltic Sea (see proposal in Appendix 5, LOICZ Meeting Report No. 16)
- Karst locations (Mediterranean: see Appendix 5, LOICZ Meeting Report No. 16)
- The North China coast (see Fei Jin abstract, Appendix 6, LOICZ Meeting Report No. 16)
- LOICZ Core Research sites (Indonesia, Malaysia, Philippines, Vietnam, and study sites identified by the biogeochemical modelling node)
- The Black Sea (see proposal in Appendix 5, LOICZ Meeting Report No. 16).

A1.2.3 The Symposium participants also recommend attention to and action on the comments and recommendations of the Symposium Working Groups, contained in Appendix 4 of LOICZ Meeting Report No. 16.

ANNEX 2 CONTACT INFORMATION: Symposium Participants and Others

The following names and addresses represent the first draft of a directory of scientists and program administrators interested in some aspect of interactions between groundwater and the coastal marine environment. It includes not only participants in the Moscow Symposium, but also other contacts and individuals who have responded to requests for information, or have published in the field.

This information is printed from a Microsoft Access contact database maintained by the LOICZ Core Project Office. The Project is also in the process of developing a linked database describing the available databases, scientific interests, geographic or environmental areas of study, and the principal techniques used by researchers who have responded to LOICZ questionnaires. In addition to these databases, there has been initial assembly of some relevant literature citations into an EndNote reference library.

Requests or suggestions for inclusion, corrections, or deletion from the databases should be directed to LOICZ at the address on the title page of this volume. LOICZ is interested in promoting better communication and availability of data in the general field of coastal groundwater and solute flux, and solicits information or collaboration to support that objective.

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