



Submarine groundwater discharge

**Management implications,
measurements and effects**



IHP



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IAEA

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International Hydrological Program (IHP)
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**by
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Preface

It would not be surprising that as a coastal planner, manager, or decision maker, you may not be aware of the growing realization of the importance of submarine groundwater discharge (SGD). Even if you are aware, you may not know how to decide whether or not SGD is relevant to the particular coast for which you are responsible. Furthermore, should you decide SGD is important, you may not know how to measure it. Groundwater discharge in the coastal zone is, as yet, insufficiently studied and difficult to measure. In this brochure, we present an overview of SGD, its implications for coastal managers, the difficulty in its assessment, and a brief summary of current activities by some international scientific organizations in this field.

International Coastal Hydrology Research Team

- ➔ *The International Hydrological Program* (IHP), UNESCO's intergovernmental scientific co-operative program in water resources, is a vehicle through which Member States can upgrade their knowledge of the water cycle and thereby increase their capacity to better manage and develop their water resources. IHP also aims at the improvement of the scientific and technological basis for the development of methods for the rational management of water resources, including the protection of the environment.
- ➔ The *Intergovernmental Oceanographic Commission* (IOC), another member of the UNESCO family, has focused on promoting marine scientific investigations and related ocean services since its inception in 1960. The IOC focuses on four major themes. These are to: (1) develop, promote and facilitate international oceanographic research programs to improve our understanding of critical global and regional ocean and coastal processes; (2) ensure effective planning, establishment and co-ordination of an operational global ocean observing system; (3) provide international leadership for education and training programs and technical assistance; and (4) ensure that ocean data and information obtained through research, observation and monitoring are efficiently handled and made widely available.
- ➔ The *International Atomic Energy Agency* (IAEA) is an independent intergovernmental, science and technology-based organization, in the United Nations family, that serves as the global focal point for nuclear co-operation. The IAEA has spearheaded the effort to build trained manpower and to facilitate the use and application of isotope hydrology in many of its Member States. For example, the IAEA's Isotope Hydrology Section has played a critical role in methodological developments and applications in the tracing of groundwater and surface water via isotopic techniques.
- ➔ The *Land-Ocean Interactions in the Coastal Zone* (LOICZ) is a core project of the International Geosphere-Biosphere Program (IGBP); its objectives are to describe and understand the interactive physical, chemical and biological processes that regulate the coastal zone portion of the Earth System, the environment provided for life, the changes occurring in the system, and the influences of human actions.

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'GROUNDWATER↔SEAWATER' INTERACTIONS

'It is ... clear that submarine groundwater discharge is widespread and, in some areas, of greater ecological significance than surface runoff'
(R. E. Johannes, 1980)

Knowledge concerning the undersea discharge of groundwater has existed for many centuries. The Roman geographer, Strabo, who lived from 63 B.C. to 21 A.D., mentioned a submarine spring (fresh groundwater) four kilometers from Latakia, Syria (Mediterranean) near the island of Aradus. Water from this spring was collected from a boat, utilizing a lead funnel and leather tube, and transported to the city as a source of fresh water. Other historical accounts tell of water vendors in Bahrain collecting potable water from offshore submarine springs for shipboard and land use, Etruscan citizens using coastal springs for 'hot baths' (Pausanias, ca. 2nd century A.D.) and submarine 'springs bubbling fresh water as if from pipes' along the Black Sea (Pliny the Elder, ca. 1st century A.D.). Thus, while the existence of submarine springs has been realized for many years, the information was largely anecdotal and not driven by scientific curiosity.

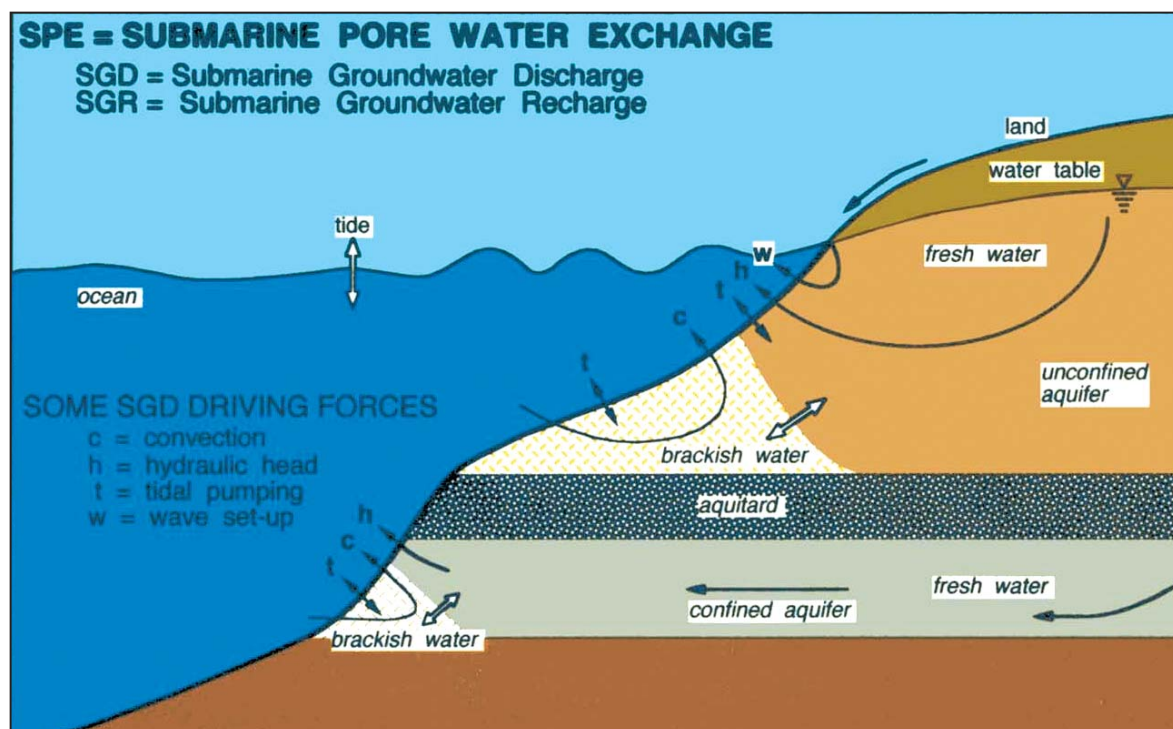
The subject has been neglected scientifically because of the difficulty in finding and measuring these features. We realize now that submarine groundwater discharge is more than a mere curiosity and its occurrence can be more subtle than the dramatic manifestations noted by our ancestors. Globally, groundwater seepage has been estimated to be a few percent of the total freshwater flux. One recent estimate suggests 2,400 km³ freshwater discharge per year (~6% of the world's river discharge) with 1,500 km³ per year from the continents, and 900 km³ per year being contributed from the world's islands. Undiscovered springs or slow, diffuse seepage through a sandy sea floor can still be important discharges. Important because they not only carry fresh water to the coastal zone but also can carry pollutants from anthropogenic sources on land into the ocean by an unseen pathway.

Managers, as well as scientists, need to be careful when talking or reading about 'submarine groundwater discharge' (SGD) because SGD is a term that may be applied to more than one phenomenon and because some designations may refer to discharges that may not be too important to a coastal zone manager while others may be critical. In its broadest sense, SGD is applied to any and all flows of water upwards across the sea floor, from the ocean bottom into the overlying water. (Since flow can also occur in the opposite direction, an even more general term – 'Submarine Pore Water Exchange' – may be used to describe any water flow across the sea floor.) Groundwater discharge may be pure freshwater entering the ocean from a coastal aquifer, or it may be recirculated seawater, or some combination of

the two. In a more narrow sense, it is sometimes used to mean only the freshwater component of that outflow.

This brochure is specifically concerned with the flow of SGD in the coastal zone, its effects, and implications for coastal managers. We will use the term SGD here to represent *all* direct discharge of subsurface fluids out across the seafloor (Figure 1). So SGD has two components, the fresh groundwater discharge originating on land, and recirculated seawater. It is that component of SGD from the land that poses the greatest concern for coastal zone managers because this component is most likely to carry pollutants. The recirculated water may be less problematic although it can still be called SGD.

Figure 1. Schematic depiction (no scale) of processes associated with submarine groundwater discharge. Arrows indicate fluid movement.



Source: Diagram modified from M. Taniguchi et al., *Hydrological Processes*, 2002 (in press).



CHARACTER OF SGD

'... these marvels of the sea (submarine springs) are justifiably classified as neglected phenomena of coastal hydrology'
(F. A. Kohout, 1966)

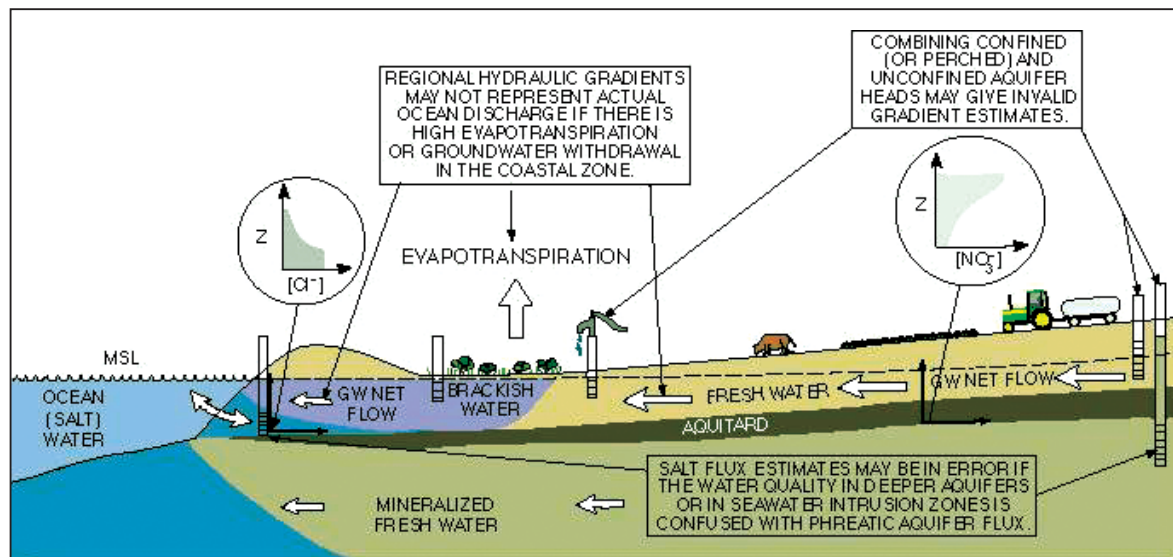
A basic driver of freshwater SGD is the amount of rainfall received by the drainage basin, coupled with evapotranspiration rates and the surface geology (particularly the surface infiltration capacity) but flow through coastal marine sediments can occur for a variety of reasons. Flow may be induced by the terrestrial hydraulic gradient as well as by marine processes such as wave set-up, tidally driven oscillations, density-driven convection, and thermal convection. The mix will be different in different regions. It will depend, for example, on the hydraulic conductivity, hydraulic head, groundwater catchment area, recharge rates and many other factors. Density-coupled modeling of the saltwater interface indicates that seawater recirculation rates of 60% and more can occur due to dispersion and mixing within the aquifer even when wave and tidal effects are ignored. Since wave-induced and tidal effects are rarely completely absent, a great deal of seawater recirculation must occur on a global scale, while the local effects of freshwater SGD can be dominant in nearshore environments.

The issue is how much water is transported to the coast via surface drainage as compared with subsurface flows. Human use of surface water and groundwater for agricultural, industrial and domestic purposes and subsequent wastewater treatment, reuse and disposal practices significantly impact the magnitude of both surface and subsurface discharges to the marine environment (Figure 2). The interactions result in variable and dynamic rates of groundwater discharge.

As a general rule, the highest freshwater SGD tends to be found closest to shore. In some places, a well defined, seepage face is found, often in the intertidal zone. In other cases, the distribution has often been described as decreasing exponentially from shore and often at a rate so that most of the flow occurs within 100 m or so of the shoreline, but this distance can be quite variable. The geological conditions might be such that substantial flow occurs kilometers offshore, as with the occurrence of springs or seeps. SGD occurring far offshore would be reflected by hydraulic heads in the aquifer at the coast that are significantly greater than mean sea level (with the exception of channelized aquifers, e.g., karst or volcanic terrain). In such cases, the aquifer must be sealed above by an aquitard (i.e. a layer resistant to groundwater flows) that prevents SGD at the coast; the saltwater interface which is an indicator of where SGD occurs will be located offshore. A famous example of the discovery of a freshwater aquifer offshore occurred about 45 km off Jacksonville, Florida during the test drilling for the original Joint Oceanographic Institutes Deep Earth Sampling Project (Figure 3).

In areas where seepage occurs through permeable sediments, seepage may be low, yet a small upward leakage over a wide area could make an important contribution to the coastal ocean. Seepage has been observed some 8 km off the Long

Figure 2. Detailed and expanded cross-section of the coastal environment, depicting problems inherent in generalizing limited measurements to obtain system-wide fluxes



Source: Diagram from R. W. Buddemeier, LOICZ/R&S/96-8, iv+179 pp. (1996), Texel, The Netherlands.

Island coast and its influence has been observed at least 37 km off the Carolina coast. Again, caution must be exercised in interpreting these observations because direct measurements include both the freshwater discharge as well as a component of recirculated seawater, which occurs throughout the ocean and can have distributions quite different from the discharge driven by freshwater SGD alone.

SGD takes different forms in different coastal settings. Freshwater discharge may be widespread and diffuse across sandy sea floors seeping up at low rates over large areas, often undetected. Alternatively, it can be intensely channelized and focused in small springs in karst regions entering the sea dramatically as submerged springs. SGD can also be a combination of the two in regions where a channelized flow at depth must seep through a blanket of uniform sediment. Only in the case of the channelized flow will it be recognizable as truly fresh water; elsewhere any terrestrially derived freshwater will be mixed more or less with the recirculated and dispersed seawater that is also being discharged. In this latter form, it may be difficult to recognize the driving force(s).

In the marine environment, submarine groundwater recharge (SGR) also occurs as a consequence of tides, waves, currents, sea level fluctuations, and density differences that force seawater into the sea floor. This water eventually must leave the sediment and, in some cases, it is discharged locally but, in others, it can emerge far from the source. It is also called by different names although it all contributes to SGD. Short period water waves agitate pore water without, necessarily, producing any net flow. This is referred to as 'wave pumping.' If the density of the ocean water increases above that of the pore water for any reason, pore water can float out of the sediment by gravitational convection in an exchange with denser seawater, again, without a net discharge. This process is sometimes referred to as 'floating' or 'salt fingering.' Some SGD is also called 'flushing.' This generally involves a continuous replacement of pore water involving a net discharge driven by the hydraulic

Figure 3. Well J1A, a geologic exploratory well 43 km offshore from Jacksonville, Florida penetrated an artesian aquifer that flowed up the drill pipe. The water, with a chloride content of only ~700 ppm (seawater = 19,000 ppm Cl), came from a depth of 250 m below the ship and had a hydrostatic head of 9 m above sea level.



Source: Photo reproduced from F. A. Kohout, *Symposium on Hydrology and Water Resources Development*, 1966, pp. 391–413.

gradients ashore or pressure gradients in the coastal ocean. Probably the most important occurrence of flushing occurs at the shore. Waves approaching the shore and tides raise the water level in the beach. This excess pressure drives water through the beach and across the sea floor into the coastal ocean. Groundwater discharge also occurs into freshwater in lakes and rivers, but, of course, the concomitant movement of salt water is not an issue in non-marine open waters.

Tidal effects on SGD can be especially pronounced. Higher tides, in general, increase the hydrostatic pressure resisting SGD, so the two should be expected to be inversely correlated. How the tide propagates into the aquifer along the water table or the tidal flooding (or draining) of coastal back-shore lowlands can confound this simple relationship, as can interactions with waves and current effects. SGD can exhibit temporal variability on a wide range of time scales in addition to the tidal ones. Wave actions can cause pore water to oscillate in its flow direction with

periods of seconds to minutes, whereas tides act on time scales of hours to weeks and can set-up equally persistent discharge patterns. Long-term patterns can also be established by other large-scale sea level variations and by changes in the onshore hydraulic gradients, as due, for example, to variations in recharge or the inverse effect of changes in barometric pressure on water tables. All these conspire to produce SGD that is both spatially and temporally dynamic on a variety of scales and pose a dilemma for coastal zone managers trying to make sense out of specific measurements provided to them by their technicians.

For the coastal manager, the quality of SGD is of great concern, regardless of whether the water itself is fresh or marine. The chemistry of SGD is typically changed during its passage through the aquifer and sediments. Nutrient, radio-isotope, trace and minor element composition of the water escaping from the sea floor assumes distinctive signatures, even in the absence of recognizable anthropogenic contamination. As coastal groundwaters are often contaminated with sewage, fertilizers, pathogens, pesticides or industrial wastes, SGD can be an important pathway for diffuse pollution to the ocean. The contaminant inputs and their potential and actual environmental impacts on coastal ecology are key reasons why SGD should be considered in coastal management.



IMPLICATIONS FOR COASTAL AREA MANAGEMENT

'Recent work suggests that hydrologic flow from continents to oceans may be more important than has generally been appreciated' (L. M. Cathles, 1987)

Traditionally, hydrogeologists have stood at the shoreline and looked landward. Their principal concern was to find potable fresh water reserves for coastal populations. At the coastline, threats to this supply came from salt-water contamination. Although this concern remains an issue of over-riding importance, hydrogeologists recently have started to look seaward at the way the groundwater in the coastal aquifers drives a flow of water seeping upwards across the sea floor. Oceanographers, on the other hand, have long stood at the shoreline and looked seaward wondering what are the main pathways for the transfer of terrestrial chemicals to the sea. They are now coming to appreciate the impacts of terrestrial groundwater hydrology. A coastal zone manager must integrate both these viewpoints.

SGD can be the principal component of freshwater to the coastal zone in areas where surface runoff is small or variable. The discharge of potable water across the sea floor may be considered a waste, especially in arid regions. In such places, the detection of SGD may provide new sources of potable or agricultural water. Indeed, until relatively recently, most studies of submarine springs were driven almost exclusively by water resources objectives. People in Greece have put up a barrier to trap fresh SGD offshore to form a freshwater 'lake' at sea. And modern versions of the ancient lead funnel, referred to in the introduction, have been designed. Even if the captured water isn't entirely fresh it may be less expensive to desalinate than undiluted seawater. It should be kept in mind, however, that reclaiming freshwater directly from the sea is quite difficult and expensive. Another approach is to stem the loss before it reaches the sea. In Japan, for instance, underground 'dams' have been installed to impede channelized SGD in volcanic or karst terrains.

SGD, controlled or not, serves an important purpose. Groundwater found in coastal aquifers is not static. It is constantly flowing and must continually discharge as it is replenished by rainwater or recharged from surface water. If plants do not take it up, this water eventually reaches the ocean, either indirectly through river flow or directly in the form of SGD. The flow is driven by the elevation of the groundwater on land (the hydraulic head). The influence of the hydraulic head does not necessarily end at the coast but may continue offshore, moving water in the submerged part of the aquifer as well. The underground motion of water actually has two complementary parts. One is SGD and the other is the seawater intrusion into the coast. SGD is responsible for limiting salt-water intrusion into the aquifer so its nature can determine the reliability and extent of potable water

supplies near the coast. Reducing SGD, for example by excessive pumping from coastal aquifers, increases saltwater intrusion.

In addition to its critical role in holding back saltwater intrusion, SGD deserves the attention of coastal zone managers because of its quality. Because groundwater typically has higher concentrations of dissolved solids than most terrestrial surface waters, SGD often makes a disproportionately large contribution to the flux of dissolved constituents. Most chemicals entering the coastal zone from land pass through a 'chemically reactive ribbon.' Importantly, the largest share of the biogeochemical reactions, which affect carbon, nitrogen, and phosphorus budgets, enters from the landward edge of the ribbon corresponding to that part of the sea floor where SGD is typically most important. Some of the most serious problems arise where SGD is carrying pollutants and nutrients, especially nitrogen, from the land into restricted coastal waters. Pollutant input via SGD has been the cause of eutrophication of coastal ponds in, for example, New England and in coastal canals in Florida. In addition, the fresh component of SGD interacts with and influences the recirculation of seawater, which can affect coastal water quality and nutrient supplies to nearshore benthic habitats, coastal wetlands, breeding and nesting grounds.

The effects of SGD in supplying dissolved constituents or, perhaps, in merely reducing salinity have been implicated in the occurrence of nuisance algal blooms of, for example, brown tide in New York, which devastated the local scallop industry. The distribution of SGD can also affect benthic habitats. Areas of eelgrass beds have been reduced and the opportunistic growth of macroalgae increased. In some places, low-salinity seeps may provide particular habitats on the sea floor especially for fishery stock. Also, SGD may actually produce changes in morphology or substrates that serve as microhabitats. Very rapid seepage can destabilize sediments, either on the sea floor or at the coastline, by sapping. SGD through sediments with a high organic content can accelerate the release of methane into the overlying water. Organic-rich SGD could lead to hypoxia in open water and contribute to the 'greenhouse' gases causing global warming.

Knowledge of the impacts in the coastal zone can be the basis for land-use planning and may place limits on development. SGD in some regions can endanger compliance with international or regional conventions on pollution source controls.

Another use of better estimates of SGD would be in the calculation of non-point sources of nutrients or chemical contaminants into embayments receiving SGD. In some places this has been a factor in deciding the degree of development to be allowed. From a management point of view, it is important to determine what fraction of SGD is manmade because altering human activity could control this fraction. In principal, however, there are several types of actions that could be taken to achieve specific goals. Pumping to decrease the hydraulic gradients and reduce flow or artificial recharge to increase the flow may be possible. Artificial recharge is widely practiced to reduce intrusion by building hydraulic barriers, which increase outflow. Such techniques have been used in coastal California for at least 30 years. Land use and pollution sites in source areas might be controlled to alter the quality of SGD, invoking a range of concepts in wellhead and aquifer protection.

The Western Australian State Government, for example, is looking into ways to reduce nitrogen inputs via groundwater to Jervoise Bay, near Perth. Currently,

ammonium-rich or nitrate-rich groundwater plumes discharge to the Cockburn Sound/Jervoise Bay area. A 'pump-and treat' option is being explored to capture the nutrient plume entering the bay. The in situ remediation technology is innovative and involves establishment of an in situ bio-treatment wall system across the flow path of nitrogen-rich groundwater as it moves toward the marine environment. Through the initial discharge quantification and mapping, it is proposed to select a 'hot spot' plume and further quantify plume dimensions and fluxes to the marine environment, so selection of locations can be finalized and an appropriate final pilot-scale design developed. For ammonium, the treatment barrier would consist of a dual treatment/delivery system in the path of the plume. One treatment would deliver oxygen and induce bacterial nitrification of the ammonium to nitrite/nitrate species as the groundwater moves past, and the other would deliver a reductant to induce bacterial denitrification of the nitrate to nitrogen gas, again as groundwater moves past. The concept would allow a single down-gradient installation that could achieve discharge of cleaned groundwater beyond the treatment zone to the marine environment, without hydraulic pumping and aboveground treatment. For nitrate in groundwater, only delivery of a reductant would be required, but with the same clean-up effect. An innovative oxygen and reductant deliver mechanism is to be used – this is currently being patented by the Land and Water Division of Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO).

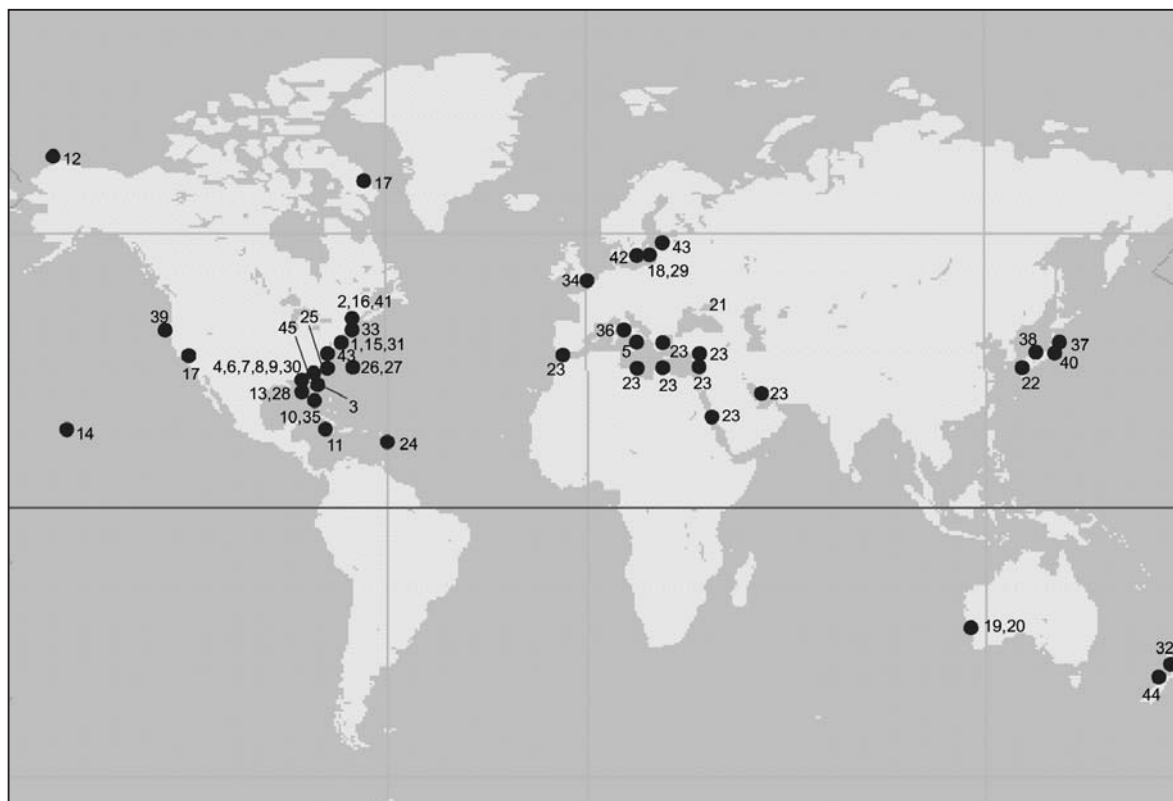
COASTAL MANAGERS AND SGD

'The submarine outflow of groundwater ... is usually the most poorly documented component of the freshwater supply and rarely measured directly' (H. Bokuniewicz, 1980)

SGD presence and importance

Given the potential impact of SGD on so many facets of the coastal zone, managers should first consider whether or not SGD is an important factor in their jurisdiction. It may be that SGD has already been measured in your area. SGD has been directly measured at over forty sites around the world (Figure 4). These are concentrated along the east coast of the United States of America, Japan, and north

Figure 4. Locations of published studies that have reported SGD estimates based on direct measurements. In addition to those noted, depressions called 'Wonky Holes' off the Locations of published studies that have reported SGD estimates based on direct Great Barrier Reef, Australia have recently been attributed to SGD processes. (Stieglitz, T. and Ridd, P.V., *Proceedings*, HYDRO 2000, Perth, November 2000)

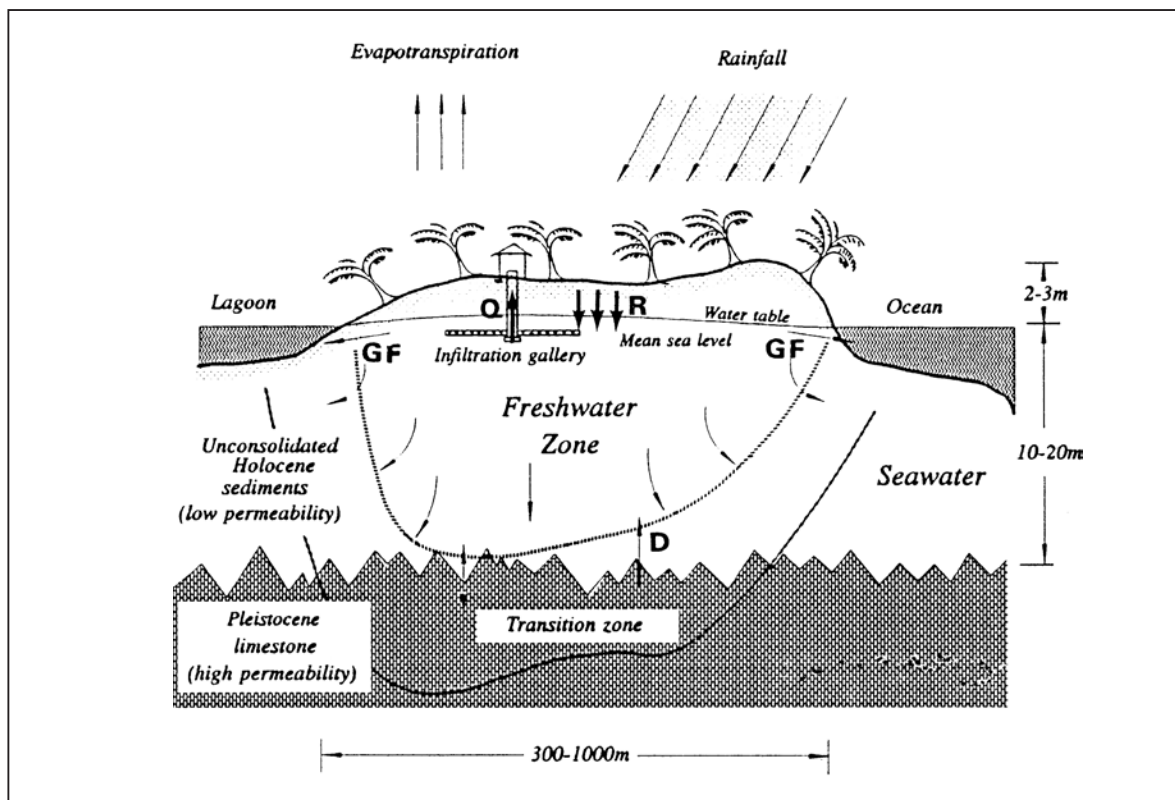


Source: Diagram from Taniguchi et al., *Hydrological Processes*, 2002 (in press).

and Italian coasts of Europe, but include some sites in Australia, the Bay of Bengal, the South Pacific, Africa, Hawaii, California, Alaska and Canada. Regionally, the groundwater flux has been estimated to be equivalent to 20 to 35% of the total freshwater inflow along the coast of Long Island, 30% off the south coast of Cape Cod, Massachusetts, 40% off the Carolina coast and 500 to 1,500 times the fluvial input off the coast of Rhode Island. These estimates may be deceiving to the coastal zone manager because they include not only freshwater from the land, which carries away potable water and may supply pollutants to the coastal ocean, but also seawater that is recirculated through the sediments by the groundwater discharge which may not have any serious impacts. SGD, therefore, may range from nearly entirely fresh water to undiluted, albeit chemically altered, seawater.

Although only a few direct measurements have been made, oceanic islands seem to be disproportionately important sources of SGD. This seems particularly true for mountainous, fractured rock islands in humid, tropical regions. In addition, people who live on small coral islands are heavily reliant on fresh groundwater as their dominant source of potable water. In such cases, groundwater is found as a thin veneer of freshwater, a freshwater lens, floating over seawater in the unconfined coral aquifer. The coral aquifers are usually layered with unconsolidated coral sands and coral debris blanketing karstic limestones (Figure 5). The pressure of the

Figure 5. Vertically exaggerated cross section through a low coral island showing the delicate balance between groundwater discharge and saline water intrusion. R is groundwater recharge, Q is extraction by pumping, GF is submarine discharge to the sea or lagoon and D is the loss due to tidally forced seawater intrusion and mixing.



ocean tides reaches easily into these permeable aquifers, mixing salt and fresh groundwater. Mixing depletes the amount of potable water in the lens.

The loss of freshwater for island peoples can determine their survival on particular islands and, the availability of freshwater is a delicate balance between the net recharge of rainwater (less evapotranspiration and human's withdrawals) and SGD. Island fresh groundwater can also be contaminated not only by humans but also by nature. Coconut trees, for example, supply both nitrogen and dissolved organic carbon to groundwater that leads to the generation of hydrogen sulfide from the reduction of sulfate. SGD delivers these and other dissolved chemicals to the surrounding sea, but the importance of these discharges are unknown.

Submarine groundwater discharge can dominate inflows in restricted seas or embayments. For example, karst comprises 60% of the shoreline of the Mediterranean and is estimated to contribute 75% of its freshwater input – much of this input must be via SGD. In places where rivers are small or nonexistent, SGD may be the principal way for freshwater to enter the coastal ocean as, for example, in the northeastern Yucatan Peninsula, Mexico.

If nothing else, the recent compilation of all studies available in the literature that reported SGD estimates by direct measurements shows that many areas of the world remain unstudied. As yet, there are no published accounts of direct measurements in South America, Africa, India, or China. Future studies by IHP, IOC, IAEA, and other organizations will likely focus on some of these regions.

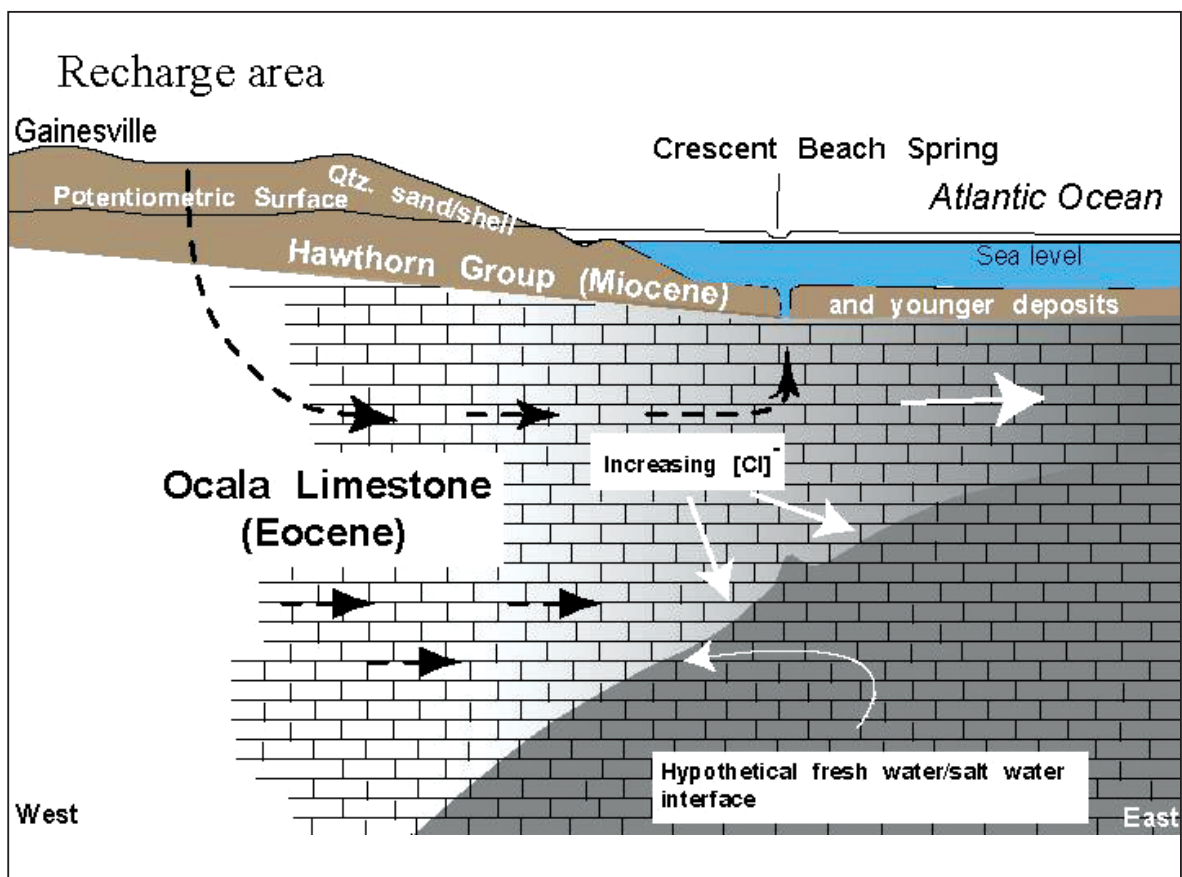
Where SGD has not been measured, there may be other clues to its importance. Several potential indirect indicators of freshwater submarine discharge have been suggested but not yet widely applied. The water might be distinguished by its color, temperature, salinity, or some other geochemical fingerprint. Escaping groundwater, for example, might stain surrounding sediments red by the oxidation of iron or itself be colored by tiny gas bubbles. Because groundwater tends to be at the average annual air temperature, cold-water anomalies in the open water during the summer and warm water anomalies during the winter, as might be detected by infrared aerial photography, can be an indicator of SGD. Salinity anomalies have also long been used to identify subsea freshwater seeps. The presence of elevated levels of radium, radon, methane, hydrogen sulfide or carbon dioxide may also be indicative of a SGD.

Particular site conditions may also provide clues to the occurrence of SGD. The presence of coastal ponds or unconsolidated coastal bluffs, which may maintain a high hydraulic head near shore, may be other indicators. Growths of freshwater coastal vegetation may indicate regions of high SGD offshore. It has also been suggested that the presence of barite, oxidized shells, or beach rock may indicate the occurrence of groundwater discharges. In Great South Bay (Long Island, New York, United States of America), there occurs a phenomenon known as 'anchor ice', in which the bay floor freezes while the saline open waters of the bay is still ice free. This is attributed to the presence of fresh water in the sediments maintained by SGD. Anchor ice is also reported to occur in the Baltic. Alternatively, in coastal areas that are covered with ice in the water, like the Schlei estuary in northern Germany, ice-free spots, sometimes called 'wind-spots', can be found above the SGD of relatively warm freshwater. In Eckernförde Bay (southeast Baltic Sea) pockmarks in the fine-grained sediments of the sea floor have been identified as a bathymetric

expression of groundwater seeps. Along the east Australian coast, pits in the sea floor, known as 'wonky holes', are created by SGD through permeable paleo-channels. These pits are found 8 to 10 kilometers from shore; are 20 or 30 meters across and 4 or 5 meters deep, large enough to cause problems for bottom trawling fishermen.

If the SGD is great enough the water itself can form a visible plume due to light shimmering effects caused by sharp salinity contrasts. A good example of an open-ocean, visually expressive spring is Crescent Beach Spring, located about 4 km off the coast of northeastern Florida (Figure 6). This submarine spring produces a large, localized 'boil' that is visible on the surface of the Atlantic Ocean, in spite of the 18-m regional water depth. In addition to this visual feature, hydrogen sulfide gas can often be detected on the downwind side of the spring. At an estimated flow rate 43 m³/sec, Crescent Beach Spring is considered a 'first-magnitude' spring, comparable to some of the largest and well-known springs on land in Florida.

Figure 6. West-to-east cross-section of the artesian coastal aquifer system in the vicinity of Crescent Beach, Florida, United States of America



Source: Diagram from P. W. Swarzenski et al., *Chemical Geology*, No. 179, 2001, pp. 187–202.

Measuring SGD

**‘Measurements or estimates of groundwater and associated chemical fluxes, especially over substantial areas or time periods, are notoriously uncertain’
(R. W. Buddemeier, 1996)**

How large is SGD? There are many ways to answer this question (even if we don't really know the answer!).

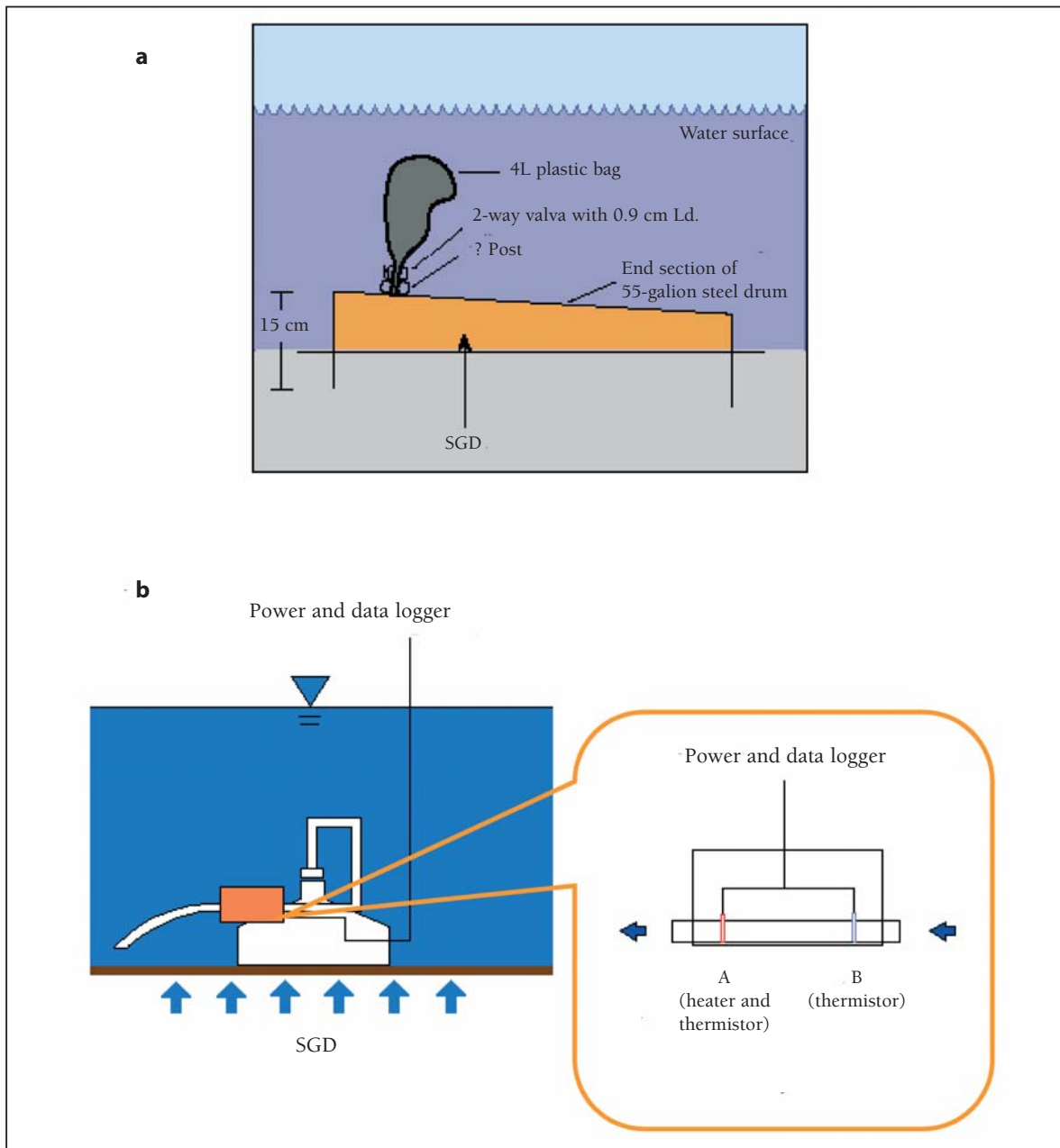
If you have reason to believe that SGD is important in your jurisdiction, a measurement program may be warranted. Measurements of SGD can be presented in several different ways – as a velocity of flow across the seabed, as a volume flux of flow per square meter of seafloor, or as the volume flow per meter of shoreline. An important flow rate might be 50 liters per square meter per day, corresponding to a flow at the sediment water interface of 5 cm/day or 5.8×10^{-5} cm/sec. This might also result in a total flow of some thousands of liters per meter of shoreline per day, depending on the distribution of SGD offshore.

An arsenal of methods is available for trying to determine the magnitude of discharge experimentally. SGD can be measured with inexpensive equipment called ‘seepage meters’ (flow chambers vented to plastic bags accompanied by volume and salinity measurements – Figure 7) however; this manual method is very labor-intensive and most useful where the flow rates are relatively high. A few measurements at point locations can be enlightening but the flow can be extremely variable in both time and space. As a result, many measurements might be needed to get reliable averages. Other types of benthic chambers measure the flow of water into them by direct acoustic measurements of the flow velocity or by tracking the flow rate using a temperature marker. Since these devices are automatic, high-resolution measurements may be made over prolonged periods. This capability has greatly increased the temporal resolution of seepage measurements. Geochemical techniques for measuring SGD look for excesses of radium isotopes or radon in coastal waters. Radium and radon concentrations are elevated in groundwater and anomalies in the open water are often indicative of a groundwater source.

All of these measurements detect total water flux (including recirculated seawater), so they do not necessarily measure freshwater discharge or even, necessarily, demonstrate its presence. Salinity decrease in the pore water of bottom sediments can be used to infer the flow of freshwater causing this change. If the discharges of fresh groundwater are great enough, the depression of salinity in the overlying water alone may pinpoint the source of SGD. The presence of excess methane in the coastal ocean or the absence of methane in sediments with a high organic content is another indicator of SGD, which flushes the gas from the sediments.

Freshwater SGD can also be calculated directly in terrestrial water budgets. At a particular spot, the total SGD might be calculated using Darcy's Law, if the vertical hydraulic gradient is measured at the sediment-water interface along with measurements of the vertical permeability of the sediment. Simple box models or hydrological budgets can quantify the role of SGD in the coastal water balance. These estimates can be useful but they must be used with caution because often the SGD is determined ‘by difference’ as the component that is needed to balance the budget. The problem is that SGD is usually small in comparison with the other

Figure 7. Seepage meters are devices that are positioned on the sea bed and measure fluid fluxes either (a) manually by displacement into a plastic collector bag; (b) by measurement of heat transport; or acoustically (not shown)



Source: Diagram 'b' courtesy of M. Taniguchi (Nara University of Education, Japan).

parts of the water balance and the SGD estimate may be on the same order as the errors of the other components. Thus, the combined uncertainties in the known terms (precipitation, recharge rate, evapotranspiration, etc.) usually make the uncertainty in SGD estimated by difference unacceptably large. In the Caspian Sea, for example, various estimates of SGD differ by as much as a factor of 150. Recent attempts to quantify the amount of total underground fluid flow into Florida Bay

by modeling vary by 3–4 orders of magnitude! Hence, models are useful for investigating SGD but they probably are not yet a substitute for direct measurements.

Care also must be exercised in interpreting mathematical models, either analytical or numerical, for the following reasons. Models typically are designed to forecast the characteristics of the potable water supply. As a result, they often oversimplify the salt water/freshwater transition. They may assume a discontinuous, stationary boundary, the saline groundwater may be assumed to be stationary, or the boundary may be allowed to move and the salt water to flow but not to mix with fresh water. Such assumptions are simplifications that can be more or less appropriate, depending both on the model's intended use and the actual geohydrologic conditions. The recirculation of seawater is an important component of the SGD but is rarely taken into account in hydrological models. Even if the model does allow the recirculation of seawater, offshore data for calibration, verification, and driving the model is usually sparse. Fortunately, new approaches to coastal hydrologic models, with due consideration to both salt-water intrusion and SGD, are being developed and show great promise.



RESEARCH GOALS FOR THE IOC/IHP/IAEA TEAM

'Data on groundwater discharge ... are so deficient that no valid estimate of its magnitude is possible' (R. L. Nace, 1970)

Approach and objectives

The Intergovernmental Oceanographic Commission, together with the International Hydrologic Program and the International Atomic Energy Agency, have formed a team and an approach to address remaining problems in the development of this field and to expand the scope into coastal management issues. The submarine groundwater discharge project intends to: (1) solve the measurement problem by comparing and standardizing existing techniques as well as exploring new methods, including remote sensing; (2) improve hydrogeologic models so SGD and salt-water intrusion may be considered together; (3) contribute to the LOICZ typological approach so that results from well-studied areas can be extended to lesser known shorelines; (4) inform the scientific community, coastal planners, and managers about SGD and its implications; and (5) engage in capacity building in areas of the world where studies of SGD are particularly lacking (Asia, Africa, and South America).

The IHP/IOC/IAEA team will achieve the educational and capacity-building goals of the SGD Project by conducting symposiums and training workshops. The training workshops will be directed towards scientists from developing countries, especially those where SGD measurements have yet to be made.

As discussed throughout this document, assessing groundwater fluxes and their impacts on the near-shore marine environment is very difficult, as there is no simple means to gauge the submarine groundwater flux. To meet this challenge, a series of groundwater discharge assessment intercomparison experiments is being conducted with base support from IOC-IHP and significant financial support from national science agencies. These experiments are conducted using many of the same techniques at each site, so that the results will be comparable from location to location. The sites for these experiments will be selected based on a variety of criteria including logistics, background information, amount of SGD expected, and hydrological and geological characteristics. Each intercomparison exercise involves as many methodologies as possible, including various hydrogeological modeling approaches, 'direct' measurements (seepage meters of varying design, piezometers), natural tracer studies (radium isotopes, radon, methane, etc.), and artificial tracers (e.g., SF₆). Approximately five such intercomparisons will be held in a variety of hydrologic/coastal environments (karst, coastal plain, volcanic, etc.) over the next several years.

SGD intercomparison experiment No. 1: Western Australia

The first such experiment was held in Cockburn Sound, near Perth, Western Australia during Nov. 25–Dec. 6, 2000. Cockburn Sound is a marine embayment protected from the open Indian Ocean by reefs, a chain of islands and a man-made causeway. The area has recently been the subject of extensive environmental assessment in order to address strategic environmental management and the management of waste discharges into Perth's coastal waters. Much of Perth's commercial and industrial activity is focused along the southern metropolitan coastline and the shoreline of Cockburn Sound. Influx of pollutants to the nearshore marine environment from these activities has been a point of major concern in recent years and SGD has been recognized as an important pathway for contaminants. Accordingly, a significant amount of baseline environmental information has been gathered over the past 20 years. The primary site for the SGD assessment intercomparison was along an open beach in the Northern Harbor area (Figure 8).

A multi-disciplinary group of about 20 investigators made estimates of submarine groundwater discharge based on a range of methodologies, including seepage meter measurements, natural isotopic tracers, onshore and offshore CTD (conductivity, temperature, depth) profiling, and hydrogeological modeling approaches. The weather conditions were generally favorable, although brisk on-shore sea breezes typical of the west Australian coast were present at times.

Several manual seepage meter measurements were made each day of the experiment for each of 8 meters deployed along the two transects normal to shore

Figure 8. Photo of beach site in the Northern Harbor area of Cockburn Sound, Western Australia, where the near-shore intercomparison was conducted. The raft that housed the continuous radon monitor is seen on the left adjacent to two piezometers. The line of buoys on the right marks the locations of seepage meters. The boat used for offshore sampling and geophysical studies is seen on the right.



Source: Photo courtesy of S. Krupa (South Florida Water Management District).

(4 meters on each transect). After several measurements were taken at each meter over the course of a day, the results were pooled as a 'daily average' and integrated by distance offshore to obtain estimates of total seepage per unit distance of shoreline (Figure 9). Having obtained such data, it is a simple matter to estimate discharge into a designated area (the study domain was 100 m wide in this case).

One of the stations in a central portion of the experimental area was equipped with a device for continuously sampling near-bottom seawater and analyzing for ^{222}Rn , a good natural tracer of SGD (high in groundwater, low in seawater). The radon data showed a pattern generally similar to that of an automated seepage meter nearby with diurnal variations and higher concentrations during the lowest tides, a feature that has been noted elsewhere. Both the radon record and the seepage meter results are suggestive of a strong tidal influence on the SGD flux. In addition, both ranges of estimates for discharge over the same period were close at 2.5–3.7 and 2.0–4.2 m^3 per meter of shoreline per day based on the seepage meters and radon testing, respectively.

Several geophysical methods were also employed during this experiment to characterize the groundwater-seawater interactions. For example, several conductivity profiles were taken by manually inserting a conductivity probe into the sand at various depths (Figure 10). Along each profile, readings were taken every

Figure 9. Daily averaged seepage fluxes along two transects normal to the shoreline at Cockburn Sound, Western Australia on November 28, 2000. The two trends correspond to the west (integrated flux = 2.2 $\text{m}^3/\text{m.d}$) and east (2.7 $\text{m}^3/\text{m.d}$) transects, respectively.

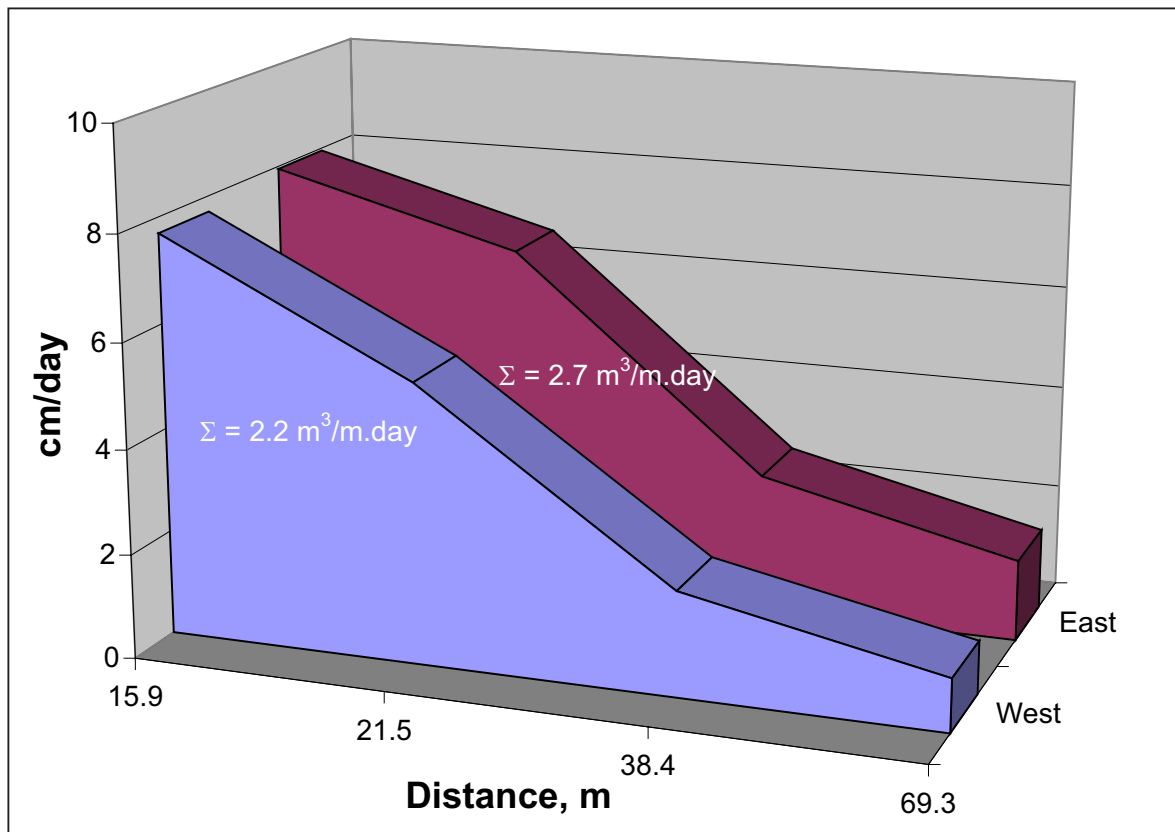
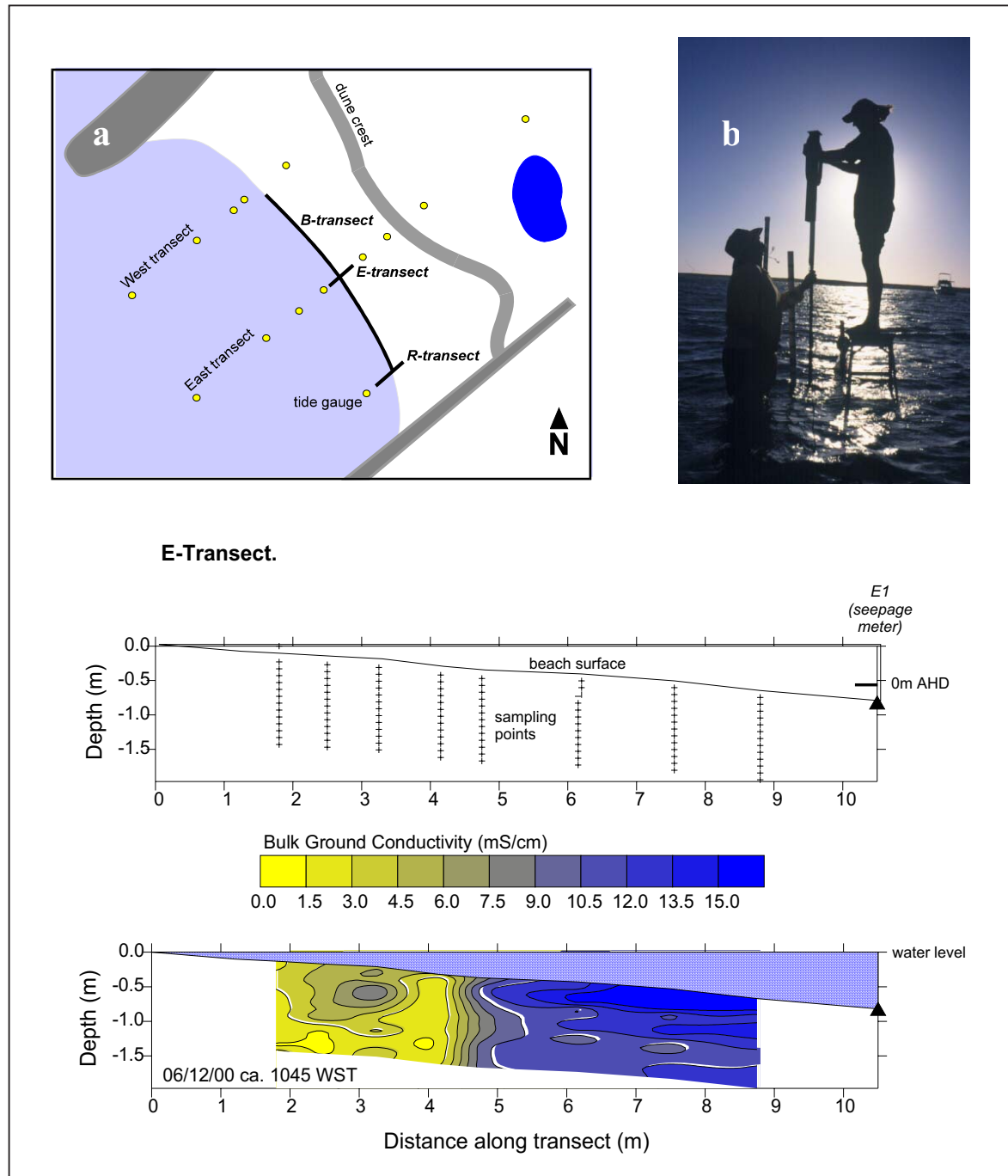


Figure 10. (a) Index map showing locations of transects; (b) positioning a conductivity probe into beach sediments; and (c) conductivity profile along the east transect (yellow = low conductivity, fresh water)



Source: Figures courtesy of T. Stieglitz (James Cook University, Townsville, Australia).

10 cm to a total depth of ~1.1 m. These profiles showed an along-beach gradient in porewater conductivity, with fresh groundwater present at the eastern part of the beach. In a shore-normal direction, fresh groundwater seems to be restricted to a distance up to ~5 meters seawards from the water line. Further offshore, the

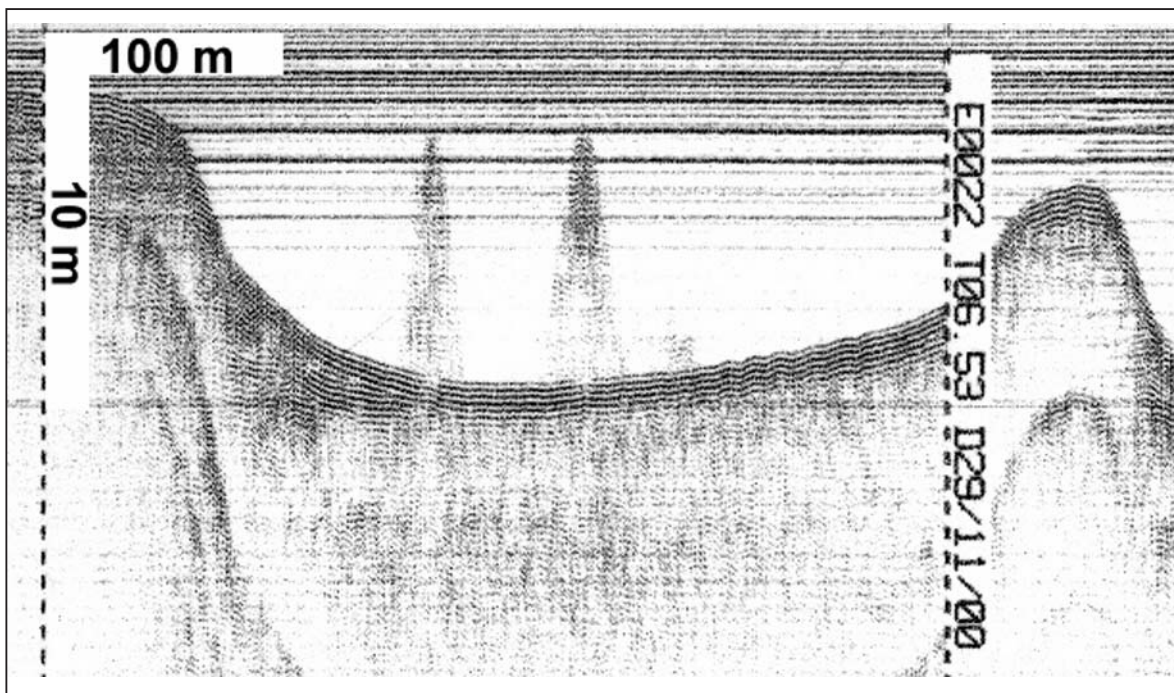
conductivity appears to be that of seawater or of water only slightly reduced in conductivity compared to seawater.

Exploratory seismic reflection surveys were also made in Cockburn Sound using a 3.5KHz ORE Systems seismic profiler mounted on the vessel *Tartan II*. Several features were seen on the resulting records that may indicate offshore springs (Figure 11). Although no definitive conclusions on the nature of these features can be drawn without more data, the shape of the plumes and the discontinuation of the seafloor surface at these sites resemble records of known seep sites. Such features could be either gas or groundwater discharge, quite likely accompanied by a sediment cloud. Karst formations are known to exist in Cockburn Sound, which would generally permit fluid discharge from the seafloor to occur in areas of cracks or fissures, as it happens in many other places in the world.

The hydrogeologic modeling results for Cockburn Sound completed to date indicate that modeled flows are approximately equivalent to those estimated from seepage meter and tracer studies. The ranges in the modeling estimates are quite large, however, and further work is needed in order to compare 'spot' measurements with steady-state models. During a preliminary intercomparison experiment performed earlier along the Gulf of Mexico coast of northwestern Florida, the hydrogeologic models indicated flow 8–10 times lower than those based on direct measurements. Reconciling hydrologic modeling with direct measurements will be an area of emphasis for future method comparison exercises.

In order to decide how to proceed with coastal planning decisions that may involve groundwater discharge, one, of course, should consult with local

Figure 11. A 3.5KHz seismic profile record in Northern Harbor, Cockburn Sound showing two possible 'spring' features



Source: Figure courtesy of T. Stieglitz (James Cook University, Townsville, Australia).

hydrogeologists. It should be realized, however, that this is a relatively new field of study. Techniques are not yet standardized nor completely tested. The status of the intercomparison experiments, principal findings, and relevant references in the literature may be found at <http://www.jhu.edu/~scor/wg112.htm> and from IOC/IHP (see SGD link at <http://ioc.unesco.org/icam/>).

Other case studies and future activities

After the Cokburn Sound case study in Australia other intercomparison experiments have been conducted in others areas; Sicily (Italy) in 2001, Long Islands (United States of America) in 2002. One campaign has been conducted in Brazil end of 2003. The results of all these experiments will be the subject of a more detailed publication. Some of these experiments have been supported by the IAEA marine laboratory located in Monaco.

SGD are considered strategic freshwater resources in the arid and semi-arid countries of the Mediterranean region. In the eighties the European Communities financed a research project to evaluate and map the existence of submarine springs in the coastal areas of Spain, Sicily and Greece. The Blue Plan programme has estimated that the Mediterranean Sea receives from its basins a discharge of an average of 520 billion cubic meters of freshwater each year; a quarter of this quantity is provided by submarine groundwater discharge (J. Margat, Plan Bleu, Mediterranean Action Plan, 1996).

In the Sicilian case study measurements and analyses of the coastal aquifers and submarine springs have been conducted since 2001 with the support of a team of Italian experts. In Sicily (Fig. 12) the well developed karst system determines the existence of important coastal springs (Fig. 13). The Sicilian case study will be finalized at the end of 2004.

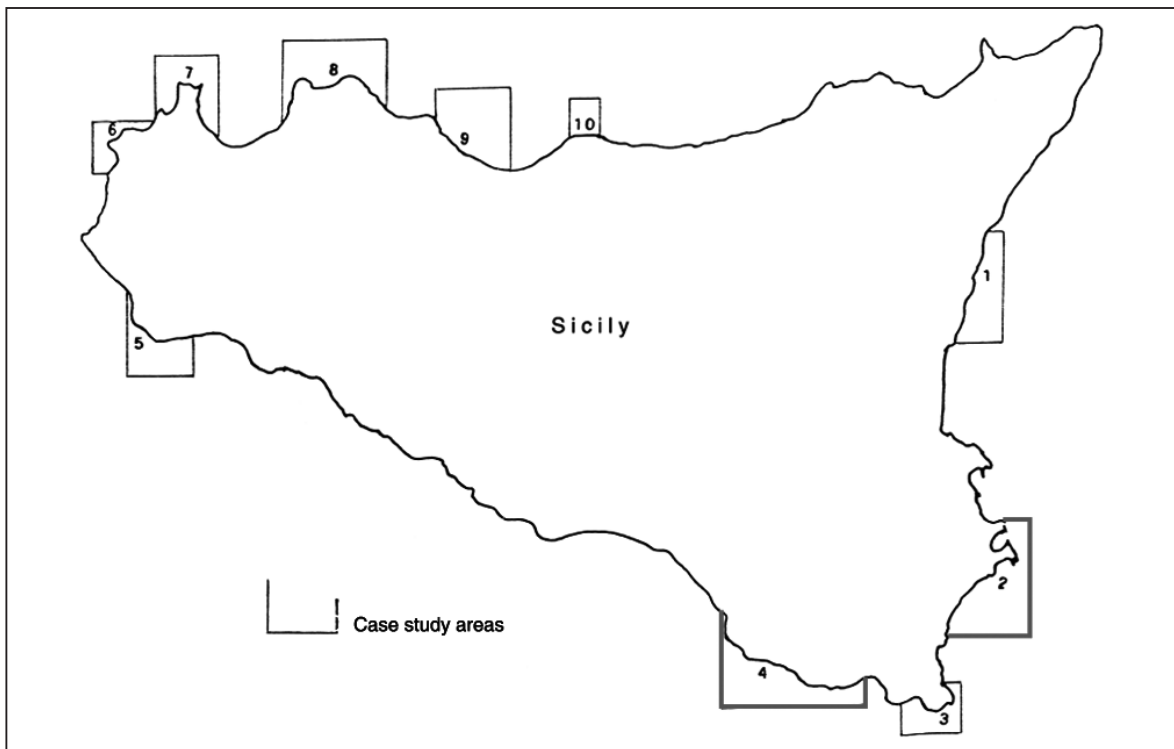
In the future other case studies will be developed in different regions of the world.

Detecting SGD from space

In the 70s, the technology of airborne thermal sensors was mature enough to launch systematic exploration campaigns based on temperature contrasts between sea water and fresh water in regions where SGD were supposed to exist. Carried by airplanes or helicopter these sensors were flying at a few hundreds of meters. These campaigns were not all crowned with success due to the difficulties to detect small thermal anomalies, because of sea surface instability. Nevertheless, some discoveries were recorded and the ground resolution and thermal accuracy of the sensors allowed to detect small thermal anomalies.

Nowadays thermal sensors onboard of satellites such as LANDSAT 7 or ASTER can provide more accurate information on temperatures contrasts. The Eastern Mediterranean coast offers numerous SGD some of them intensively studied. The Figure 14 shows the visibility of one of the largest SGD in the

Figure 12. Case study areas in Sicily



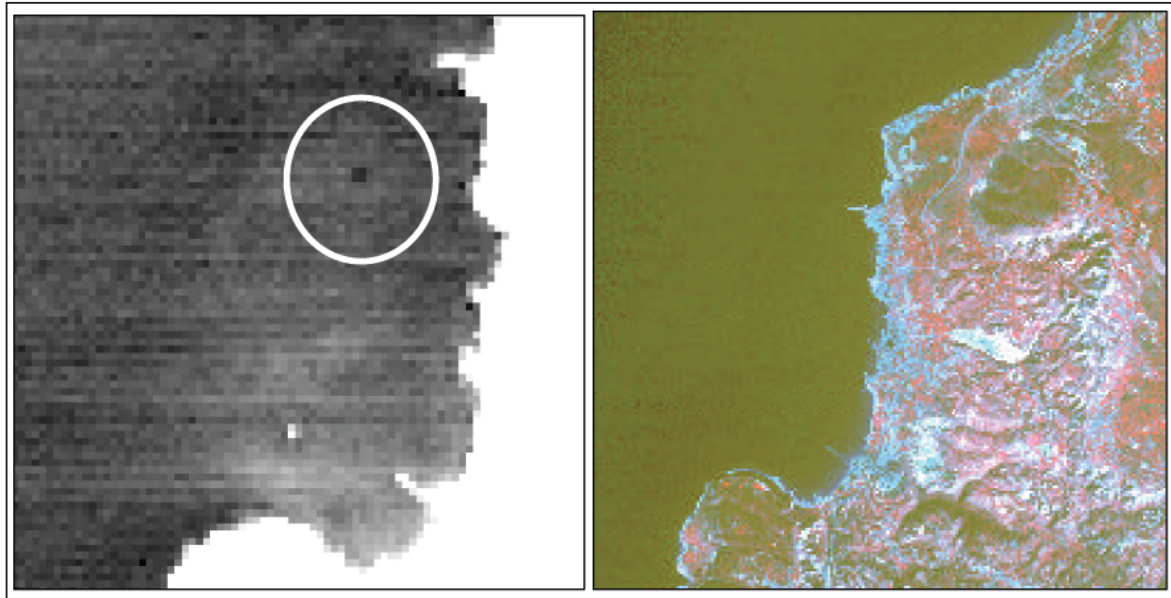
Source: Diagram courtesy of A. Aureli (University of Palermo, Italy).

Figure 13. Submarine springs in the Sicilian coast



Source: Photo courtesy of A. Aureli (University of Palermo, Italy).

Figure 14. In the circle, dark spot is the cool signature of a major intermittent SGD, detected by its contrast with surrounding sea water, on channel 14 of Aster. Image. On the right a classical colour composition of the same area with other ASTERS channels.



Source: Preliminary assessment of the application of space remote sensing for SGD detection (Geosciences Consultants, Report to UNESCO IHP/Water Sciences Division, February 2003).

Mediterranean sea studied using the thermal channel 14 of an ASTER image, at approximately 1 km from the coast in the Chekka bay, in northern Lebanon.

The detection of the spring did not require sophisticated transformation of aster signal, since the contrast between seawater and freshwater is important and extended enough to be detected directly on the original channel 14.

Springs of smaller size or very close to the cost are not directly detected from the space imagery, mostly because the resolution is not clear enough. A better ground resolution of future thermal sensors would be a major improvement for the detection of smaller SGD from space. High spectral and ground resolution will help greatly in the identification of geological features prolonged into the sea such as fault lines.

Suggestions for further reading

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Appendix

International Symposium

Low-lying coastal areas

Hydrology and integrated coastal zone management

9 – 12 September 2002, Bremerhaven, Germany

Low-lying coastal areas including small islands are among the most intensively used regions in all countries. More than 60 % of today's world population of approximately six billion people live there. Coastal areas are not only among the most densely populated regions of the earth, they are also subject to extraordinarily intensive use through industrial and commercial sites, agriculture, aquaculture and tourism. This intensive exploitation has considerable impact on hydrological conditions in coastal regions. Problems arise from conflicts between different uses of coastal land and waters, overexploitation of coastal resources, discharge of wastes and effluents into coastal waters, elevated risk of storm damage, increasing stress by sea level change and growth of coastal population.

The IHP/OHP National Committees of Germany and the Netherlands in co-operation with UNESCO, WMO and IAEA conducted this symposium in Bremerhaven from 9 to 12 September 2002 to address emerging coastal zone issues. The aim of the symposium was to increase public and political awareness of the vulnerability of coastal zones and to discuss tools and measures for sustainable water management in coastal areas at an expert level. Main topics of the symposium were tools for coastal zone management, groundwater and measures for integrated coastal zone management. Keynote lectures introduced the focus of the conference.

The participants came from 20 countries and organisations like UNESCO, WMO, UN-ESCWA and the global change science community. The conference supported IHP-VI Focal area 3.4 Small islands and coastal zones. At the end of the symposium the participants summarized their conclusions and made the following recommendations.

The Conference recognizes that

low-lying coastal areas are crucial to the development of nature and of society. They

- are heterogeneous domains, dynamic in space and time;
- comprise less than 20% of the earth's surface;
- contain more than 60% of the human population;
- are the location of 70% of cities with more than 1.6 million inhabitants;

- yield 90% of the global fisheries;
- produce about 25% of global biological productivity;
- host previous and fragile natural biotopes;
- are the major sink for sediments;
- are very vulnerable to natural hazards and the effects of climate change;
- are areas where seawater intrusion threatens freshwater resources and where submarine groundwater discharge is an important pathway for both freshwater and nutrients;
- are a zone where integrated management is complex but achievable;
- are areas where there should be strong commitment and support from national governments and international organisations;
- are a zone in which both freshwater and salt water play a paramount role;
- pose considerable problems such as population growth, pollution and degradation of natural resources. They are exposed to natural hazards, and the global climate change and sea level rise are likely to exacerbate many of these problems;
- will be affected by human efforts to adapt to the changing environmental conditions.

The Conference agrees that

- a number of valuable scientific and operational tools, methodologies and models are available to address water-related issues in low-lying coastal areas;
- there is a strong need to integrate the available tools to solve the complex multidisciplinary problems in integrated coastal zone management;
- there is a lack of easily available and easily accessible data on the hydrological cycle in low-lying coastal areas;
- submarine groundwater discharge is the expression at the sea floor of the processes that drive both salt water in and freshwater out under the shoreline. Although inseparable in nature, these two processes are currently being investigated by separate groups using different methodologies;
- submarine groundwater discharge should be consistently and explicitly integrated into coastal water budgets;
- there exist possibilities to conduct multinational, multidisciplinary, multi-spatial and multitemporal research work to solve complex coastal problems using expertise, equipment, data and methodologies from various nations;
- great threats and water problems will be posed for low-lying coastal areas in the near future;
- human adaptation to the consequences of global environment needs to be integrated more strongly into existing frameworks of coastal planning in order to build adaptive capacity and to avoid maladaptation;
- the conference has highlighted the need for a stronger integration of aspects of social vulnerability into integrated coastal zone management (ICZM);
- knowledge management is important for the diverse and vast knowledge already available.

The Conference recommends that

- UNESCO enhance its efforts, for example in education and training, to contribute to a better understanding of all water-related processes which play an important role for a sustainable development of low-lying coastal areas.
- UNESCO further enhance the coordinated implementation of cross-cutting projects, and education and training activities between IHP, MAB, IOC, IGCP, CSI and MOST ¹ under the leadership of IHP.
- UNESCO invite other GOs and NGOs to contribute to its water-related projects in low-lying coastal areas.
- UNESCO take the initiative to establish regional sub-centres and make use of the expertise in the universities and advanced research centres of the numerous (developing) countries for its various projects and activities.
- WMO encourage the strengthening and improvement of hydrological monitoring in low-lying coastal areas.
- UNESCO/WMO explore methods to promote integrated approaches to coastal zone management.
- UNESCO, in recognition of local, regional and global efforts towards the advancement of coastal change sciences, establish and/or strengthen its links with the scientific community, e.g. the relevant programmes under the Earth System Science Partnership of IGBP, IHDP, WCRP and DIVERSITAS ².
- UNESCO/WMO promote awareness of the key issues and approaches to coastal zone management and uses knowledge management to develop efficient communication strategies.

The Conference suggests the following activities and projects:

- The initiation of a project on submarine groundwater discharge that will investigate the pathways for freshwater and nutrients to the coastal zone in an integrated fashion. This can best be done by development of type or 'flagship' sites for extrapolation to larger areas. These sites would be characterized by joint studies using hydrological modelling, geophysics, geochemical tracers and other approaches.

¹ IHP : International Hydrological Programme
MAB : Man and the Biosphere
IOC : Intergovernmental Oceanographic Commission
IGCP : International Geological Correlation Programme
CSI : Coastal Regions and Small Islands
MOST : Management of Social Transformations Programme

² IGBP : International Geosphere-Biosphere Programme
IHDP : International Human Dimensions Programme on Global Environmental Change
WCRP : World Climate Research Programme
DIVERSITAS : An Integrated Programme of Biodiversity Science

- The initiation of a submarine groundwater recharge project to investigate the process, potential and possibilities for sustainable use of the coastal areas of the world. Studies could make use of remote and in situ data and the results could be published as a handbook of detailed investigations and later as an atlas.
- Specialized thematic workshops such as submarine groundwater discharge, salt water intrusion, remote sensing and GIS for ICZM, so that national level specialists could interact with international experts for further detailed research work.
- The initiation of projects and meetings which explore efficient mechanisms for integrating scientific, engineering, social and institutional analyses of the coastal zone to reduce conflicts and promote better management.
- The initiation of a project that will investigate the sediment transports starting from the catchment areas through the rivers to and along the coast, including the problem of coastal erosion.
- The development of 'knowledge portals' whereby a team is assigned to build such portals. Possible topics are hydrogeomorphology, land use, socio-economic aspects and groundwater.

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SCOR is the leading non-governmental organization for the promotion and co-ordination of international oceanographic activities. SCOR does not have the resources to fund research directly; therefore, SCOR science activities focus on promoting international co-operation in planning and conducting oceanographic research, and solving methodological and conceptual problems that hinder research. Scientists from the thirty-seven SCOR member nations participate in SCOR working groups such as Working Group 112, 'Magnitude of Submarine Groundwater Discharge and its Influence on Coastal Oceanographic Processes.'



The objectives of LOICZ (Land-Ocean Interactions in the Coastal Zone), a core project of the International Geosphere-Biosphere Program (IGBP), are to describe and understand the interactive physical, chemical and biological processes that regulate the coastal zone portion of the Earth System, the environment provided for life, the changes occurring in the system, and the influences of human actions. The global network of LOICZ researchers contributes scientific knowledge and skills to understanding material fluxes and the controlling biogeochemical process in the coastal zone and the implications of human dimensions.

