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The typological approach to submarine groundwater discharge (SGD)

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Abstract. Coastal zone managers need to factor submarine groundwater discharge (SGD) in their integration. SGD provides a pathway for the transfer of freshwater, and its dissolved chemical burden, from the land to the coastal ocean. SGD reduces salinities and provides nutrients to specialized coastal habitats. It also can be a pollutant source, often undetected, causing eutrophication and triggering nuisance algal blooms. Despite its importance, SGD remains somewhat of a mystery in most places because it is usually unseen and difficult to measure. SGD has been directly measured at only about a hundred sites worldwide. A typology generated by the Land–Ocean Interaction in the Coastal Zone (LOICZ) Project is one of the few tools globally available to coastal resource managers for identifying areas in their jurisdiction where SGD may be a confounding process. (LOICZ is a core project of the International Geosphere/Biosphere Programme.) Of the hundreds of globally distributed parameters in the LOICZ typology, a SGD subset of potentially relevant parameters may be culled. A quantitative combination of the relevant hydrological parameters can serve as a proxy for the SGD conditions not directly measured. Web-LOICZ View, geospatial software then provides an automated approach to clustering these data into groups of locations that have similar characteristics. It permits selection of variables, of the number of clusters desired, and of the clustering criteria, and provides means of testing predictive results against independent variables. Information on the occurrence of a variety of SGD indicators can then be incorporated into regional clustering analysis. With such tools, coastal managers can focus attention on the most likely sites of SGD in their jurisdiction and design the necessary measurement and modeling programs needed for integrated management.

Introduction

Groundwater is one of the variables over which coastal zone management may be integrated. Groundwater is often the principal source of potable water for coastal communities especially since rivers and ponds are brackish near the shore. In addition, coast-dependent industry may be reliant on groundwater for their operations. Coastal managers must control development especially to prevent 'mining', and eventual depletion, of freshwater reserves but also to avoid excessive draw down and the consequent intrusion of saline groundwater from the sea. In turn, coastal development adds pollutants to the groundwater from septic systems, agricultural practices, industrial waste, road runoff and a host of other sustained activities. Even if contaminants do not directly affect the portable water supply, their impacts in the coastal ocean can impair other management objectives, such as the sustainability of coastal fisheries, aquaculture or recreation. This link is made through submarine groundwater discharge (SGD).

While there is strong evidence that SGD must be factored into many biogeochemical management decisions in the coastal zone, the scientific information is incomplete. SGD is insufficiently studied and difficult to measure. Even if managers are aware of SGD, they may not know how to judge its importance in their jurisdiction. If they recognize that it is important, they may not know how to quantify the process. Other articles in this special issue discuss the science of SGD, the technology available for its quantification, and the results of site-specific studies. Intercalibration experiments have been done, and reported in this issue at least in part, in order to better define the methodology. Another aspect of the intercomparison, however, is to facilitate the integration of the scientific inquiry into management decisions. Here, we attempt to address coastal zone management concerns for water quality, water quantity and coastal ecology. As a first step, coastal zone managers are faced with deciding if there is a 'reason to believe' that SGD may be relevant in their jurisdiction. In this article, we will discuss some indicators of SGD and potential impacts. Next, we will consider tools available to coastal zone managers for exploring the potential for SGD in various global settings. In particular, we will describe a methodology by which coastal zone managers, who are trying to decide if SGD might be an important factor in one particular area, may find similar sites worldwide where measurements of SGD may have already been made. Three examples will be provided.

Making the case for SGD

Part of SGD is the seepage of terrestrial groundwater directly across the sea floor. (Another component of SGD is the recirculation of seawater. The component of recirculation is usually of less concern for the coastal manager but knowing that it can, and does, occur can be important when trying to understand the measurements). Along some coasts, SGD itself can be a valuable source of potable water. The folk wisdom of many areas includes the accounts of sailors obtaining fresh water from submerged springs on the sea floor. In the first century AD, Strabo tells of a submarine spring, 8 km from shore in the Mediterranean Sea, from which potable water was routinely recovered with a lead funnel and leather hose. In the modern era, related engineering works have been used to provide potable water from submarine springs. In Greece, for example, barriers have been constructed around a submerged spring to create a freshwater 'lake' in the sea. Even if the water collected is brackish, it may still be an economic advantage to desalinate brackish, SGD water, rather than undiluted seawater, in regions where the shortage is critical. Although SGD may not provide freshwater directly, its continued occurrence is critical to the potable water reserve because the discharge of fresh groundwater prevents the invasion of seawater into supply wells. If SGD was reduced or eliminated, seawater could transgress further into the freshwater aquifers, contaminating potable supplies in its path.

Measurements of SGD have been made at about a hundred sites around the world and most of them are along the east coast of the United States, around the Mediterranean Sea and in Japan (Taniguchi et al. 2002). In many other areas, however, there is anecdotal or indirect evidence of SGD. Several potential, indirect indicators of freshwater submarine discharge have been suggested but not yet widely applied. Submarine groundwater might be distinguished by its color, temperature, salinity or some other geochemical fingerprint. Escaping groundwater, for example, might be stained red by the oxidation of iron or colored by tiny gas bubbles. Because groundwater tends to be at the average annual temperature, cold water anomalies in the open water during the summer, and warm water anomalies during the winter can be an indicator of SGD. These can be detected by infrared aerial photography (Fischer et al. 1964; Roxburgh 1985; Banks et al. 1996; Miller and Ullman in press). Salinity anomalies have also been used to identify subsea freshwater seeps at a variety of scales from regional water budgets to vertical profiles at specific locations (e.g., Johannes and Hearn 1985; Valiela et al. 1990). For instance, SGD has been identified as the cause of low salinity anomalies in the Gulf of Gdnask of the Polish Baltic (Matciak et al. 2001). The presence of elevated levels of radium or radon (e.g., Cable et al. 1996; Moore 1996) methane, hydrogen sulfide, silica or carbon dioxide may be indicative of a groundwater source.

Particular site conditions may also provide clues to the occurrence of SGD. Clues might be found in the presence of coastal ponds or unconsolidated coastal bluffs, which may maintain a high hydraulic head near shore. It has also been suggested that the presence of barite, (B.L.K. Somayajulu 1999, personal communication) oxidized shells, or beach rock (J. Turner. 2000. CSIRO Land and Water, personal communication) may indicate the occurrence of SGD. In Great South Bay (NY, USA), there occurs a phenomenon known as ‘anchor ice’, where the bay floor freezes while the saline open waters of the bay remains ice-free. Anchor ice is attributed to the presence of fresh water in the sediments maintained by SGD. Bottom ice is also reported to occur in the Baltic (Groen 1967). Alternatively, in coastal areas that are covered with ice in the winter, like the Schlei estuary in northern Germany, ice-free spots, called ‘wind-spots’, can be found above the SGD of relatively warm freshwater. If the SGD is great enough the open water surface itself can be doomed up and ‘boiling’.

As early as 1939, Douglas Johnson suggested that groundwater seeping across the sea floor might leave morphological traces. He proposed SGD as a mechanism for forming submarine canyons off the east coast of North America. Although large canyons have other causes, the dissolution of submarine limestone by SGD has been shown to create distinctive escarpments and box canyons at the margins of continents (Paull et al. 1990). Other geomorphic indicators of SGD are also recognized at smaller scales. For example, in the southeast Baltic Sea pockmarks in the fine-grained sediments of the sea floor have been identified as a bathymetric expression of groundwater seeps (Khandriche and Werner 1995; Wever and Fiedler 1995; Sauter et al. 2001). In Australia, rapid SGD through buried paleochannels create pits, locally referred to as ‘wonky holes’ as far as 10 km from shore (Stielitz and Ridd 2002).

Biological indicators may also be found. Macroalgal mats may be a symptom of nutrient-rich SGD. Vigorous growths of freshwater coastal vegetation at the shoreline also may indicate regions of high SGD offshore. Finding isolated, brackish-water benthic habitat in an otherwise marine environment would be another signature of SGD. Patches of *Marenzelleria viridis*, a polychaete tubeworm, mark lower salinity seeps on the floor of Delaware Bay and use these seeps as 'stepping stones' to spread through more saline environments (Miller and Ullman in press).

Many of the famous examples of submarine springs are in karst terrain as, for example, the *vruljes* of the Adriatic Sea (e.g., Bonacci et al. 1995). Others occur around high, volcanic islands where rainfall on the mountain seeps through fractured rock offshore. Thick, permeable coastal plain aquifers like that of the US east coast provide other important conduits for SGD. Buried paleochannels filled with especially permeable sediments may create 'pipes' for carrying groundwater across the shoreline (e.g., Gaswirth et al. 2002). Such geological conditions can give even coastal plain aquifers some karst-like characteristics. Although concentrated springs in homogeneous aquifers may be rare, diffuse seepage can occur over large areas of the sea floor and buried clay layers (aquitards) can also force fresh groundwater far offshore.

SGD provides one of the pathways, perhaps the most important one, by which contaminants find their way to the sea. SGD has been implicated in instances of eutrophication, nuisance algal blooms, and macroalgal invasions. High nutrient loads carried by SGD, especially from developed coastal land, are known to cause eutrophication in restricted, open waters. Opportunistic macro algae, such as *Cladophora*, *Ulva*, *Enteromorpha*, and *Gracilaria*, are indicators of sewage enrichment that could be provided by SGD (Lapointe and O'Connell 1989). Increased macroalgal growth in the Florida Keys has been attributed to excess nutrients carried in by SGD (Lapointe et al. 1990). The spread of macroalgal mats can displace eelgrass meadows (*Zostera marina*) and reduce productive habitat as it has in coastal embayments in New England (Valiela et al. 1990). In shallow embayments on Long Island (New York, USA), intense blooms of 'brown tide', a unicellular microalgae (*Aureococcus anophagefferens*) has devastated the scallop industry. SGD has been implicated in the occurrence of these nuisance algal blooms. During years of high SGD, bay salinities are reduced; blooms of mixed macroalgae and phytoplankton are fueled by dissolved, inorganic nitrogen. When SGD is low, however, salinities are high and production relies on remineralized nitrogen. Both of these conditions favor the 'brown tide' organism (LaRoche et al. 1997). Control of coastal pollution may, therefore, involve management of SGD.

Any of these lines of evidence might help in identifying stretches of the world's coast along which SGD has significant management implications. In most cases, however, attempts to apply such criteria would involve a good degree of luck because specific diagnostic characteristics have not been catalogued worldwide. Comprehensive, global databases may provide a tool for a more systematic search. One such system has been developed by the Land–Ocean Interactions in the Coastal Zone (LOICZ) Program, which is a core project of the International Geosphere–

Biosphere Programme: A Study of Global Change (IGBP) of the International Council of Scientific Unions (ICSU). The LOICZ database may be particularly useful in screening large areas according to their potential for SGD. It is the purpose of this article to explore this tool.

The LOICZ typology and cluster analysis

'Typology' is a study, analysis or classification based on type. The typological approach adopted by LOICZ is an attempt to deal with two limitations which plaque coastal zone managers. One is the data gaps and our necessarily imperfect understanding of the complex interactions that characterize the coastal zone. Often proxy parameters and indirect indicators must be used as surrogates to assess the impacts of poorly resolved processes. The other is the restriction of both human and financial resources available to carry out coastal studies. A typology is intended to help the situation by identifying empirical 'building blocks' that can serve as a basis for more focused investigations.

The LOICZ typology divides the world's coastal zone into one-half degree cells. Some of the cells are entirely on land near the shoreline, some contain the shoreline and some are entirely in the adjacent, coastal ocean. There are 47,057 cells, 15,278 of these are coastal, that is they contain a part of the shoreline. Each cell has data associated with it. Hundreds of variables are tabulated for each cell ranging from air temperature to population density and from bathymetry to soil texture. The typology system is web-based (www.kgs.ukans.edu/Hexacoral) within which data can be filtered and transformed in, at least, a few standard ways (log-transform, absolute values, squares or square-root). A correlation matrix can also be generated. The resulting data set is linked to tools for assessment and visualization, which can be used for classification and scaling. The LOICZ database is also linked to other terrestrial coastal, and ocean databases.

In principle, a subset of parameters within the typology might be identified that would be indicative of locations prone to high SGD. This multivariate subset can then be sorted by a technique known as clustering to identify similar coastal sites. Clustering involves grouping data together according to some measure of similarity. Clustering is intended both to extract trends from raw data sets as well as to develop a compact representation of a data set by creating a set of models that represent it. The former is generally the goal in geographic information systems, the latter generally the goal of pattern recognition systems. Both fields use similar, or identical, techniques for clustering data sets. If there is a lack of site-specific information on SGD at any particular site, its cluster would identify similar sites elsewhere where SGD may have been measured already.

Clustering analysis, specifically the k-means algorithm, was developed for consolidation and rapid analysis of large, multi-dimensional datasets (Farber 1994). The *k*-means algorithm, originally described by MacQueen (1967) groups data through an iterative process. In the initial iteration, reference points are chosen arbitrarily, data points are then partitioned into clusters assigned to the reference points. During the second iteration, each reference point is moved to the calculated centroid, or archetype, of the initial cluster. The archetype represents the average of the data residing in the cluster. If a data point in a cluster is closer to the centroid of a different cluster, the point is reassigned to the other cluster. Centroid values are then recalculated before the next iteration (Farber 1994).

There are two general types of clustering that are used on geographic data: unsupervised and supervised clustering. The method just described is referred to as unsupervised clustering. Unsupervised clustering tries to discover the natural groupings inside a data set without any preconceived categories. The main input to the unsupervised clustering algorithm is merely the number of clusters desired. The goal of unsupervised clustering is to create the requisite number of groups in which each member of the group is similar to the others but different from those in other groups. Supervised clustering, on the other hand, uses a set of example data to classify the rest of the data set. Supervised clustering requires the user to specify the archetypes in advance. The algorithm then assigns points to each cluster, as it does in unsupervised clustering, that minimize the variance within the group in an iterative process until the variance in each group is minimized.

The tool for doing this is the Web-LOICZ View geospatial clustering software package (http://www.palantir.swarthmore.edu/~maxwell/loicz/). Web-LOICZ View provides the user with a set of data analysis tools for working on geographic data sets with multiple variables defined at each location. These tools are intended to facilitate analysis and understanding of trends and groupings that exist in a spatially indexed data set. The primary data analysis tool is a set of clustering routines that group together similar data points into classes as described above. Web-LOICZ View then gives the user a variety of ways to visualize the classes and the data. To provide for ease of experimentation, there are a variety of data management tools that allow users to manipulate and control how the data is treated in each analysis step. For example, subsets of variables can be selected and weighted according to their perceived importance.

The Web-LOICZ View has proven a successful tool in classifying other coastal typologies. Bartley et al. (2001) applied clustering analysis to coastline complexity along the Yucatan peninsula in Mexico. In this case, supervised clustering analysis was applied via Web-LOICZ View to a database of coastal angle distributions to classify coastal complexity for biogeochemical fluxes under LOICZ. Bartley et al. (2001) determined that the results provided an objective, quantitative scale-dependent measure of the coastline complexity, showing distinct differences in coastal environments. Maxwell and Buddemeier (2002) tested Web-LOICZ View robustness, analyzing a dataset of seventeen environment variables from coastal Australia and neighboring regions. Unsupervised clustering of the data resulted in broad agreement with expert typologies for the regions, and unexpectedly highlight localized phenomena that were absent from pre-established typologies. It was concluded that Web-LOICZ View offered a consistent, time saving, quantitative and objective method to compare classes both spatially and temporally (Maxwell and Buddemeier 2002).

We would like to present some illustrations of how managers might use the LOICZ database in conjunction with Web-LOICZ View for exploring SGD on a global basis. Of the parameters in the LOICZ typology, many, like sea temperature, are not directly related to groundwater seepage. Others are statistical variations of the same basis parameter, like annual precipitation, maximum precipitation, monthly precipitation etc. Still others are highly correlated. In this situation, the number of parameters available for a SGD typology is greatly restricted, but can provide instructive frameworks for global comparisons.

Four clustering schemes of increasing complication will be presented as illustrations: a simple four-parameter clustering which is fairly easy to interpret but still generates some interesting results; a more complicated, seven parameter cluster; a weighted, eight parameter cluster; and a supervised clustering. At this stage there is little evidence with which to test the relevance of any of these clusters to quantification of SGD. However, they do provide reasonable groupings and patterns, which can more readily be seen by working up from simple clusters to the more complex analyses. Coastal zone managers in one area might look to other areas in their cluster in a search for shared experience. Each also can be considered testable hypotheses, from which researchers can design site-specific investigations to expand global coverage of SGD.

Results

A simple SGD typology might include four parameters: precipitation, evapotranspiration, runoff and the standard deviation of elevations within the cell. Precipitation is a primary, ultimate source of freshwater SGD although areas with high evapotranspiration and high runoff would have less meteoric water available to contribute to SGD. The standard deviation of the land elevations is a surrogate for the steepness of the coastal zone chosen with the rationale that steeper coastal zones could support higher, onshore hydraulic gradients on shore to drive SGD. (The correlation between the piezometric surface and topography is well known and has been used in quantitative analyses of discharge and recharge as, for example, by Salama et al. 1999.) The generation of six clusters from these parameters (Figure 1) divides the world's coast into (1) areas of high 'steepness'; (2) areas of high runoff and medium 'steepness'; (3) areas of medium evapotranspiration, low runoff and low 'steepness'; (4) areas of high evapotranspiration low runoff and low steepness; (5) areas of medium 'steepness' low evapotranspiration and low runoff; and (6) low evapotranspiration, low 'steepness' and low runoff.

The first cluster (Figure 1, red) identifies long stretches of the south coast of Alaska, the northwest coast of Canada, southwestern Mexico and parts of the west coast of South America. The archetype location in this cluster is in Vancouver. Norway is in this category as well as Hawaii, northern Spain, the Adriatic coast and the eastern shore of the Black Sea. The second category (Figure 1, green) tends to be in geographical proximity to places in the first cluster. The archetype location is along the west coast of Madagascar but this cluster also includes some of the northwest coast of Canada and the southwest coast of South America as well as the Isthmus of Panama, western equatorial Africa, western India and large parts of the Malaysia peninsula and Indonesia.

Figure 1. Six cluster, unsupervised, unweighted, four parameter SGD typology.

Figure 2. Four cluster, unsupervised, weighted, eight parameter SGD typology.

The third cluster (Figure 1, dark blue) tends to be associated with coastal plains. This is an interesting feature of the distribution because there was no specific parameter for 'coastal plains' in the typology. They were apparently identified primarily on the basis of steepness. It includes the US coast of Florida, Texas and parts of the Mexican Gulf coast, Argentina, northern Europe, southwest Africa (Mozambique) northern and eastern Australia and parts of China and Korea. We know from work along the north coast of Europe, as well as the east coast of the USA and the east coast of Australia, that SGD is an important process in the third cluster. Therefore, by analogy, other places in that cluster, like the southern east coast of Africa (Mozambique), might be a likely candidate for SGD of significance even though no measurements have been made there.

The fourth cluster (Figure 1, yellow) includes Florida, Cuba and parts of the Mexican Gulf coast (e.g., the Yucatan), western equatorial Africa, Bangladesh and Malaysia are in this category. The archetype location is in Brazil, south of the

Amazon delta. The fifth class (Figure 1, purple) is typified by Spitzbergen and includes the Galapagos and includes the Baja peninsula and California, the western Mediterranean as well as the Red Sea and the Saudi Peninsula, arid regions.

The sixth category (Figure 1, light blue) represents relatively arid western and southern Australia, Namibia and Somalia as well as the Mediterranean coast along northern Africa in the vicinity of the Nile. Other important deltaic coasts in the northern Black Sea and the Indus are in the category, but most, like the Amazon, Mississippi or the deltas of southeast Asia, are not. Patagonia and almost all of the arctic coast is in this grouping, in fact, the archetype of this cluster is in the arctic coast of Canada. It must be realized that the groupings are merely statistical ones based on a minimal amount of coastal data. They are intended to provide one 'building block' but further structure must be provided by site-specific information and professional judgment beyond the scope of this articles. For example, it has to be pointed out to us, that, even though Patagonia and the Canadian Arctic are grouped in the same cluster, their groundwater hydrology is fundamentally different; unlike the situation in the Arctic, Patagonian groundwater is often saline.

A more complicated clustering, using seven parameters (precipitation, evapotranspiration, water budget surplus, the standard deviation of the elevation, the soil texture and soil moisture) is harder to interpret, but shows similar patterns. In particularly, the east coast of the USA shares commonality with northern Europe and east Australia. However, as an SGD-cluster, it now also included the karst regions of Florida (USA) and the Mediterranean, where SGD is known to be an important phenomenon. Norway, the Adriatic, the eastern Black Sea and the northwest coast of Canada and southern Alaska remain in the same class, as do the coastal plain areas of the US east coast, Argentina, northern Europe and eastern Australia. The dry regions of Namibia, Somalia, the Saudi peninsula and the Red Sea coast remain grouped with Western Australia. This clustering implies that the mid-latitudes of eastern South America (i.e., Argentina) would be a potentially interesting region in terms of SGD, because it is similar to the east coast of the USA, northern Europe, Italy, and eastern Australia, all areas of significant SGD.

The next trial was a weighted clustering based on eight parameters of the LOICZ database. There were: precipitation (gage corrected, 12-month total); water surplus (average annual total); water deficit (average annual total); evaoptranspiration (average annual total); mid-month soil moisture (sum of monthly averages); standard deviation of the land elevation; soil texture and annual mean run off. In an attempt to avoid bias due to correlated variables, a correlation matrix was calculated and each parameter was weighted by a value equal to one minus the correlation coefficient of its correlation to precipitation. That is, precipitation was assigned a weight of 1.0; the correlation coefficient between precipitation and water surplus, for example, was calculated to be 0.9 so a weighting of 0.1 (that is, $1.0-0.9$) was assigned to the value of water surplus. Similarly, the other weightings were 0.8 for the water deficit; 0.2 for evapotranspiration, 0.3 for soil moisture 0.8 for the standard deviation of the land elevation; 0.7 for soil texture and 0.1 for runoff. Four clusters were generated and the results shown in Figure 2.

Figure 3. Four cluster, supervised, weighted, eight parameter cluster. Type locations were chosen to be on Long Island, NY; northeastern Gulf of Mexico, Florida; south of Osaka Bay, Japan; and the vicinity of the Nile Delta.

The first cluster (Figure 2, red) was represented by a site in Terra Del Fuego and included the California coast, the Arctic coast, parts of the Black and Mediterranean seas, the northeastern coastal plain of the USA and southern Africa and Australia. The second grouping (Figure 2, green) was represented by the coast in China and included Indonesia, parts of eastern South America, China, equatorial east Africa and the Gulf of Mexico. The third cluster (Figure 2, blue) included the arid coasts of Baja California, Namibia northwestern Australia, the Saudi peninsula and the south-eastern Mediterranean. Its archtypical location was along the west coast of the Gulf of California. Hawaii was in the fourth category (Figure 2, yellow), which also included the Malaysia peninsula as well as western Canada and Norway. Its archetype location was in the central west coast of Japan, not far, in fact, from one of its representative locations chosen for a supervised clustering in the next step.

Our final illustration was a supervised cluster using the same, weighted eight parameters. Four type locations were chosen. One was on Long Island, NY, a thick coastal plain aquifer where SGD rates have been measured to be on the order of 4 cm/day (entry No. 2 in Taniguchi et al. 2002). The second was on the Florida panhandle (Gulf Coast) where rates were 1–11 cm/day (entry No. 6 in Taniguchi et al. 2002). A third type location was chosen in Japan (entry No. 38 in Taniguchi et al. 2002) where SGD rates were 12–37 cm/day. A fourth location was chosen on the Nile Delta. Although discharge rates were not available, submarine discharges are known to occur (Kohout 1966) and this stretch of coast seems representative of an important cluster in the previous experiments. The results are shown in Figure 3. The first grouping (Figure 3, red) clustered the Long Island coastal plain site with coasts in northwestern Canada, Scandinavia, Mozambique and Australia. The second cluster grouped the fractured rock aquifer of Japan with coasts in Hawaii, New Zealand, Indonesia and Malaysia, parts of the Adriatic and Black seacoast, western Canada and the isthmus of Panama. The dry, deltaic coast of the Nile was in a cluster with Baja California, the Saudi peninsula, Namibia and Western Australia as well as the Arctic coast. The Florida Gulf Coast was grouped with coastal settings in Argentina, eastern Australia and northern Europe.

It is perhaps not surprising to find patterns repeated in these various trials. The dominant parameterization is basically dominated by precipitation regardless of the number of confounding factors introduced as variants. It is fortuitous that some of the clusters seem associated with geology even though not explicitly incorporated into the typology. Major coastal plain aquifers in different regions often seem to share some hydrologic characteristics, as do some karst terrains. In all these experiments, large island nations, like Madagascar and Iceland, as well as the Mediterranean coast, appear to be particularly interesting regions because they contain short stretches of coastline in almost every class in close proximity.

Discussion

Because of the composition of the LOICZ typology, the SGD typologies constructed here are based primarily on characteristics of the water budget. The classifications with only a small set of parameters seems to yield reasonable typology but it is also clear that the classifications break down in detail. Better parameters are needed. At present, water quality data is not yet represented in the metadata tables, and both geological and geomorphological information needs to be included. Soil texture and the surrogate for relief (i.e. the standard deviation of the topography) represent the only geologic discrimination. Other geological and geomorphological characteristics are not yet in the LOICZ database. Incorporating coastal aquifer rock type, estuarine geomorphology and, perhaps, even quantitative measures of shoreline tortuosity would seem to be reasonable additions to the typology with relevance to SGD.

A classification of the coastal aquifers by rock type, for example, would include seven types. These are: unconsolidated deposits of sand and gravel sandstone, interbedded sandstone and carbonate semi-consolidated, carbonate, basalt and other types of volcanic and an 'other rock' category (http://nationalatlas.gov/aquifersm.html). The morphological classification associated with estuaries may be particularly appropriate because the occurrence of estuaries indicates the degree of 'focusing' of SGD into embayments. With regards to estuaries seven categories have been described (Fairbridge 1980 as described by Perillo 1995). These are: fjords (high relief); fjords, or firths, or sea locks (moderate relief); ria, aber, calengue or cala (moderately high relief, winding valleys); coastal plain estuaries (low relief, branching valleys); bar-built estuaries (low relief, relatively straight shorelines); blind estuaries (low relief, blocked, seasonally, by a straight barred coast); deltaic estuaries; and tectonic estuaries.

The second issue is that of shoreline geography. Quantitative, non-geological measures have been suggested to capture the tortuosity of the coast (Bokuniewicz 2001; Bartley et al. 2001). Along a straight shoreline, SGD might be expected to be uniformly distributed into the coastal ocean, but if the shoreline is contorted, SGD derived from the land will be focused into embayments and dispersed around headlands. Mandelbrot (1967) embodied this characteristic of shoreline measurement in the concept of a fractional dimension, or fractal dimension, D. If a coastline of an island is approximated by straight line segments of equal length, s, then the total shoreline length, L, can then be calculated as the product of the total number of segments, N, and the segment length, or Ns. As the size of the segment increases, the total shoreline length is found, empirically, to decrease. This relationship is described by a fractal dimension calculated as one plus the slope of the line defining the (linear) relationship between logarithms of the shoreline length as a function of the logarithm of the line segment length. Although not uncritically accepted, the fractal dimension is intended to provide a quantitative measure of the tortuosity of a shoreline (Turcotte 1991).

The fractal dimension is a number between 1 and 2. More contorted shorelines have higher fractal dimensions. The smooth coast of South Africa, for example, has a fractal dimension of 1.02. The more irregular coast of Britain is 1.25 (Mandelbrot 1967). In general the shoreline length is $L(s) = Ms^{1-D}$ where M is an empirical constant. For example, the fractal dimension, D, is calculated for the coast of Sicily to be 1.05. The coefficient, M, is found to be 1026.36 when both s and L are measured in kilometers. The shoreline length based on a pace of 0.865 m is 1460 km while a 1-mm step requires 2048 km to circumnavigate the coast of Sicily. For a Standard International Unit step size of 1 m, the Sicilian shoreline is 1450 km in length. These measures have been explored along the US coast (http://coastal.er.usgs.gov/barton/pubs/fractalmap.pdf) and the Baja peninsula and Gulf of California (http://kgs.ukans.edu/Hexacoral/Products/BARTLEYFIN3.html), but they are not yet available globally.

Conclusions

SGD should be broadly integrated into coastal zone management. Although it has to be directly measured in relatively few locales, there is reason to believe that SGD is important in a wide range of settings and relevant to broadly-based policy issues of freshwater supply, waste disposal, pollution and marine resource utilization. Analytical tools (e.g., Web LOICZ View) are available to help managers evaluate the potential relevance of SGD in their jurisdiction; clustering techniques can be used to relate relevant characteristics of coastal regions where the importance of SGD is unknown, to other regions where SGD has been determined. Implementation of the typological approach, however, must be acknowledged as incomplete. Specific geologic and geomorphic parameters must be incorporated and the interpretation of the clustering experiments requires site-specific professional judgment.

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