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Editorial

Coastal areas and resources pose complex, multidimensional problems for the management of the various systems and subsystems in operation. Human activities have a growing impact on the marine environment, the degree of impact varying with distance from the coasts. Coastal management research is now sufficiently well advanced for the type of problems that exist to be known. The sources or drivers of these problems are varied. In the context of India, for example, our research suggests that the following are the main drivers: population growth, technology choices, short time horizons or a concern with the present, consumptive behaviour, absence or failure of policy, unpriced or under-priced resources, poor governance, aspirations and attitudes of local population, and the changes in relations between people and ecosystems. This is probably not very different for other parts of the developing world.

Vital tools for management are methods to map the extent of the problems, to analyse and understand the nature of stresses, and to arrive at management and conservation solutions that can be implemented. In this issue of Coastin, we provide short articles on such tools. One of the major issues of groundwater is the common pool problem. As water does not remain static but moves underground, if one person digs deep or extracts too much, it can affect availability in the shallow wells of the same aquifer. There are a number of areas on the Indian coast where water levels have declined and where there is seawater ingress. There is need to identify aquifers that are vulnerable to such seawater intrusion. Our project partners provide here a new method to map the vulnerability of aquifers to seawater intrusion, using the GALDIT index and applying data generally available. Another ecosystem that is most impacted by human activities on the coast is coastal vegetation. Coastal management requires methods to not only classify and map remotely sensed data of coastal vegetation types but also to analyse vegetation stress. Our project partners discuss methods that can be used for such analyses.

We also have a guest article on marine protected areas, which serve as small-scale models of integrated coastal management, and provide 'a geographic arena to promote effective conservation'. A framework of indicators to identify potential coastal vulnerability is also presented.

We hope you find these articles of use and interest.

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Updates on the project

- Data collection and analysis in the North Goa district have been completed. Major works include
  - Socio-economic analysis
  - Estimation of potential impacts of various human activities
  - Assessment of coastal vegetation cover using NDVI (normalized difference vegetation index) and fractal analysis
  - Land use change using remotely sensed images
  - Groundwater vulnerability mapping
  - Ecological footprint analysis of tourism activity.

The process of integration of the data from different work packages through the GIS (geographical information system) is in progress.

- Data collection from the Thane district for industries and East Godavari for aquaculture have been started by different teams.
- Preparation of the village-level database is ongoing.

Marine protected areas: solutions to global ocean issues

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The global marine environment is undergoing rapid changes at the hands of humans despite its vastness and the seemingly inexhaustible array of resources it supplies. Threats to marine life are numerous and include both direct and indirect impacts. Historically, overexploitation of certain organisms such as baleen whales, sea turtles, and pinnipeds have caused inherently vulnerable species to become endangered. Rather than getting abated, over-exploitation has spread, and continues to reduce stocks, extirpate populations, and affect food webs. This overfishing is not just restricted to commercial fishing but also includes subsistence fishing in areas where coastal population density is high. Humans also directly impact the seas by coastal development. Indirect degradation takes its toll as well—from run-off of agricultural nutrients causing eutrophication to introduction of alien species. Finally, humans impact marine systems at the global scale through climate change and other global-scale phenomena.

What possible conservation solution could exist to tackle such a complex suite of threats? To develop effective responses, a four-pronged approach is needed.

1 Define sustainable limits to resource use
2 Develop recovery plans for endangered species
3 Mitigate indirect impacts
4 Protect the ecologically most critical habitats that maintain ecosystems.

Marine protected areas or MPAs allow these four activities to be practiced simultaneously—they provide the geographic arena in which to promote effective conservation.

Marine protected areas are fundamentally different from terrestrial protected areas, though whether these differences are in kind or degree is debatable. An important factor underlying these differences is the nebulous nature of boundaries in the fluid environment of the sea, making it difficult to attach boundary conditions to marine ecological processes and threats to those processes. Although this is also true for inland freshwater systems, these ecosystems usually have distinct horizontal layers and more discernable outer bounds. As on land – but to a far greater extent – it is impossible to ‘fence in’ living marine resources or the critical ecological processes that support them, just as it is impossible to ‘fence out’ the degradation of ocean environments caused by land-based sources of pollution, changes in hydrology, or ecological disruptions occurring in areas adjacent or linked to a protected area. Long-distance dispersal and the vastness of linkages among critical habitats in coastal and marine ecosystems require comprehensive management of all its parts.

The general benefits of MPAs are twofold. There are the obvious in situ benefits such as conservation of populations, species, and habitats and providing mechanisms for management of resource use within sustainable limits. This requires a clearly articulated and adaptive management plan (i.e. management is set up as a verifiable scientific experiment).

Second, there are the ex situ benefits. For instance, MPAs raise awareness about the sea and can increase the perceived value of a particular place (which in turns generates the political will to protect it). MPAs also provide a small-scale model of integrated coastal management—a tractable scale from which management can be scaled up to provincial or even national levels. This integrated management has three components: strict nature conservation, conflict resolution and sustainable use, and recovery and restoration of degraded ecosystems.

Marine protected areas are being increasingly used worldwide to protect biologically rich habitats, resolve user conflicts, and help restore overexploited stocks and degraded areas. The upsurge in the use of the tool is, in part, due to fisheries managers now looking to reserves to complement conventional fisheries management techniques. Many of the latest MPAs are more ambitious than conventional marine protected areas are, resulting in multiple-use reserves that try to accommodate many different users groups, each with their own needs and objectives. Administrators are finding that different uses can indeed be fostered without adversely impacting ecosystem function as long as planning is based on ecological realities, relies on specific objectives from the outset, and balances established objectives. These protected areas can provide a footing for integrated coastal management and better ocean governance overall. But the problems of marine degradation are so numerous and the threats to marine biodiversity so ubiquitous that some method for identifying geographic priorities is needed. The next section describes an objective methodology for evaluating the potential for MPA investment in coastal countries worldwide.

Marine protected area site selection or placement, design, and type of management relate to the very specific goals being targeted by the protected area establishment. Therefore, the most crucial information that is needed is that of the specific objectives the protected area is designed to achieve. This information is ultimately societal, not scientific. We should keep in mind that there is no single 'model' MPA that can be applied in any country, any biome, or any setting.

Assuming that the MPA is being used to protect marine resources and biodiversity, optimize management, and allow recovery of degraded areas, there are basic information needs that must be met in the process of designing, implementing, and maintaining MPAs. These data and resulting information must answer the following.

- Where, in a broad geographic sense, to establish MPAs
- How to design MPAs and locate specific sites within them that should be protected as core, no-take areas
- How to establish regulations and effectively manage the protected area in order to meet objectives
- How to monitor and evaluate whether goals are being met, including benefit valuation.

Scientific information on biomass, dispersal patterns, recruitment dynamics, trophic interactions, and critical habitat are often used to design the size, shape, and management of MPAs. But what is needed first and foremost, and what is most often overlooked when the process of establishing an MPA is initiated, is information on what the protected area is being established to achieve. This goal-setting or objective elaboration is critical in order to determine expectations, effectively design the reserve, and have in place targets and benchmarks against which progress towards the objectives can be measured. Once objectives are elaborated, a management plan (often coupled with a zoning plan) must be developed and implemented. Part of this management plan should be a monitoring program that can shed light on whether the objectives are truly being met.

For MPAs serving marine conservation generally, several essential steps must be taken to increase the likelihood of success. These steps are listed in Table 1, and are particularly germane to MPA establishment in developing countries, especially where communities play a role in the design, management, and evaluation of reserves.

Table 1 Ten key principles for success of MPA

1	Clearly define specific objectives for the MPA at the onset
2	Design zoning to maximize protection for ecologically critical areas and processes
3	Design MPA boundaries such that they reflect ecological reality and be prepared to alter the design as more ecosystem information is derived
4	Design the MPA and develop its management plan with feasibility in mind
5	Make the planning process truly participatory
6	Develop monitoring and evaluation methodologies that are appropriate to the specific objectives of the protected area
7	Use the MPA to raise awareness
8	Form an independent, non-partisan or multi-user group body to manage the MPA
9	Undertake valuation exercises periodically to ensure that the full value of the protected area is being realized
10	Use individual MPAs as a starting point for more effective marine policies overall

In some cases, individual MPAs may not meet the goals outlined either because the geographic scope of the target area is too vast or because the threats to the ecosystem are too varied. In such cases, conservation and sustainable use is best served through a network of MPAs designed to conserve the wider ecosystem through strategically placed and scientifically determined site protection.

Fishers, nations, and indeed the entire biosphere can benefit from the establishment of MPAs at all scales and in all coastal environments. As noted, the rationale for MPA establishment is no longer lacking—defining priorities and launching initiatives in new places is often difficult. Despite incomplete knowledge and imprecise science, steps must be taken to establish protected areas now and use the additional information we gain as time goes on to upgrade these reserves, remove superfluous ones, and add new reserves. By clearly defining objectives and using science to design the best possible plans for meeting these objectives, we can improve our management of marine activities before the health of the seas is compromised and with it the ability of marine systems to provide us with the resources and services on which we increasingly depend.

The most effective MPAs, regardless of where they are established, will be those that change as environmental conditions and human needs change. This is at the core of adaptive management. However, to change MPAs as per current needs, a rigorous program for monitoring must be in place, along with periodic evaluations. This monitoring should be directed at both the environment (environmental quality and biodiversity) and users of the MPA in order to see if the specific objectives for which the MPA was established are being met.

It is very important that a monitoring program be geared to gauge the effectiveness of MPA management towards the specific objectives it sets out to achieve. There is no model program for monitoring that can be used in all circumstances. The optimal situation is to develop local capacity for monitoring as this not only reduces costs for monitoring but, more importantly, provides a mechanism for more fully involving local people in the operation of the protected area.

Marine protected areas that are optimally designed to meet clearly articulated objectives, and that are monitored to assess whether objectives are indeed being met, are one of the most powerful conservation tools available today. Both centralized governments and communities have key roles to play in using these tools effectively, and working together to save our seas. We must remember that no MPA can exist as an ‘island of protection’ in perpetuity, unless the context in which these islands sit is also protected through effective maritime policies.

Analysing coastal vegetation stress

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The analysis of satellite imagery offers the opportunity to document major coastal changes that have occurred and to define their relationship to both natural and human-induced causes (Leatherman 1993). The use of computerized GIS (geographical information systems) makes it possible to process large volumes of geographically referenced data from multiple sources, which can then be integrated to produce maps, monitor changes in resources, coordinate resource uses, and simulate impacts from management decisions.

To classify and map remotely sensed data of coastal vegetation types and to analyse vegetation stress, the following methodologies can be used: (a) visual interpretation, (b) calculation of vegetation index, (c) unsupervised classification, (d) supervised classification, (e) principal component analysis, (f) spatial pattern analysis, and (g) fractal analysis.

Visual interpretation

Visual interpretation requires a radiometric enhancement to facilitate visual comprehension of the information displayed in the imagery (Green, Clark, Mumby et al. 1998).

Calculation of vegetation index

Vegetation indices are linear or non-linear combinations of reflectance acquired in several wavebands. They were developed to minimize the influence of some ‘confounding variables’ the reflectance values. In particular, these indices are designed to minimize the effect of irradiance conditions (sensors onboard satellite platforms measure radiance, which is very sensitive to variations in irradiance conditions) and those due to variations in soil optical properties which depend on soil type, surface roughness, and moisture (Baret 1995).

A widely used index is the NVDI (normalized difference vegetation index) or greenness index, which has been interpreted as a measure of regional to global vegetation patterns. It is derived from canopy reflectance in the red and near-infrared wavebands. The red spectral measurements are sensitive to the chlorophyll content of vegetation and the near-infrared to the mesophyll structure of leaves (Townshend, Tucker, and Goward 1993). Thus, the NDVI is interpreted as indicating the presence of chlorophyll and expresses the degree of pixel greenness. This index is used as an indicator of canopy structure (leaf area index, see below), percentage vegetation cover, green leaf biomass (the NPP [net primary production], which is the resultant of photosynthetic energy fixation), light absorption and photosynthetic activity, evapotranspiration (a commonly used general ecological index integrating simultaneously warmth and soil water availability, assuming a vegetation cover), etc. (Box, Holben, and Kalb 1989; Gamon, Field, Goulden et al. 1995). The NDVI is thus widely used in monitoring and mapping the dynamics of terrestrial vegetation.

The leaf area index is the area of leaves per unit ground area (m^2/m^2). It is a key variable for the characterization of the vegetation structure because it translates, in a standardized form, the foliage amount per area of different vegetal formations. This parameter measures the plant canopy density and the optical depth in the stand. It has been proven to be strongly correlated with many ecophysiological processes at the stand and regional levels, such as evapotranspiration and photosynthesis rates (Running, Nemani, Peterson et al. 1989). Variations in LAI were found to be linearly related to site water balance, above-ground NPP, and stand volume growth of forests.

To obtain all field data relating to plant canopy characteristics and to verify the accuracy of the data derived from elaboration of satellite images, it will be necessary to acquire, in all study areas, some *hemispherical photographs*. Hemispherical photography provides an upward-looking view of all or part of the sky. Hemispherical images are obtained using a camera fitted with a fisheye lens (180° of view) pointed upward. The resulting photographs can be analysed to determine which parts of the sky are visible and which parts are obstructed by plant canopy. Based on these measurements of the geometry of sky visibility and sky obstruction, hemispherical photographs can be used to calculate solar radiation regimes and various plant canopy characteristics. Hemispherical photography can be thought of as an 'upside–down' remote sensing.

Unsupervised classification

Unsupervised classification is a technique for the computer-assisted interpretation of remotely sensed imagery. The computer routine does this by identifying typical patterns in the reflectance data. These patterns are then identified by undertaking site visits to a few selected examples to determine their interpretation. It is possible to perform an unsupervised classification of an imagery using the ISODATA clustering algorithm of Ball and Hall (1965).

Supervised classification

Supervised classification is a technique for the computer-assisted interpretation of remotely sensed imagery. The operator trains the computer to look for surface features with reflectance characteristics similar to those of a set of examples of known interpretation within the image. These areas are known as training areas. This classification technique can also be used to produce the land cover map.

Principal component analysis

The principal component analysis works on set of image bands and produces a new set of images—components that are not correlated with each other and explain progressively less of the variance found in the original set of bands. The technique is used for data compression as the first two or three components explain 95%–99% of the variance in the original set of bands. In cases like this, the components explaining less than a certain percentage of the variance can be dropped. It is also useful in the analysis of time series data. The selection of band ratios should be based on the physical properties and canopy spectra of mangrove vegetation (Green, Clark, Mumby et al. 1998).

Spatial pattern analysis

Space is where events (everything that could happen) may take place. Pattern relates to the location of events in real space (geographical space) and in abstract space (the space that can only be described mathematically by the variables describing objects and/or phenomena and by objects and/or phenomena themselves) or the manner of arrangement of event in space/time. Spatial pattern analysis of ecological events is done in order to describe and understand the relationships between and within living organisms and between organisms and the chemical–physical environment. To study the spatial pattern of the ecological components and processes, it is necessary to define the OGUs (operational geographic units). These are points or small areas representing georeferenced individuals (areas or pixels) (Feoli and Zuccarello, 1996). There are several methods and indices to perform such an analysis (e.g. contagion or fragmentation and fractal dimension).

The contagion index has been used in ecosystem analysis to quantify the amount of clumping or aggregation of patches (contiguous grouping of identically valued integer cells in an image). It is also used as an indication of the degree of fragmentation of a landscape (Altobelli 1999) that could be used to study the structure and distribution of areas most exposed to some environmental risk (i.e. soil erosion). It has been used to relate the effects of contagion patterns on such ecosystem processes as habitat fragmentation, vegetation dispersal, and animal movements (Li and Reynolds 1993)

Fractal analysis

Fractal is a general term for figures or phenomena with no characteristic length, self-similarity, and non-integer dimension. Geometric shapes have a characteristic length, such as the radius or circumference of a circle and the edge or diagonal of a square. Fractal figures are unique in that they cannot be measured with a single characteristic length because fractal figures hold self-similarity, their shape does not change even when observed under a different scale. This feature is also called scale-invariance.

When applied to remote sensing data, the fractal dimension represents the complexity of the image (the roughness of a surface, like the complexity of the vegetation spatial data) (Altobelli 1999). Fractals have been used to describe spatial patterns in many landscape-level applications to measure the geometric complexity of landscape features (Olsen, Ramsey, and Winn 1993).

To compute the fractal dimension, a remotely sensed image is considered a three-dimensional surface, and its complexity is expressed in terms of its variability over the space. Similar to a natural surface such as a hilly terrain or flat plain, this complexity is a function of its vertical variability of pixels values. A hilly terrain has more ups and downs than a flat plain does, thus representing a surface with a greater complexity. This complexity function can be expressed by the fractal dimension D and is a quantitative measure of the 'roughness' of a surface (De Jong and Burrough 1993).

This method is applied to the NDVI image to examine the landscape spatial complexity, particularly green vegetation distribution.

References

Altobelli A. 1999
Landscape ecology analysis of remote sensing images: spatial pattern indices
Training Package, Area Science Park, Trieste, Italy: ICS-UNIDO

Baret F. 1995
Use of spectral reflectance variation to retrieve canopy biophysical characteristics
In *Advances in Environmental Remote Sensing*, pp. 33–51, edited by F M Danson and S E Plummer
Chichester, UK: Wiley

Box E O, Holben B N, and Kalb V. 1989
Accuracy of the AVHRR: vegetation index as a predictor of biomass, primary productivity and net CO_2 flux
Vegetation 80: 71–89

De Jong S M and Burrough P A. 1993
A fractal approach to the classification of Mediterranean vegetation types in remotely sensed images
Photogrammetric Engineering and Remote Sensing 61 (8): 1041–1053.

Feoli E and Zuccarello V. 1996
Spatial pattern of ecological processes: the role of similarity in GIS applications for landscape analysis
In *Spatial Analytical Perspectives on GIS*, vol.4, GISDATA, pp. 175–185, edited by M Fischer, H J Scholten, and D Unwin
Torun, Poland

Gamon J A, Field C B, Goulden M L, Griffin K L, Hartley A E, Joel G, Penuelas J, Valentini R. 1995
Relationships between NDVI, canopy structure and photosynthesis in three Californian vegetation types
Ecological Applications 5: 28–41.

Green E P, Clark C D, Mumby P J, Edwards A J, Ellis A C. 1998
Remote sensing techniques for mangrove mapping
International Journal of Remote Sensing 19(5): 935–956

Leatherman S P. 1993
Coastal change
In *Atlas of Satellite Observation Related to Global Change*, pp. 327–339, edited by R J Gurney, J L Foster, and C L Parkinson
Cambridge, England: Cambridge University Press

Li H and Reynolds J F. 1993
A new contagion index to quantify spatial patterns of landscapes
Landscape Ecology 8: 155–162

A modified fractal dimension as a measure of landscape diversity
Photogrammetric Engineering and Remote Sensing 59(10): 1517–1520

Running S W, Nemani R R, Peterson D L, Band L E, Potts D F, Pierce L L, Spanner M A. 1989
Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation
Ecology 70(4): 1090–1101

Townshend J R G, Tucker C J, and Goward S N 1993
Global vegetation mapping
In *Atlas of Satellite Observation Related to Global Change*, pp. 301–311, edited by R J Gurney, J L Foster, and C L Parkinson
Cambridge, England: Cambridge University Press

Sea water intrusion vulnerability mapping of aquifers using the GALDIT method

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Introduction

The overuse of groundwater along parts of the coastal belts of India for various purposes has affected groundwater quality and quantity. It has led to rapid decline in groundwater levels, leading to saltwater intrusions and water quality deterioration particularly in parts of Gujarat, Tamil Nadu, Andhra Pradesh, Orissa, and West Bengal.

Experiences show that remediation of the groundwater system, which has undergone saltwater intrusion, is rather difficult and uneconomical in most of the cases. Therefore, a methodology to assess and map the probable potential areas of seawater intrusion by standard scientific methods needs to be developed.

In the present paper, a new approach based on four intrinsic hydrogeological parameters, one spatial parameter, and one boundary parameter has been proposed to map the potential coastal areas of seawater intrusion. The basic assumption made is that seawater mixing into fresh groundwater is essentially a pollution problem.

A new concept for defining groundwater vulnerability to pollution

Groundwater regime can be regarded as a system. The analysis of system performance focuses on system failure. Three concepts – reliability, resiliency, and vulnerability – provide useful measures of system performance (Lobo-Ferreira 1999). The concept of vulnerability defined in the context of system performance may also be used in the context of groundwater pollution due to seawater mixing by replacing 'system failure' by 'intensity of groundwater pumpage' due to which the seawater mixing takes place.

It is believed that the most useful definition of vulnerability is one that refers to the *intrinsic* characteristics of the aquifer, which are relatively static and mostly beyond human control. It is proposed, therefore, that groundwater vulnerability to pollution be defined, in agreement with the conclusions and recommendations of the *International Conference on Vulnerability of Soil and Groundwater to Pollutants* held in 1987 in the Netherlands (Anderson and Gosk 1987; van Duijvenbooden and van Waegeningh 1987), as 'the sensitivity of groundwater quality to an imposed groundwater pumpage in the coastal belt, which is determined by the intrinsic characteristics of the aquifer'. Thus defined, vulnerability is distinct from pollution risk. Pollution risk due to seawater mixing depends not only on vulnerability but also on the existence of significant groundwater pumpage in the proximity of the coast. It is possible to have high aquifer vulnerability but no risk of seawater intrusion if there is no significant groundwater pumpage in the proximity of the coast, and to have high pollution risk despite low vulnerability if the groundwater pumpage is exceptional. It is important to make clear the distinction between vulnerability and risk. This is because risk of seawater intrusion is determined not only by the intrinsic characteristics of the aquifer, which are relatively static and hardly changeable, but also on the existence of intensive activities of groundwater pumpage along the coast, which are dynamic factors that can in principle be changed and controlled.

Methodology

Hydrogeological conditions and human activities close to the coast mainly affect groundwater pollution due to seawater mixing. There has been no methodology for evaluating the spatial distribution of the seawater intrusion potential, which essentially takes into account hydrogeological factors and allows seawater intrusion of coastal hydrogeological settings to be systematically evaluated in any selected coastal area where hydrogeological information is available. It is therefore necessary to adopt a mapping system that is simple to apply using the data generally available yet capable of making best use of those data in a technically valid and useful way.

Some of the systems for aquifer pollution vulnerability evaluation and ranking include a vulnerability index, which is computed from hydrogeological, morphological and other aquifer characteristics in a well-defined way. The adoption of an index has the advantage of, in principle, eliminating or minimizing subjectivity in the ranking process.

Suggested system of vulnerability evaluation and ranking

Inherent in each hydrogeologic setting are the physical characteristics that affect the seawater intrusion potential. The most important mappable factors that control the seawater intrusion are

- Groundwater occurrence (aquifer type; unconfined, confined and leaky confined)
- Aquifer hydraulic conductivity
- Depth to groundwater level above sea
- Distance from the shore (distance inland perpendicular from shoreline)
- Impact of existing status of seawater intrusion in the area
- Thickness of the aquifer which is being mapped.

The acronym GALDIT is formed from the highlighted letters of these parameters. These factors, in combination, include the basic requirements needed to assess the general seawater intrusion potential of each hydrogeologic setting. GALDIT factors represent measurable parameters for which data are generally available from a variety of sources without detailed reconnaissance.

A numerical ranking system to assess seawater intrusion potential in hydrogeologic settings has been devised using the GALDIT factors. The system contains three significant parts: weights, ranges, and ratings. Each GALDIT factor has been evaluated with respect to the other in order to determine the relative importance of each factor. Each GALDIT factor has been assigned a relative weight ranging from 1 to 4 (1: least significant to 4: most significant).

A rating value between 1 and 10 is attributed to each parameter depending on local conditions. High values correspond to high vulnerability. The attributed values are generally obtained from tables that give the correspondence between local hydrogeologic characteristics and the parameter value. Next, the local index of vulnerability is computed through multiplication of the value attributed to each parameter (rating) by its relative weight (GALDIT weight) and adding up all six products. Therefore, the minimum value of the GALDIT index is 13 and the maximum value is 130. The impact of each of the above six parameters on seawater intrusion is described.

Factors	*GALDIT weights*
Groundwater occurrence (aquifer type)	1
Aquifer hydraulic conductivity	3
Depth to groundwater level above sea	4
Distance from the shore	2
Impact of existing status of seawater intrusion	1
Thickness of aquifer being mapped	2

- *Groundwater occurrence (aquifer type) (G):* In nature, groundwater generally occurs in the geological layers and these layers may be confined, unconfined, or leaky confined. This basic nature of groundwater occurrence has an influence on the extent of seawater intrusion. For example, an unconfined aquifer under natural conditions will be more affected by seawater intrusion as compared with a confined aquifer as the confined aquifer is at a pressure higher than atmospheric pressure. Similarly, a confined aquifer may be more prone to seawater intrusion as compared with a leaky confined aquifer as the leaky confined aquifer maintains minimum hydraulic pressure by way of leakage from adjoining aquifers. Therefore, while assigning the relative weights to *G*, one should carefully study the disposition and type of the aquifers in the study area. The ratings are generally as follows: unconfined (9), confined (10), and leaky confined (8). The confined aquifer is more vulnerable due to a larger cone of depression and instantaneous release of water to wells during pumping. In a multiple aquifer system in an area, the highest rating may be adopted. For example, if an area has all the three aquifers, the rating of 10 for an unconfined aquifer may be chosen.
- *Aquifer hydraulic conductivity (A):* This parameter is used to measure the rate of flow of water in the aquifer. By definition, aquifer hydraulic conductivity is the ability of the aquifer to transmit water. Hydraulic conductivity is the result of interconnected pores (effective porosity) in the sediments and fractures in consolidated rocks. The magnitude of seawater front movement is influenced by hydraulic conductivity—higher the conductivity, higher the inland movements of the seawater front. The high conductivity also results in a larger cone of depression during pumping. In this case, the user should take into account such hydraulic barriers as clay layers and impervious dykes parallel to the coast, which may act as walls to seawater intrusion. Typical ratings can be obtained from Aller, Bennett, Lehr et al. (1987).
- *Depth to groundwater level above sea (L):* The level of groundwater with respect to mean sea level is a very important factor in evaluating seawater intrusion in an area primarily because it determines the hydraulic pressure availability to push the seawater front back.

As seen from the Ghyben–Herzberg relation, for every meter of freshwater stored above mean sea level, 40 m of freshwater is stored below it down to the interface. In assigning the ratings to *L*, one should look into the temporal long-term variation of groundwater levels in the area. Generally the values pertaining to minimum groundwater levels above sea (premonsoon) may be considered, as this would provide the highest possible vulnerability. The ratings can be adopted from Aller, Bennett, Lehr et al. (1987).

- *Distance from the shore (D):* The impact of seawater intrusion generally decreases as one moves inland at right angles to the shore. The maximum rating of 10 can be adopted for distance less than 100 m from the coast. The rating value can be reduced by one for every 100-m increase in the distance from the coast till 800 m. A rating of 2 is suitable for a distance range of 801–1000 m and a rating of 1 is adopted for all distances greater than 1001m.
- *Impact of existing status of seawater intrusion (I):* The area under mapping is invariably under stress, and this stress has already modified the natural hydraulic balance between seawater and fresh groundwater. This fact should be considered while mapping aquifer vulnerability to seawater intrusion. Three distinct ratings can be (a) areas already intruded by seawater in all seasons or groundwater samples showing the ratio of $Cl/(HCO_3 + CO_3)$ greater than 2 epm, (b) areas where seasonal seawater intrusion prevails or groundwater samples showing the ratio of $Cl/(HCO_3 + CO_3)$ ranging between 1. 5 and 2 epm, and (iii) areas where no seawater intrusion was witnessed in the past or groundwater samples showing the ratio of $Cl/(HCO_3 + CO_3)$ less than 1.5 epm. The information for the above rating can be gathered from historical reports, inquiry from the local people, and chemical analysis data.
- *Thickness of the aquifer being mapped (T):* Aquifer thickness or saturated thickness of an unconfined aquifer plays an important role in determining the extent and magnitude of seawater intrusion in coastal areas. It is well established that larger the aquifer thickness, smaller the extent of seawater intrusion and vice versa. Keeping this as a guideline, the rating of 10 is given for aquifers less than 1-m thick and this rating reduces by a factor of 1 for every 1-m increase in aquifer thickness till 8 m. For aquifers 8.1–10 m thick, a rating of 2 is assigned; beyond 10.1 m, a constant rating of 1 is used.

Mapping of the final GALDIT index

According to the GALDIT method, each of the six parameters has a predetermined fixed relative weight that reflects its relative importance to vulnerability. When the GALDIT method is adopted, the aquifer vulnerability index to seawater intrusion is obtained by the following expression.

$$\mathrm{GALDIT} = 1*G + 3*A + 4*L + 2*D + 1*I + 2*T$$

Thus, the user can use hydrogeologic settings as a mappable unit, define the area of interest by modifying to reflect specific conditions within an area, choose corresponding ratings and calculate the seawater intrusion GALDIT index. This system allows the user to determine the numerical value for any hydrogeological setting by using an additive model.

Once the GALDIT index has been computed, it is possible to identify areas that are more likely to be susceptible to seawater intrusion than other areas. Higher the index, greater is the seawater intrusion potential. The GALDIT index provides only a relative tool and is not designed to provide absolute answers.

References

Aller L, Bennett T, Lehr J H, Petty R J. 1987
DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeologic settings
U.S. EPA Report 600/2-85/018

Andersen L J and Gosk E. 1987
Applicability of vulnerability maps
In *Vulnerability of Soil and Groundwater to Pollution*, edited by W van Duijvanbooden and H G van Waegeningh
[Proceedings and Information No. 38 of the International Conference, the Netherlands, 1987, TNO Committee on Hydrological Research, Delft, The Netherlands]

Lobo-Ferreira J P. 1999
The European Union experience on groundwater vulnerability assessment and mapping
Coastin 1: 8–1

Lobo-Ferreira J P and Cabral M. 1991
Proposal for an operational definition of vulnerability for the European community's atlas of groundwater resources
In *Meeting of the European Institute for Water*
[Groundwater Work Group, Brussels, February 1991]

van Duijvenbooden W and van Waegeningh H G. 1987
Vulnerability of soil and groundwater to pollutants
In *Proceedings and Information No. 38 of the International Conference*
[Organized by the TNO Committee on Hydrological Research,Delft, the Netherlands, 1987]

Identifying potential coastal vulnerability

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The main constraint to coastal planning and management is the lack of information and data to study the interactions between development and coastal environment. One way to provide this information is to work with indicators. We present here a process [adapted and modified from CALFED Bay – DELTA ERP indicator framework (CALFED Ecosystem Restoration Programme Indicators Work Group 1999)] used to develop a framework of indicators of potential vulnerability of coastal areas to development pressures and illustrate this with reference to India. The paper is a part of the INCO-DC project 'Measuring, Managing, and Monitoring Sustainability: the coastal dimension'.

Goal

The main objective behind developing this set of indicators was to arrive at the potential vulnerability of coastal regions in India through examining the links between human activities and the health of three coastal ecosystems – coastal water, coastal aquifers, and mangroves/dune vegetation.

Geographic scope and management units

The coastal region of India is studied with reference to administrative units (i.e. coastal districts as socio-economic data are available in these units) and to the ecosystems found in the coastal stretches of these districts.

Identify significant development drivers

To identify the important drivers of change, a focus group meeting was held involving coastal policy makers, experts, and local NGOs (Details of the EU project and the panel discussion held in Goa, India, on 22 February 1999 is available at http://teriin.org/teri-wr/coastin). The group identified urbanization, industrial activity, intensive aquaculture/agriculture, tourism, and port activity as the main drivers of change in the Indian context. A detailed literature survey was done to examine these activities and to arrive at their characteristics.

Characteristics of drivers and ecosystems

The main characteristics of urbanization were population, density, and workforce in non-agricultural sectors; of tourism were tourism infrastructure and tourist arrivals; of intensive agriculture/aquaculture were extent of cultivated and irrigated land, fertilizer consumption, area under aquaculture; of industry was number of potential polluting industrial units as per CPCB; and of port activity was the amount of cargo handled.

The key characteristics for the ecosystems were identified by consulting with experts and doing a literature search: water quality for coastal waters; level and water quality for groundwater; and area covered, trends in composition, and abundance for mangrove vegetation.

Conceptual model

To connect drivers with coastal ecosystems, we adopted the pressure-state-response framework, which has its origins in the condition-stress-response framework, first proposed by Statistics Canada, subsequently modified and adapted by numerous organizations, and further developed, used, and popularized by the OECD in 1993. Pressure indicators describe pressures that are placed on the domains. These pressures can be positive or negative and are caused by anthropogenic factors. State indicators describe actual conditions in the domains/systems and are important in problem identification and awareness building. Response indicators measure actions taken in response to environmental problems/stresses (USA EPA 1995). For our work, we used only pressures and state indicators.

Establish categories of indicators

Using this conceptual model, we established corresponding categories of indicators for each attribute of ecosystem and driver.

The pressure indicators measured the following.

- *Persons/km^2 (population density)* Threats from increased sewage waste, land-cover clearance, groundwater depletion and overexploitation of resources.
- *Density of tourist rooms (tourist infrastructure)* Threat to land-use and land cover, potential groundwater depletion, water and beach pollution from recreational activities

- *Area under intensive aquaculture* Threats to mangrove clearance, potential land-use change, saline intrusion into coastal aquifers, eutrophication, threats to wild stock
- *Fertilizer use/hectare, cultivated area, irrigated area* Threats of eutrophication, groundwater depletion, soil degradation, and land-cover change
- *Number of potentially polluting industrial units* Threats from industrial pollution, potential land-cover change, and groundwater depletion
- *Total cargo handled at ports* Threats from oil spills and impacts on marine life, from species introduction through release of ballast water, and need for port extensions and consequent impacts on marine life.

State indicators are based on the attributes of the ecosystems or surrogates that provide information on conditions of the ecosystems.

- *Coastal water* Physical, chemical, biological parameters
- *Coastal aquifers* Physical, chemical, biological parameters
- *Mangroves/dune vegetation* Basal area covered, number of species, canopy cover

Selection of potentially vulnerable coastal districts

To select potentially vulnerable coastal areas, we (1) ranked coastal districts according to the most intense operation of the drivers as measured by pressure indicators; for each driver, an index was constructed by giving equal weight to component indicators and (2) ranked coastal ecosystems in these districts according to their level of stress through expert opinion, secondary data from local bodies, and national-level databases. Every district was then ranked on relative stress levels of the three-component coastal ecosystems to arrive at a single index of stress.

Districts whose coastal ecosystems are most threatened or vulnerable to development activities are those that are ranked high for both drivers and for stressed ecosystems (Figure 1).

Conclusion

The methods presented here were chosen to help us overcome the limitations we faced, such as

- Inadequate data, which constrained the use of a more rigorous statistical method to establish the connection between pressure and state indicators
- Difficulty in matching socio-economic with ecological information
- Inadequate information about the general vulnerability of the coastal area

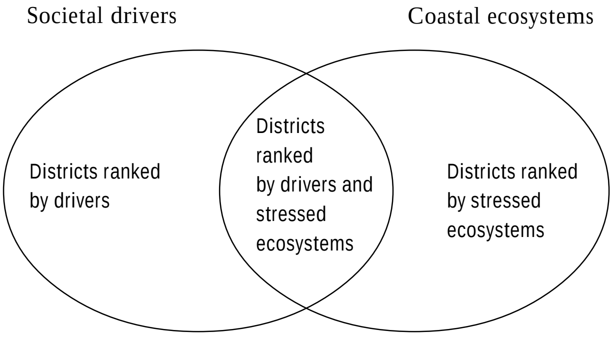

Figure 1 Venn diagram of districts whose coastal ecosystems are most threatened or vulnerable to development activities

The main limitations of the method are

- As we chose only the most important drivers, some pressures, such as fishing activity, were not considered
- A limited set of ecosystems was included because these are the ecosystems being studied in the project and for some ecosystems (e.g. dune vegetation, land forms) there was no available data

The framework can, however, be seen as a first step in the development of a more sophisticated system of indicators to track coastal vulnerability.

References

Bryant D E, Rodenburg T, Cox A, Nielsen, D 1995
An index of potential development related threats to coastal ecosystems
World Resources Institute
(http://www.igc.org/wri/indictrs/coastrs2.htm)

CALFED Ecosystem Restoration Program Indicators Work Group. 1999
Proposed indicators of ecological integrity for the CALFED bay-delta ecosystem restoration program
Presented at the *International Congress on Ecosystem Health*
[Sacramento, California]

OECD. 1993
OECD core set of indicators for environmental performance reviews
Paris

Laszlo P, Hardi P, and McRorie-Harvey L.1995
Performance measurement for sustainable development : compendium of experts, initiatives and publications
Winnipeg: International Institute for Sustainable Development

US EPA. 1995
Conceptual framework to support development and use of environmental information in decision-making
Washington, DC: EPA
[Document No. 239-R-95-012]

Forthcoming events

Crimea, Ukraine 12–16 March 2001	International Conference on Coastal Cities, Towns/Villages of the Azov-Black Seas Region: cojointly toward sustainable development *E-mail* shadrn@fossil.ukrcom.sebastopol.ua
Washington, DC, USA 31 March 2001	6th International Wildlife Law Conference: marine issues and international law *Fax* 801 838 4710 • *E-mail* jiwlp@pacbell.net
St. Andrews, UK 31 March 2001 – 5 April 2001	Glacial–interglacial sea level changes in four dimensions: sea-surface changes and coastal flood hazards in Europe *Fax* +33 388 366987 • *E-mail* rheywood@esf.org
Pontvedra, Spain 24–27 April 2001	1st International Congress on Marine Science and Technology: Oceans III Millennium *E-mail* fomar@fomar.org
Santiago de Cuba, Cuba 14–15 May 2001	1st Workshop on Integrated Coastal Zone Management University of Oriente, Santiago de Cuba, Cuba *Fax* 53 226 43186 • *E-mail* Nery@csh.uo.edu.cu
Falmouth, Cornwall, UK 15–16 May 2001	Future COAST 2001, Second Annual Symposium *Fax* +44 (0) 1224 27233 • *E-mail* d.r.green@abdn.ac.uk / s.d.king@abdn.ac.uk,
Quebec, QC, Canada 16–19 May 2001	2001 Canadian Coastal Conference on Coastal Science and Engineering: challenge for the new millennium *Fax* (418) 654 2615 • *E-mail* CCC01@inrs.uquebec.ca
Saïda, Liban 28–31 May 2001	International Seminar on Small Historical Coastal Cities. Urban Development — finding a balance among land, sea and people *Fax* +33 1 45 685728 • *E-mail* b.colin@unesco.org
Lund, Sweden 11–14 June 2001	Coastal Dynamics 2001: forcing and response in coastal dynamics *Fax* +46 46 2224435 • *E-mail* cd01@tvrl.lth.se
Halifax, Nova Scotia, Canada 18–20 June 2001	CoastGIS 2001: managing the interface *Fax* (902) 426 4104 • *E-mail* sherin@agc.bio.ns.ca
Cleveland, OH, USA 15–19 July 2001	Coastal Zone 01: 12th Biennial International Symposium on Coastal and Ocean Management
Amsterdam, The Netherlands 30 August–1 September 2001	People and the Sea. Maritime research in the social sciences – an agenda for the 21st century *E-mail* mare@siswo.uva.nl
Sheffield, UK 11–13 September 2001	International Conference on Changing Wetlands: new developments in wetland science *Fax* +44 114 2797912 • *E-mail* wetlands@sheffield.ac.uk
London, UK 26–28 September 2001	Coastal Structures and Breakwaters 2001 *Fax* +44 (0) 20 7233 1743 • *E-mail* Sue.Frye@ice.org.uk
Nanning, Guangxi, P R China 5–8 November 2001	The First International Conference on Ecological Sanitation *Fax* +86 10 6422 0162 *E-mail* jszykjb@263.net • *Website* www.wkab.se

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