Groundwater–seawater interactions in tsunami affected areas: solutions and applications

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Abstract The December 2004 tsunami in the Indian Ocean caused a disaster affecting thousands of kilometres of coastal zone in SE Asia. Many coastal wetlands were affected in the short term by the large inflow of salt seawater and littoral sediment deposited during the tsunami, and in the longer-term by changes in their hydrogeology caused by changes to coastlines and damage to sea-defences. Many water quality and associated problems were generated by the tsunami. The tsunami has created an accelerating process of salt-water intrusion and freshwater contamination in the affected regions that now require drastic remediation measures. According to the International Commission on Groundwater–Seawater Interaction (CGSI) these measures have to be economically feasible, environmentally sound and socially acceptable. We report here some results of preparation of the CGSI EU FP7 project related to the study of the processes of groundwater–seawater interactions in tsunami affected areas.

Key words coastal zone; submarine groundwater discharge; salt-water intrusion; tsunami; groundwater–seawater interactions

INTRODUCTION

On 26 December 2004, devastating tsunami waves caused a terrible humanitarian disaster affecting thousands of kilometres of the coastal belt in SE Asia. It is likely that many coastal wetlands were affected by the large inflow of salt seawater and littoral sediments that were deposited during the tsunami, with longer-term effects that include changes in the local hydrogeology caused by changes to coastlines and damage to sea-defences (Gupta, 2005). Serious problems pertaining to salinity changes were encountered in coastal south India during this tsunami (Fig. 1) and the consequent loss of fertility of agricultural land has been reported in requests for remedial measures to revitalize economic growth in these regions. Many water quality and associated problems generated by the tsunami and influencing coastal environments, are related to past and on-going contamination of terrestrial groundwaters, because those groundwaters are now seeping out along the shorelines affected by the tsunami. For example, chronic inputs of fertilizers and sewage on the land surface over several decades has resulted in higher groundwater nitrogen concentrations which, because of slow yet persistent discharge along the coast, eventually result in coastal marine eutrophication (Alagarswami, 1993; Krishnamoorthy, 1996; Sonak, 2000; Ramesh, 2001). Such inputs may thus contribute to the increased occurrence of coastal hypoxia, detrimental algal blooms, and associated ecosystem consequences. Tsunamis, in addition to increasing the magnitude of salt-water intrusion, can significantly affect these nutrient pollution problems.

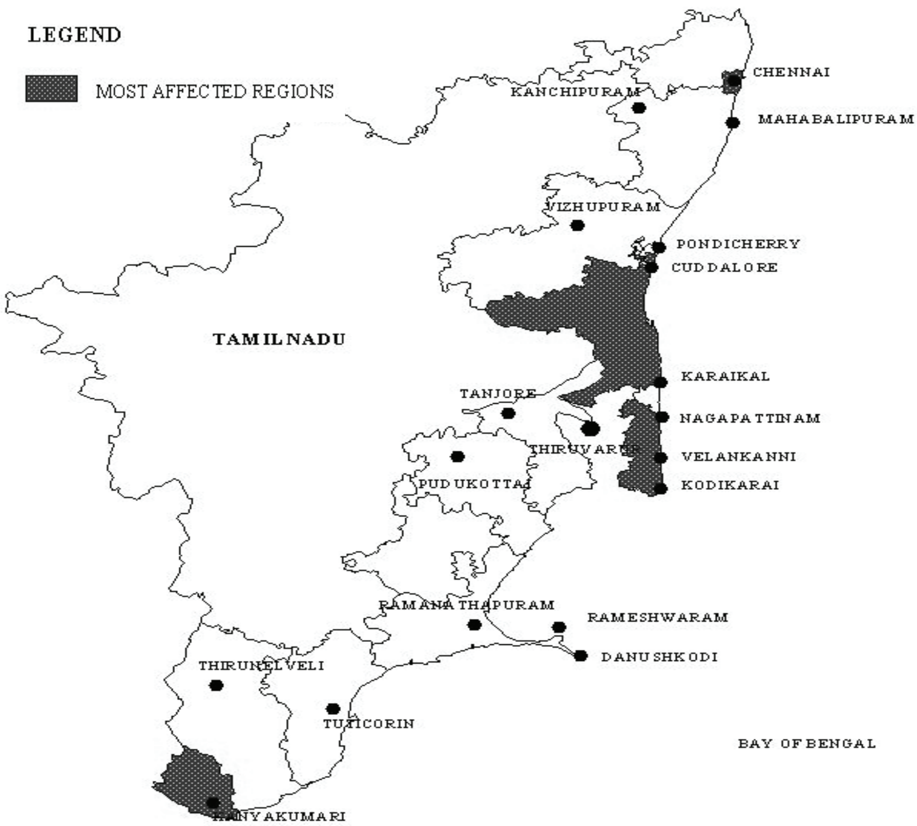

Fig. 1 Coastal areas most affected by the December 2004 tsunami in Tamil Nadu, India.

The International Commission on Groundwater-Seawater Interaction (CGSI) is working on preparation on of the EU FP7 integrated project related to the study of processes of groundwater–seawater interaction in tsunami affected areas.

RESEARCH DIRECTION

The coastal zone of the Indian Ocean is an intensively populated region where the December 2004 tsunami waves tragically altered land forms and land-use practice, causing perturbations and impacts on the river–sediment–soil–groundwater system. Saltwater intrusion caused severe modifications of the hydraulic regime of coastal aquifers, the position of the salt–freshwater interface, the chemical composition of surface and subsurface waters, and adversely affected the fauna and flora. The studies on the impact of tsunami-wave-induced changes to coastal zone soils and sediments are being focused on interfaces and transition zones characterized by steep gradients. Shifts in these boundary lines and transition zones are sensitive indicators for ongoing processes and trends. Specifically, the Research Direction will investigate the tsunami-related shifts of the subsurface salt–freshwater interface, phase switches between dissolved and free gas (e.g. methane), relocation of the oxic–anoxic boundary in soils and sediments, and changes of the spatial distribution of key organisms sensitive to changes in salinity, nutrients, oxygen and methane concentrations. The Research

Direction is building on the "state of the art" by combining hydrological, chemical, and biological expertise on sampling and modelling of regions characterized by steep gradients generated by the tsunami. This allows an assessment of interrelations between different forcing factors, such as hydraulic head, re-mineralization kinetics, and subsurface fluid flow.

The spectre of groundwater contamination looms over industrialized, suburban and rural coastal areas. The sources of groundwater contamination in tsunami affected countries are many, and the contaminants numerous. The disposal of domestic waste-water is accomplished in many areas through the use of septic tanks and drainage canals. The tsunami has accelerated the process of contamination in these affected regions, which now require drastic remediation measures.

These measures have to be economically feasible, environmentally sound and socially acceptable. In this project, a basic estimate will be conducted to assess the economic, environmental and social impacts of the tsunami and the feasibility of remediation measures suggested to overcome the damage. Interventions to secure liveli-hood through innovative solutions will consider gender as a part of the social analysis.

The scientific and technological objectives can only be covered by a well coordinated interaction of data mining (Zektser, 2000), expert knowledge (Kontar *et al.*, 2002; Lobkovsky *et al.*, 2003), well focused field work (Bokuniewicz *et al.*, 2004; Burnett *et al.*, 2002, 2003; Taniguchi *et al.,* 2006), and modelling (Kontar *et al.*, 2004, 2006). Field work is scheduled after intense compilation of data contributed by the partners of the Research Direction and data mining of former EU Projects (e.g. ELOISE and other research frameworks), LOICZ and CGSI reports. Data acquisition in the tsunami-effected transition zone between land and sea is requiring innovation, so cost and time efficient techniques are being applied by the partners. This includes shallow seismic, geoelectric and radar systems for characterization of the subsurface aquifer system (Kontar & Ozorovich, 2006). Investigations within former EU projects revealed that research is generally not limited to the availability of basic parameters such as salinity, hydraulic heads or major chemical components, so the Research Direction includes a strong expertise in trace gases, isotopes, and radio-nuclides suitable for dating of coastal groundwater, detection of subsurface freshwater discharge, and to derive kinetics of re-mineralization processes (Valiela *et al.*, 2002).

Data mining and field work will be compiled for spatial modelling by Geo-Information System (GIS). This allows computation of spatial patterns (Batelaan & De Smedt, 2001). Difference maps, visualizing changes between present and former maps, provide essential information on shifts in ecology and chemical transition zones in the soil–sediment–water system affected by the tsunami. Furthermore, GIS will be applied to deliver essential data for the assessment of hydrological budgets derived by modelling, e.g. by MODFLOW (Valstar, 2001). For numerical modelling of transport and reaction processes in coastal aquifers and sub-seafloor, well established algorithms derived by CGSI partners will be used. The model results will be validated by field measurements. The impact of scenarios associated with tsunami, global change, and smaller-scale perturbations will be evaluated by prognostic modelling.

The soil–groundwater–sediment system function will be investigated in detail for selected coastal areas affected by the tsunami using data acquisition, data mining and selected field work, as well as spatial analysis by GIS, and numerical modelling. The present status of target areas that represent a large section of Indian Ocean coastal environments will be derived and upscaled via spatial and numerical process-oriented modelling. In cooperation with CGSI, the numeric modelling of soil–water–sediment functioning in tsunami affected coastal areas will be implemented in an integrated coastal zone soil–water numerical model.

During the project, special groundwater information will be collected and used. For example pre-tsunami groundwater quality data is available (a few months before and one month before) in the affected areas (selected locations through out the affected areas). There is also post-tsunami data for one month, two months and four months for groundwater quality throughout the affected areas in Tamil Nadu, India. There is also data for groundwater level changes (including fluctuation maps) throughout the region, before and after tsunami. There are statistics about the number of hand pumps, bore wells, how people rejuvenated their open wells after the tsunami, statistics of new wells dug after the tsunami, emergency water supply for tsunami impacted areas, impact of water scarcity after the tsunami on the village population, etc. There is some data on the seawater intrusion in the coastal areas over the past decade (coastal Tamil Nadu region), and on the subsurface groundwater discharge in selected locations of tsunami affected regions (see Fig. 1). This data will supplement these studies.

The project will be concentrated on these lines because there are already some sufficient data and experience.

IMPLEMENTATION PLAN

This Research Direction combines intensive exploitation and compilation of existing data sources complemented by land and marine field research in India, geo-statistical analysis and numerical modelling, to achieve an integrated view of the impact of perturbations on groundwater quality and ecology, and shifts of the salt–freshwater interface in the areas affected by tsunami. For several tsunami affected key regions, land and marine soils and sediments, hydrology, biogeochemistry of groundwater and coastal waters, and ecological indices will be integrally addressed from existing data sources and by targeted field research, respectively.

Target zones, considered as representative of the tsunami affected areas, were identified as: (1) karstic coasts off North Sentinel, Nicobar; (2) soft, glacial sediments characteristic for delta system of Adyar River at the confluence with the Bay of Bengal; and (3) the coastal lagoon system in Pichavaram Mangrove, Tamil Nadu. The karstic environments at Nicobar have been experiencing strongly increasing coastal urbanization, and, thus, undergo predominantly anthropogenic perturbations. The delta system of the Adyar River coast is predominantly of glacial origin with diffusive subterranean and submarine flow. Its coastal lagoon system in Pichavaram Mangrove, Tamil Nadu, is situated within a humid temperate climate within the target regions that are affected by the tsunami, sea level rise, and an increasing number of storm events.

Historical data/Data mining and compilation

Within the project's initial phase, existing data and published pre-investigations are used to gather information needed to characterize the coastal soil–water continuum at the selected tsunami-effected regions. A database management system (DBMS) will be coupled to GIS and topographic and bathymetric charts, remote sensing data, thematic maps of the coastal zone (land and sea), and attribute data like biological and geochemical measurements that will be made available for modelling purposes. The DBMS will be used as a base from which to proceed with field work. The format and structure of data will be harmonized with all partners in order to have compatible data sets for integrative modelling.

Assessment of aquifer contamination

The three-dimensional study of salinization of waters and soils along the east and west coasts of India, with particular reference to the coasts of Tamil Nadu and the Car – Nicobar Islands caused by the tsunami of 26 December 2004, will be investigated by geophysical (resistivity and self-potential), geochemical and hydrological methods, with the objective of developing mitigation scenarios. In some cases, the tsunami-caused salinization may have been superimposed on anthropogenic salinization caused by excessive exploitation of groundwater. Within this project, the localization and quantification of submarine groundwater discharge, the efflux of dissolved constituents and trace gases from sub-seafloor aquifers, and the shifts in the subsurface freshwater–seawater interface towards the shore will be investigated by geochemical analyses of dissolved and particulate components (including stable and radio-isotopes, trace gases, and xenobiotics). The importance of sub-seafloor pathways will be estimated by CGSI studying interfacial transport and reaction processes with techniques especially appropriate for the individual regions. These activities include natural tracer studies (^{222}Rn, ^{226}Ra), physical parameters measurements, major ion and nutrient measurements, and sediment pore water sampling. They are all planned to be performed hand-in-hand with bathymetric and shallow seismic surveys. Special emphasis is focused on the interfacial exchange of carbon, nitrogen and phosphorous compounds. Their processes will be observed throughout all research directions. For consideration of shifts in the landside freshwater–saltwater interface, advanced radar systems and geoelectric techniques will be applied, along with seafloor photography.

On land as well as in the marine environment, several natural (including tsunami) and man-made perturbations are affecting the occurrence and fate of organisms. In the marine environment, taxa such as polychaetes, bivalve and bacteria, and plants such as seaweed, are closely associated with salinity or nutrient level supplied by ambient waters. In coastal margin sediments, it is well known that such organisms and consortia are indicative of seepage of fluids through sediments. In the sediments of the Bay of Bengal there is a strong indication that the occurrence or disappearance of polychaetes is linked to freshwater seepage from the land to the marine sediments. For coastal areas characterized by glacial sediments and a karstic/rocky seabed, the impact of the freshwater cycle on the benthic community will be studied. This suits two objectives: (1) to use organisms as an indicator for sub-seafloor freshwater discharge, and (2) to study the impact of perturbations on benthic communities in the coastal zone by analysing remains in deeper sediment strata. The study will use existing data sets, will investigate selected sites in the different target areas, and will conduct field experiments at the seafloor. Tsunami-generated changes in salinity, nutrient supply, etc. on the benthic community will be simulated. This allows simulation of perturbations, such as a sea level rise that affects the hydraulic head and therefore the admixture of freshwater at seep sites, the influence of dissolved nutrients, or changes in turbidity, caused e.g. by an increase in storm intensity and frequency. These aspects are directly linked to the changes of the physical, chemical and biological properties of soils/sediments generated by tsunami.

The hydrological budget for the different target areas will be derived by using models well established in civil engineering (e.g. MODFLOW). This allows comparison of model results derived for the different target areas and transfer of the modelling concept to other coastal regions impacted by tsunami. Based on the model calibrated with respect to the field data, sensitivity analyses of the impact of tsunami sea level rise and the natural and man-made perturbations mentioned above on the hydrological cycle, will be conducted. By this means, the response times of the three distinct environmental settings to perturbations can be studied and compared. This is a step towards a detailed understanding of water–soil system functioning and as a tool for the integrated management of coastal soil–water systems under the influence of tsunami.

The modelling efforts can be divided into three branches: (1) modelling of the water cycle in coastal areas considering groundwater renewal and submarine groundwater discharge, (2) shifts of the freshwater–saltwater interface, and (3) transport reaction modelling.

Shifts of the freshwater–saltwater interface due to over pumping or changing hydraulic heads (as a consequence of tsunami or sea level rise or intense storms that transport seawater into the groundwater recharge areas) are severe risks for coastal aquifers, as seawater can spoil water supply wells. Within this project, data sets obtained by chemical analysis and geoelectric techniques will provide detailed information about the density and concentration distribution in coastal aquifers. Such data sets will be used to support a calibration of numerical models suitable to resolve sharp density gradients and to predict the reaction of an area under tsunami and anthropogenic forcing. Shifts of the oxic–anoxic interface will also be considered in detail as a common issue throughout the Research Direction. Scenarios of enhanced erosion of soils and transfer of DOM to coastal waters via surface or subsurface pathways can be considered in detail. This component proceeds from the end of the initial data mining through to the field work components.

Tracing sewage contamination

Sewage is a generic term for the faecal waste from animals, although it is usually applied to human derived materials. This highlights one of the principal problems with assessing sewage inputs: is it human derived or from other, predominantly agricultural, sources? Notwithstanding this issue, the term sewage used here will predominantly apply to human wastes. Unlike most contamination, sewage is not a single compound, element, or even a class of compounds. Rather it is primarily a mixture of organic and inorganic components, along with intact biological entities (bacteria and viruses); together, this makes a very complex mixture. This mixture changes from region to region, diurnally and with distance from source due to partitioning between solid and solution phases. Some of the more water-soluble components will be moved with the liquid phase, while others are principally associated with the solid or particulate phase and may only move small distances. Therefore, different tracers may exist for each environment and at a range of distances from potential sources. Chemicals that are intrinsic to sewage, such as the stanols and sterols associated with human faecal matter, additives like detergents, microbiological communities present in wastewaters and effects caused by sewage to communities will be examined.

Sampling will take place in key locations and on key resources. These include drinking water, groundwaters (especially those used for potable waters), agricultural land and crops, bathing beaches and urban (semi-urban) environments where inhalation or ingestion pathways are important. Principal chemicals to be studied will be those derived from human faeces, such as the stanols and sterols, while key bacterial components will also be investigated. The often-used bacterial markers for sewage (faecal coliforms, streptococci, Intestinal Enterococci, etc.) are not appropriate in some locations. These organisms are not pathogens in themselves but are used as markers for other pathogenic ones. However, many of the bacteria are susceptible to UV irradiation and saline waters, and die off fairly quickly (<<24 hours in many cases). The differential die-off may lead to a false sense of security as negative *E. coli* results do not necessarily mean no bacteria are present. Therefore, a combination microbiological approach will be used.

Agricultural solutions for use of coastal contaminated aquifers

A systematic study pertaining to salinity problems encountered in coastal south India during tsunami, and the consequent loss of fertility of agricultural land, including remedial measures to revitalize economic growth in the region, will be conducted.

The study suggests that the tsunami affected area will be unproductive due to: (a) deposition of littoral sediments containing heavy minerals on the surface; and (b) contamination of soil and groundwater aquifers due to sea water intrusion. To revive the fertility of the land, the following measures are suggested: (1) Removal of littoral deposits – the littoral deposits containing heavy minerals should process through weathering and change into clay minerals or soil. Moisture, temperature climatic condition, salinity-stressed vegetation and time are the main factors that affect weathering (artificial weathering). Although the scraping of the inert littoral sediments from the agricultural field is a permanent solution, it is not economically viable due to the large size and extent of the affected area. (2) Desalinization of soil and groundwater – the surface water and groundwater of the tsunami-effected area are affected by seawater intrusion into the aquifer. To prevent salt-water contamination, over pumping and unnecessary mining of groundwater should cease. Earth-filled barriers may be constructed along the coast to limit the salt-water intrusion. Further, earthen bunds should be provided in flat areas so that rainwater gets trapped and can percolate through the soil. The amount of salt and harmful elements leached from the soil profile depends on the quantity of water that passes through the soil. For leaching to be effective, salt rich leachates must be discharged out of the area. The desalinization of the land can be accomplished by: (1) providing subsurface drainage; (2) surface water management; and (3) growing salt resistant crops. An ideal package of cultural practices besides other soil management and agronomic practices can ensure a good crop stand vis-à-vis good yield. In saline soils, germination of seeds is a very serious problem. Poor germination and crop stand can be counter-balanced by heavy pre-sowing irrigation, increased seed rate or plant population, treatment of seeds/seedlings for inducing tolerance to salinity, good seed bed preparation, optimum time and proper method of sowing/planting, appropriate crop geometry and direction of sowing, inter-tillage to ensure good aeration and control of weeds, etc. Removal of salts through leaching from the root-zone is an important aspect in the reclamation and management of salt-affected lands and in maintaining the long-term productivity of irrigated lands. As reclamation is meant for growing crops, leaching should be in conformity with the tolerance limits of the crops to be grown. The cost will be high if salts are leached beyond a threshold value, as no additional benefits will accrue, because yield stabilizes at the threshold value. Site-specific suitable agricultural solutions for use of the contaminated aquifer can be adapted to revitalizing agricultural land and to promote economic growth in the tsunami affected areas.

Conventional agricultural techniques to combat salinization processes due to the contamination of the aquifers can be characterized by four practices: (1) Root zone desalination by soil leaching – two options occur – when there is an impermeable layer, salts will be concentrated above this layer; on the other hand, when there is no impermeable layer, aquifer contamination may be observed. (2) Use of subsurface trickle irrigation – economical of water, and therefore less additional salts; however, the problem of groundwater contamination due to natural rain or artificial leaching remains. (3) Enhanced fertilization increases the tolerance to salinity (however, sensitivity also increases), but the contamination will be increased by other hazardous chemicals such as nitrate. (4) Use of salt tolerant species – this technique will be very useful to the plants, but does not solve the problem of soil or groundwater contamination.

Agricultural environmentally safe and clean techniques to combat the salinization process due to the contamination of the aquifers can be characterized by: (1) use of salt removing species; (2) use of drought tolerant crops species; (3) reduction of salt application by deficit irrigation; (4) re-use of minimal levels of saline water enough to obtain a good visual appearance GVA of the landscape. The study of these new techniques is being carried out. The research work will be focused on the combination of conventional agricultural techniques and environmentally safe and clean techniques in order to increase the best economic and environmental solutions to control salinity and maintain the sustainability of the agricultural areas and landscape.

Costing solutions and remediation/economic, environment and social impacts of tsunami and the feasibility of remedial actions (innovative solutions)

The spectre of groundwater contamination looms over industrialized, suburban and rural areas (Zektser, 2000). The sources of groundwater contamination in tsunami affected countries are many and the contaminants numerous. The disposal of domestic waste-water is accomplished in many areas through the use of septic tanks and drainage canals. The tsunami accelerated these processes of contamination in affected regions, and they now require drastic remediation measures. These measures have to be economically feasible, environmentally sound and socially acceptable. In this project we estimate the economic, environment and social impacts of tsunami and the feasibility of remediation measures suggested in previous projects to overcome the tsunami damage.

Interventions to secure livelihood through innovative solutions will consider the involvement of gender as a part of the social analysis. Most of the affected people are generally poor, and are also more vulnerable to environmental risk and disasters, and therefore the remedial solutions should address the issue of poverty alleviation. The effectiveness of the solutions to alleviate poverty in the affected areas will be investigated. The main consideration of this project is to ensure the proposed remedial actions are appropriate for the local institutional, environmental, social and economic conditions. The analyses will be carried out through field surveys and standard environmental/economic/econometric analyses.

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