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Tsunamis as Long-Term Hazards to Coastal Groundwater Resources and Associated Water Supplies

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1. Introduction

Tsunamis are potential hazards in most of the world, (Figure 1), but risks are higher in areas associated with close and direct proximity to high seismic activity areas in marine and coastal areas, such as Indonesia, Japan, Chile, Peru, and SIDS (small island developing states) (UNISDR, 2009) (Figure 2). They generally hit in relatively limited areas: the coastal zone - up to few kilometres inland from the shore.

Tsunamis are short-term events, but impacts on human infrastructure and environment can be severe and enduring. Especially coastal freshwater resources, most often the source of public and private water supplies, are vulnerable to the imprint of saltwater that comes along with the tsunami flooding event. Safe, adequate, accessible, and socially acceptable water supply is of essential importance, both as a priority in the immediate aftermath of a disaster like a tsunami, but also in the longer term to ensure proper human health and prosperous livelihoods. Time horizon and severity of tsunami impacts on water resources and water supply systems depend on: magnitude and extent of the event, type of land mass hit (island vs. large mainland, low topography vs. rising coasts) and its natural protection (e.g. mangroves), population density, type and extent of freshwater resources present, and dependence on them for water supply. Often, alternative water supply solutions can be provided in the interim of a tsunami, from external sources and with external support because of the often limited geographical extent of the impacted areas. However, this is not always possible e.g. islands, and other aspects are relevant: recovery and sustainability of fundamental and primary freshwater resources, human health, optimal and efficient use of resources at any time of the disaster risk management cycle (Figure 3). Here, a distinction between groundwater and surface water systems is relevant. Groundwater systems are generally much slower in recovering due to longer internal residence times. However, since groundwater sometimes is the only freshwater resource available in coastal areas and on small islands, it is critical to assess the vulnerability and potential impacts.

Since significant coastal populations around the world depend on groundwater for their water supply, either from decentralized, often small schemes and private wells, primarily in rural and peri-urban areas, or from larger centralized schemes, primarily in urban areas,

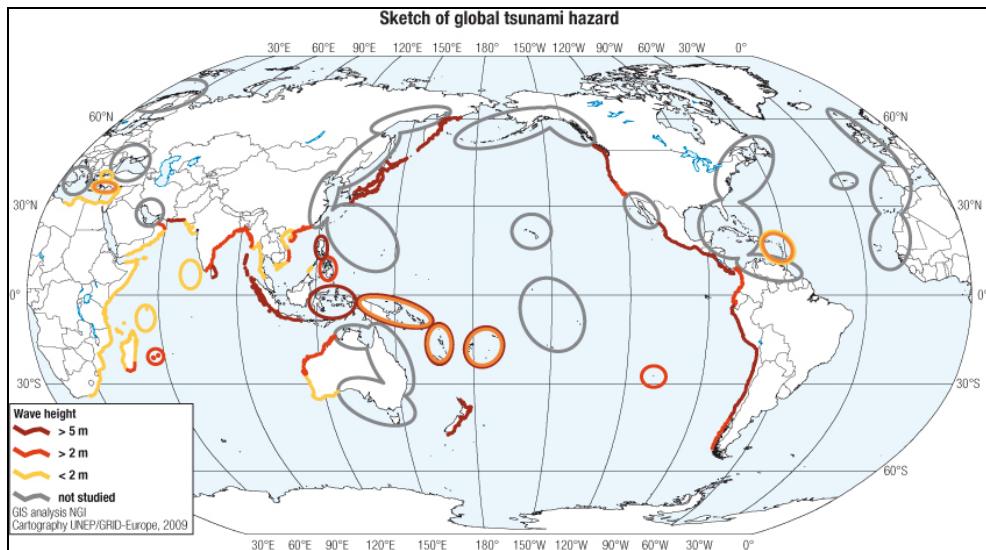


Fig. 1. Global map of tsunami hazard (From UNISDR, 2009)

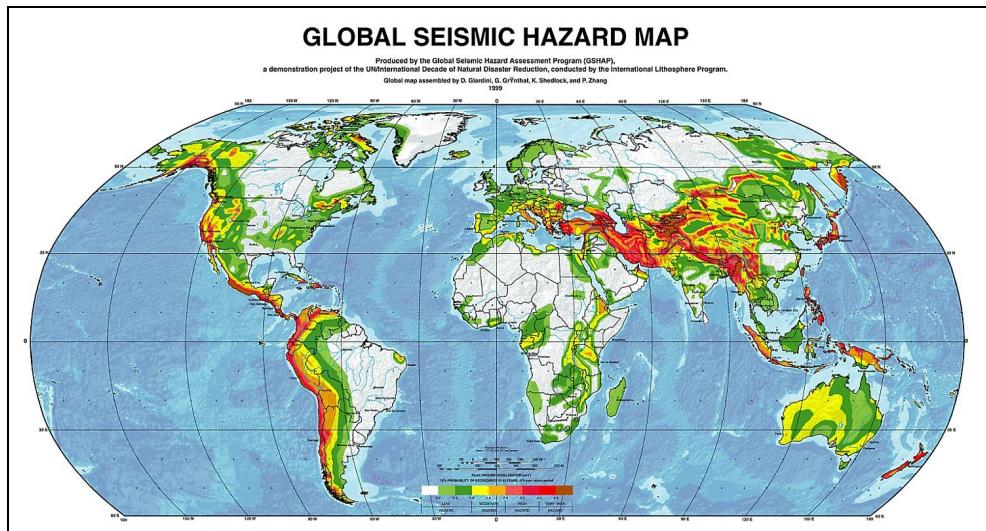


Fig. 2. Global seismic hazard map (From Giardini, 1999)

it is of critical importance to know the risks associated with these supplies from natural and other types of disasters and extreme events, in this case from tsunamis. Furthermore, it is equally critical to bring that knowledge into frameworks for prevention, protection, recovery, response, and rehabilitation strategies, plans and actions. Though water supply receives principal attention during disasters, there is a general lack of focus on the link to the (potentially long-term) impacts on the water resources and in particular on the groundwater

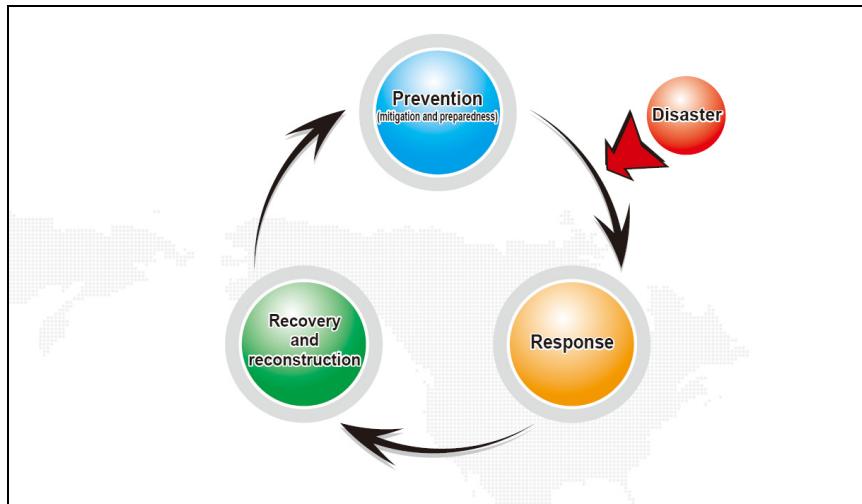


Fig. 3. Phases of disaster risk management (From JICA, 2008)

resources. This paper intends to enhance the knowledge and the dissemination of such knowledge. It is proposed to advance this work through further detailed guidelines and frameworks as described in Section 4.

The present paper addresses tsunami events as potential hazards to groundwater resources and associated water supply systems in coastal areas around the world. The objective is to provide a coherent framework for understanding these potential hazards and for managing the risks and impacts associated with them, with focus on salinity impacts. The paper accordingly first reviews and summarizes the present knowledge and experience of impacts, and secondly, presents a framework for managing the risks and impacts associated with these events. This relates to practical as well as policy implications and also to which continued research efforts are essential. The ultimate goal is to enhance water security and human health in tsunami-prone areas of the world.

2. Effects of tsunamis on coastal groundwater and water supplies

Focusing on the impacts of a tsunami on water, two aspects and systems are essential: the freshwater resource itself and the systems of water supply derived from it. Accordingly, the consequences of a tsunami are two-fold. Firstly, there is a direct and immediate physical shock on water infrastructure, like water pipelines, sewer systems, water storage tanks, and groundwater wells that break down due to the force of the incoming and retreating waves and masses of water and debris. Secondly, the water resources and their quality are often severely impaired by the tsunami.

2.1 Effects on water supplies

Severe impacts on water and sanitation infrastructure were observed from the 2004-tsunami in the countries of Indonesia, Sri Lanka, India, Thailand, and the Maldives (Tang et al., 2006; ADB et al., 2005; UNEP, 2005). Water main pipes in estuaries broke, water wells supplying inter-mediate size populations and industrial areas located coastal-near were destroyed or

their quality impaired. Pit latrines and other sanitation structures were destroyed and sewage disposal lines discharging to the sea were affected and possibly led to conduits for tsunami water¹ entry into main sewers (UNESCO-IOC, 2008). Open and natural drainage canals conducting drainage water from agricultural fields and public wastewater were disturbed and in many cases blocked due to coastal erosion and sedimentation processes. However, only limited systematic research and reporting on the consequences of the 2004 tsunami on water infrastructure in affected regions was carried out and knowledge is mostly based on rapid impact assessments immediately after the event. Larger water infrastructure systems, like dams and larger urban water supply schemes were not impacted, simply because they were not located within the affected areas (Ballantyne, 2006). Also, no major or mega city was affected by the 2004-tsunami. Water supply systems, as they relate to hardware and infrastructure, were mostly rehabilitated and built back to previous conditions within relatively short timeframes, in the order of months to half a year after the tsunami. In some cases, new systems were constructed to replace damaged ones, within same or slightly longer time horizons. A critical issue here was the establishment of interim water supplies for people displaced in temporary camps as coastal-near settlements were completely destroyed (Fernando et al., 2009).

The maybe most severe and enduring impact of the 2004-tsunami in terms of water supply was the destruction and contamination of drinking water wells in the coastal strips inundated by the flood waves. A large percentage of the coastal population in the affected areas of the hardest-hit countries, like Indonesia, Sri Lanka, India, Thailand and the Maldives, depends on wells, often relatively shallow (< 10 m deep) household wells, and large proportions of these wells were inundated and impacted by infiltrating tsunami water. No rigid inventory on the number of wells impacted exists but they number in many thousands throughout the region. In Sri Lanka alone, 40-60.000 (ADB et al., 2005; UNEP, 2005) and most likely many more (Villholth et al., 2010) were influenced and similar reports exists from Indonesia, the Maldives, and Thailand (UNEP, 2005). A predominant part of these populations are poor farmers and fishermen who live in dispersed communities along the coast, but with locally relatively high population densities. Though the 2004-tsunami waves reached relatively short distances inland, up to 2 km (Chidambaram et al., 2010, Kume et al., 2009; Villholth et al., 2005), and hence alternative water sources from further inland could temporarily replace damaged ones, the immediate and longer-term impacts were considerable.

2.2 Effects on water groundwater resources

A tsunami affects groundwater through a number of mechanisms. During the run-up of the tsunami (could be more than one wave during an event) on the shore and further inland and subsequent partial retraction, soils and land mass previously not affected by saltwater get inundated for a relatively short time (5 min up to one or few hours), leaving a period for saltwater to infiltrate and enter through the soil and subsequently to the groundwater table below. Some tsunami water gets trapped in local landscape depressions or other sinks leaving this water to potentially further contaminate the groundwater. A special case of this is open wells that have direct contact with the groundwater and hence constitute a very fast pathway for contamination of the subsurface. Which of these various sources is more

¹ Tsunami water in this context means seawater, potentially mixed with inland (clean or contaminated) freshwater, sediments and debris.

important cannot be assessed unilaterally as it depends on the local conditions but neither should be overlooked. The infiltration from the land surface during the inundation is short-lived but covers a large area, whereas the percolation from depressions comprises large localized volumes infiltrated over much longer times (Chidambaram et al., 2010). Prolonged effects of saltwater leaching has been documented from the entrapment of tsunami water in the soil profile during dry periods leading to precipitation of salts that subsequently get washed out in rainy periods (Chidambaram et al., 2010; Sivakumar & Elango, 2010; Violette et al., 2009).

If the Tsunami run-up is high enough to overflow a local topographical divide, larger parts of the tsunami water will flow inland and not retract to the sea, with an overall larger impact. Coastline configuration, bathymetry, and natural coastal protection from e.g. mangroves, may initially modify tsunami wave impact even before entering land. Finally, river mouths may serve as 'highways' (Mitamura et al., 2006) for tsunamis increasing inundation distances significantly in adjacent areas with subsequent impact on underlying groundwater. Coastal lagoons and estuaries may also be flooded with impacts on surrounding and further inland areas. While such areas may initially be more severely impacted, they may also be relatively rapidly rinsed due to flushing of these water bodies by freshwater from upstream catchments (Fesselet & Mulders, 2006).

The underlying shallow groundwater will be primarily and initially affected while deeper groundwater will be affected later as a pulse or plume of infiltrated saltwater spreads and migrates downwards and laterally back to the sea (Figure 4). If multiple overlying aquifers are present, lower confined aquifers may be partly protected from the tsunami impact (Figure 4). Identifying and utilizing such aquifers may provide tsunami-resilient water supply.

Secondary impacts on the groundwater system involve the potential displacement or disturbance of the freshwater-saltwater interface or balance below the shore (Figure 4) due to the incoming force and increased hydraulic pressure of the waves (Cartwright et al., 2004). This, however, has not been documented, e.g. through direct monitoring of the

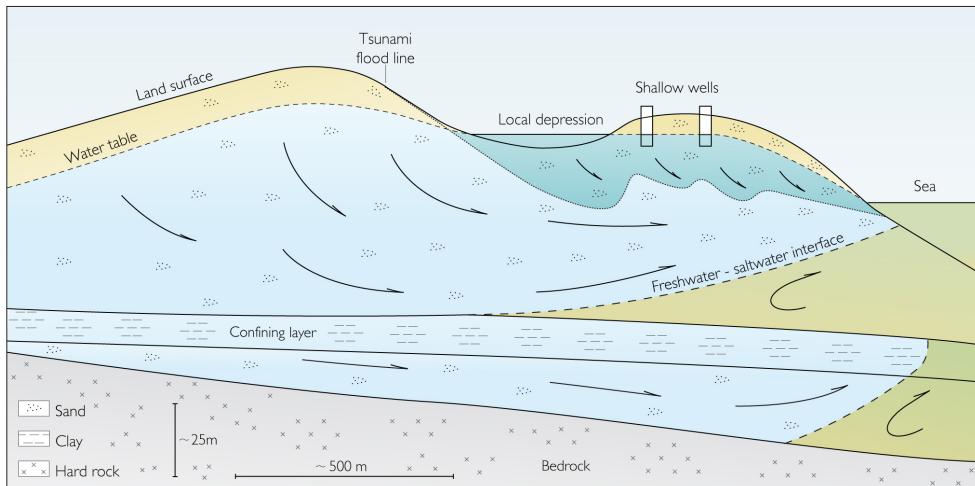


Fig. 4. Conceptual sketch of tsunami salinisation impacts on groundwater.

interface before and after a tsunami. Observations of gushes or geysers of water from wells just prior to a tsunami have been reported (Kumar & Alam, 2010) as well as sudden and intermittent rise in groundwater levels (Muralideran et al., 2005), which gives testimony to large forces in play from the earthquake and ensuing tsunami. Incidentally, such phenomenon may also be used in the local early warning of an event.

Groundwater and interactions between pre-tsunami fresh and saltwater may also be influenced by coastal erosion processes launched by the tsunami, which may shift the coast line with accompanied landward displacement in the transition zone between fresh and saltwater². Subsidence and activation of sink holes in coastal limestone aquifers in Thailand and Malaysia have also been reported (Al-kouri et al., 2008; UNEP, 2005). This could be attributed either directly to the seismic impact or indirectly to the seismically induced fluctuations in groundwater.

Seawater has much higher salinity content than most natural water bodies and environments in coastal areas. Previous sources of drinking water, be it surface water or groundwater bodies, easily reach salinity levels well above drinking water quality standards and guidelines³. Even a 5% mix of seawater with freshwater will render it unsuitable for drinking (Violette et al. 2009), indicating the vulnerability of freshwater systems towards tsunami risks, and in general seawater flooding, and the critical issue of reverting contaminated sources to pre-tsunami fresh conditions.

Salinity is here used as a relatively simple, but yet critical indicator of tsunami impact in groundwater. Two aspects of this should be noted. Firstly, broader impacts of seawater flooding on coastal aquifers could occur, like chemical shifts in ionic composition of groundwater (Andersen et al., 2005) and potential contamination with micro-constituents, like heavy metals, from the seawater itself or from marine sediments washed to land (Ranjan et al., 2008; Szczuciński et al., 2005). Especially the latter could have (even) longer term impacts on soil and groundwater quality.

The second aspect of using salinity as an indicator relates to the inherent complexity of saltwater-freshwater interactions in coastal zones. Aquifers may be influenced by pre-tsunami saltwater, complicating the assessment of post-event impacts. These pre-event influences involve primarily the natural, and more or less stable, ingress of saltwater below the freshwater in the aquifers, which is manifested through a triangular shaped wedge of saltwater, which is kept in balance by out-flowing freshwater discharging at the upper limit of the wedge (Figure 4). Pre-event salinity may also be present in the groundwater due to remnant salinity partially entrapped in formations influenced by earlier tsunamis or cyclonic storms or longer-term sea transgressions associated with pre-historic sea-level rises (Singh et al., 2011; Riedel et al., 2010). This is more likely in deeper and less permeable formations where flow and circulation is slower. Hence, general knowledge of the salinity profile of coastal aquifers and pre-historic events is important to qualify post-tsunami salinity impact assessments. Finally, pre-event groundwater salinity could be influenced by coastal land-use practices, such as irrigation, wastewater disposal and prawn farms.

Secondary contamination factors induced by tsunamis, which sometimes tend to be forgotten or neglected, are due to the rupture of sanitary systems, storage facilities for

² <http://www.igrac.net/publications/140> (Accessed on May 12, 2011)

³ There are no health-based water quality guidelines or standards for salinity, as the lower potable levels are governed more by taste and habit than by health considerations. Here, we use a measure of electrical conductivity of 1000 µS/cm as the threshold for drinking water.

chemicals and wastes, which are released and mixed with previous freshwaters and the incoming saltwater. This causes a situation where waters present and available immediately after a tsunami have to be considered contaminated with a known source (the sea), as well as a wealth of unknown but very likely additional sources. A typical and wide-spread problem here relates to the release of and spread of pathogenic bacteria via floodwaters derived from sanitary installations (Vaccari et al., 2010; Navaratne, 2006; Piyadasa et al., 2005). Secondary effects were also observed in the March 2011 Great East Japan earthquake (also called Tohoku earthquake) and tsunami where nuclear contamination posed risks to drinking water supplies (WHO, 2011).

2.2.1 Time scales for impact and recovery in groundwater

An immediate concern after recognition of salinity impacts of a tsunami on groundwater and associated water supply is the duration of the problem. This can typically only be evaluated through continuous post-tsunami monitoring and contrasting with background pre-tsunami levels or the situation in comparable non-affected areas. Alternatively, and additionally, numerical modelling may inform assessment and projection of long-term impacts. From a literature review, the recovery time of groundwater systems after the 2004-tsunami has been assessed to between 1.5 to 15 years in affected regions (Table 1). The figures clearly depend on whether only the upper shallow groundwater is considered or the entire aquifers are the unit of focus, with the small figures representing groundwater down to 5-10 m while the larger figures apply for entire aquifer extensions down to about 30 m. Such figures should be taken only as indicative and as a guide. The recovery will depend on a number of factors, most notably the hydrogeological conditions, including the excess rainfall that infiltrates over the affected area and recharges groundwater, accelerating the displacement and dilution of tsunami-trapped saltwater.

Most areas investigated to date are located in low-lying sedimentary (fluvial and marine) coastal basins, with unconsolidated materials, consisting mostly of sands but also finer-textured materials. They are quite common in relatively flat dune-type coastal areas due to the coastal processes of sedimentation. These systems are permeable with continuous porosity rendering flow and transport of water and solutes easy and relatively fast. This relates both to the ingress of salinity during the tsunami as well as the flushing out of chemicals post tsunami. Hence, what appear to be fragile systems from a contamination point of view may also be systems that get rinsed fairly easily. This is opposed to other systems where flow mechanisms are significantly different, such as fractured and fissured systems, typically fractured rock, where saltwater may, or may not, enter fairly easily and rapidly but retention may be much longer due to long term capture in, and very slow release from, secondary pores between the fractures (Berkowitz, 2002). Such systems have not been investigated as part of tsunami research, but could potentially present systems where recovery could be extremely slow.

Tsunami groundwater impact modelling is still relatively new and some issues need further research. The impact and importance of density effects in such large scale systems are not clear. This is the phenomenon that saltwater, due to its higher density relative to freshwater, tends to sink and create unstable and heterogeneous flow when accumulated on top of freshwater, which is the typical case in tsunami-impacted groundwater systems. This has been observed and documented in laboratory (Hogan et al., 2006) as well field investigations (Andersen et al., 2005). The overall impact of this is an initially faster and more heterogeneous downward movement of the saltwater pulse from the upper groundwater

	Lit. source	Method			Recovery time (depth ^b)	Rainfall ^c (mm/yr)	Location			
		Field	Model							
				DDF ^a						
1	Vithanage et al., 2011	Transect of 20 piezometers	HST3D + HYDRUS-1D, 2D cross-section	yes	15 years (28 m)	1500	East coast, Sri Lanka			
2	Sivakumar & Elango, 2010	20 wells over 2 km coastline	Feflow, 2D distributed	no	2 years (15 m)	1220	Southeast coast (Tamil Nadu), India			
3	Piyadasa et al., 2009	90 wells over 8 km coastline	-	n/a	> 4 years (7 m)	2400	South coast, Sri Lanka			
4	Violette et al., 2009	16 wells over 21 km coastline	MODFLOW + HYDRUS-1D	no	6-10 years (12 m)	1220	Southeast coast (Tamil Nadu), India			
5	Kume et al., 2009	10 wells over 62 km coastline	-	n/a	1.5 years (5 m)	1200	Southeast coast (Tamil Nadu), India			
6	Villholth, 2007	150 wells over 4 km coastline	-	n/a	1.5 years (~3 m)	1500	East coast, Sri Lanka			
7	IGRAC, 2005 ^d	-	MOCDENS3D	yes	10 years (7 m)	2000	Maldives			

^a DDF: density-dependent flow considered

^b Depth: maximum depth to which freshening of upper aquifer is assessed

^c Rainfall: Average annual rainfall. Actual rainfall and groundwater recharge after the tsunami may vary significantly

^d <http://www.igrac.net/publications/135#ref4> (Accessed on May 12, 2011)

Table 1. Recovery times assessed from the 2004-tsunami in similar hydrogeological conditions

with zones of high salinity intermixed with zones of lower salinity, relative to a smooth and homogeneous plug-like flow of uniform density fluids. Later in the leaching process, these density effects dissipate and flow becomes dominated by ordinary convective and diffusive processes.

Related to the importance of the density effects is the vertical disaggregation and resolution of flow processes in the modelling system and associated with that whether a 2D-cross-sectional representation of processes is better at capturing the saltwater movement than a 2D lateral and distributed representation (Reilly & Goodman, 1985). From Table 1, it appears that the former tends to estimate longer recovery times (6-10 years) (Violette et al., 2009) compared to the latter (2 years) (Sivakumar & Elango, 2010) for the same affected area in southeast India, which suggest that representation of the vertical flow component is important. Supporting such knowledge generation would be to ensure monitoring of deeper groundwater in the affected systems, as so far, only upper groundwater has been monitored. Finally, having better knowledge of the source of contamination is critical in the simulations.

This entails knowing the duration of inundation(s), the depth of the wave(s), and any secondary sources from accumulation of saltwater in depressions (Violette et al., 2009).

Anthropogenic factors may also influence the recovery time of aquifers affected by tsunami flooding. Post-event extraction of groundwater may influence the natural processes of saltwater sinking and movement, and field investigations suggest that excessive pumping of shallow wells, performed to rinse the wells of saltwater, may actually disturb the natural sinking of groundwater and displacement with freshwater, in effect prolonging and exacerbating the saltwater problem (Villholth et al., 2010; Vithanage et al., 2009; Chandrasekharan et al., 2008; Leclerc et al., 2007; Fesselet & Mulders, 2006; Saltori & Giusti, 2006).

The knowledge gained as part of the assessment of impacts of tsunamis on groundwater and associated time-scales with implications for disaster risk reduction (DRR) are summarized in Box 1.

- Most influential factors in the persistence of tsunami-salinity in groundwater are the local geology, rainfall and recharge conditions
- Shallow aquifers are impacted first, then deeper layers are affected as saltwater moves through the aquifer
- Pumping of groundwater post-tsunami should take the natural recovery processes into account, e.g. by not pumping to rinse wells
- Deep groundwater extraction may be feasible just after a tsunami, but it may also induce saltwater ingressions from the saltwater zone at the bottom of the aquifer close to the coast (Figure 4) or from pre-event saline formations
- Saltwater effects in groundwater may protract in the vicinity of larger stagnant flooded water bodies, while they may diminish in areas close to flowing freshwater sources such as rivers
- Deeper confined coastal aquifers may be relatively protected from the influence of a tsunami (Figure 4)

Box 1. Lessons-learned for disaster risk reduction from impact assessment of tsunamis on coastal groundwater

3. Framework for risk management of tsunami-related hazards to groundwater and associated water supply

Tsunamis are normally relatively low-frequency, but high impact events. Also, they are impossible to prevent. Hence, emphasis in risk management tends to be on the recovery and rehabilitation efforts, rather than on prevention. However, with improved seismic science and technology, increasingly, early warning systems are put in place (Antony, 2011). These systems and increased dissemination of information on natural and local signs of an arriving tsunami (UNESCO-IOC, 2010) still do not prevent a tsunami from occurring but potentially significantly minimizes the impacts and human losses and degree of disaster involved, mostly through pre-event evacuation of susceptible and to-be-hit areas. So, while some damage and losses can be avoided due to evacuation and other protective measures, significant efforts in risk management is related to minimizing the damage occurred after an event, attending to immediate needs and recovering as fast and well as possible.

The 2004 Indian Ocean tsunami, which had an unprecedented impact, in terms of physical destruction and human death toll, significantly increased the attention to tsunamis, especially in developing countries because of its strike in countries like Indonesia, Sri Lanka, the Maldives, and India. What characterize these regions are relatively dense semi-rural to peri-urban populations in the coastal areas with already insecure access to water supply. Recognizing the backdrop against which the tsunami impacts should be seen, it is clear that on the one hand, the tsunami severely restricted a functioning and safe water supply in these regions and on the other hand may serve to generally improve the water supply situation in these countries.

A framework for addressing tsunamis in a water supply context needs to take into account both the significant weight on post-disaster emphasis while pushing for further development of pro-active and preventative measures. A framework will also, though generic to a certain level, need to be 'context-specific'. While drawing on available broad experience, focus in this paper is on vulnerable and susceptible regions like the ones hit by the 2004 tsunami. Finally, while tsunamis are particular in their origin and nature, their expression in terms of coastal flooding is not unique. These impacts are also characteristic of cyclones, hurricanes, typhoons, tidal waves, and sea surges. Hence, to some degree, the framework developed here may also serve for risk management of these types of events.

3.1 Achievements and gaps

In devising a framework for risk management of tsunami-related hazards to groundwater and associated water supply, Table 2 summarises the achievements and gaps, primarily as accumulated and identified from or since the 2004-tsunami.

The 2004-tsunami revealed the vulnerability of coastal groundwater systems and the populations dependent on them, and as relief and recovery progressed and experiences were collected, called for better, integrated, pro-active and knowledge-based approaches (Villholth & Lytton, 2008). Achievements obtained based on these post-tsunami lessons include field and numerical investigations of groundwater salinity impacts and best procedures for rehabilitation of salinised wells, including a set of guidelines indorsed by the World Health Organization as part of their technical notes for emergencies (WHO, 2008). It was realized that the impacts and processes affecting groundwater after a saltwater flooding event differs significantly from an inland and freshwater flooding event, entailing the need for separate guidelines for rinsing wells and protecting the groundwater resource. Geophysical investigations of groundwater resources, including impacted and pre-tsunami saltwater resources and protected freshwater resources, were conducted (Steuer et al., 2008). Experience with alternative water sources or water treatment for tsunami relief water supply, like desalination by reverse osmosis (Weerasinghe et al., 2006) and water harvesting (Song et al., 2009), has been collected.

It is important to improve water supply from groundwater in tsunami-prone or impacted areas. As open wells easily get contaminated and exacerbate the problem of groundwater salinisation, sealed wells improve the resilience of the water supply system (Chandrasekharan et al., 2008). In addition, re-enforcing well heads and raising standpipes in the terrain, either by placing them in naturally higher positions or placing them on raised platforms (Figure 5) is an option if placing wells outside the tsunami flood risk zone is infeasible.

	Achievements	Gaps
Technical		
Prevention	-Experience with climate-proofing water supply	-Hazard maps of areas and populations in risk of tsunamis -Identification of fresh GW ^a resources -Better water supply and sanitation infrastructure in risk areas -Coastal protection -Protection of GW
Response	-Experiences and guidelines on rehabilitating water supplies -Experience with water treatment and new water sources	Rehabilitating water supplies with GW protection in mind
Rehabilitation	-Numerical models of impact assessment -Geophysical techniques for identification of impacted and protected freshwater aquifers	-Further testing and validation of models
Institutional		
Prevention	-Networks for GW in emergency situations -Documents of lessons learned from 2004-tsunami	-Guidelines for impacts of tsunami on GW and improvement to water supply -Liaison of hydrogeologists with DRR ^b community -Coastal GW monitoring -Building codes that consider water supply -Water safety plans that consider GW
Response	-Experience with WASH ^c clusters	-Hydrogeological response unit -Follow guidelines for well cleaning and GW protection
Rehabilitation		-Involvement and information of affected communities

^a GW: groundwater; ^b DRR: Disaster risk reduction; ^c WASH: Water, sanitation and hygiene

Table 2. Achievements and gaps in addressing tsunami impacts on groundwater and associated water supply

On the institutional side, awareness and initiatives related to the role and vulnerability of groundwater in emergencies and extreme events have increased. The UNESCO-spearheaded project Groundwater for Emergency Situations made an analysis of the importance of groundwater and observed impacts under various theoretical disasters as well as concrete cases (Vrba & Salamat, 2007; Vrba & Verhagen, 2006). A second phase of the project strives to consolidate the findings of the 1st phase and implement pro-active measures to safeguard disaster-prone areas. This is exemplified with a pilot area of coastal Odisha, which is susceptible to severe cyclones and seawater flooding⁴. Such interventions

⁴ <http://www.indiawaterportal.org/sites/indiawaterportal.org/files/GWES%20Workshop%20Brochure.pdf>. (Accessed on May 12, 2011).



Fig. 5. Example of 'flood-proofed' water well (Photo: courtesy of Jørgen Kristensen, Danish Red Cross)

aim at risk assessment through mapping of previous events and impacts, identification of protected and accessible freshwater aquifers in the vulnerable areas, capacity building and preparedness planning. The project also takes its cue from the World Conference on Disaster Reduction and ensuing Hyogo Declaration (ISDR, 2005), which categorically noted the importance of national and local institutional and technical capacity building to effectively address disaster prevention, preparedness and emergency response.

Experiences and lessons-learned so far on tsunami hazards for groundwater and associated water supply need to be consolidated and integrated into wider on-going initiatives for DRR. Though water supply receives paramount attention during emergency situations, groundwater, as an important source of this supply, generally receives little and often inappropriate attention (Lytton & Bolger, 2010; Lytton, 2008). This is often due to insufficient knowledge and technical capacity on part of the actors involved on the ground. However, without the development of capacity and management plans that can be quickly and effectively implemented, such events may compromise the viability of groundwater resources, and hence also the water supply, in the longer term (Chave et al., 2006).

In order to enhance such capacity and management strategies for risk reduction during disasters and in particular for tsunamis, it is recommended to address the gaps listed in Table 2. These build on accumulated achievements and relate to both the prevention and preparedness phase as well as the response and rehabilitation phase.

It is important to assess the risk of tsunami impacts on groundwater in tsunami-prone areas and incorporate this knowledge into planning for better water supply and sanitation infrastructure as well as protection of critical groundwater resources. Such plans should be integral to water safety plans (Davison et al., 2005), coastal zone management and environmental protection. In addition, groundwater monitoring of water quality and quantity aspects needs to be an operational part of such plans, in all disaster phases as a basis for proper decision making.

Further, development of awareness raising material and guidelines for best practices aimed at the general public and partners involved in DRR on the impacts of tsunamis on groundwater and the proper protection of coastal aquifers is needed (Violette et al., 2009; Villholth & Lytton, 2008). Along with this is the need for further scientific improvement of modelling and projection of tsunami and other coastal groundwater salinity impacts and integration of this into strategic planning.

An overriding requirement is the availability of capacity for professionally and effectively incorporating hydrogeological knowledge and information into the disaster risk management process. To further enhance such development it is recommended to establish hydrogeological response units, which can enter into emergency situations and act as sounding boards for best response options and interact with the DRR community. In this context, such units could support the UNICEF initiative of WASH clusters that aim to coordinate efforts within the humanitarian water, sanitation and hygiene sector, both at the global as well as country level (Bourgen & LeTurque, 2009). Such need for general technical support to groundwater in DRR has been expressed by the global WASH cluster at their meeting in 2007⁵.

4. Perspectives

Groundwater is a strategic resource during disasters. While the analysis performed in this paper applies primarily to tsunami hazards to groundwater and associated water supplies, it is recognized that groundwater plays a critical role in water supply in most parts of the world and hence improving disaster resilience of water supplies to a large extend depends on proper knowledge and protection of groundwater resources, not the least in coastal areas, where large majorities of populations live, where groundwater is already under great stress from human exploitation and degradation and natural salinisation processes, and where risks of a large number of disasters prevail. Experience from tsunami research and response relate mostly to rural and peri-urban areas where wells are small and numerous and poorly protected, rendering pro-active measures for decreasing vulnerability difficult compared to more centralised and urban schemes. Nevertheless, lessons learned need to feed into preventive and preparatory strategies that limit hazard impacts.

The framework proposed for risk management of tsunami-related hazards to groundwater and associated water supply is interdisciplinary in scope, drawing on capacity and expertise of water, and especially groundwater, professionals, chemical and health experts, social scientists as well as the practitioners of NGOs, humanitarians and international relief and donor organizations, and national and local authorities. As such, the challenge may be more on the aspects of coordination and communication. However, it is hoped that with relatively simple frameworks, such coordination and collaboration is rather enhanced than complicated. Also, it is hoped that the integrated approach, looking at water supply as well as the broader water resources, will provide a more coherent and sustainable approach to DRR related to coastal flooding (Schmoll et al., 2006).

The occurrence of large devastating tsunamis is infrequent; hence the investment to prevent and counteract impacts should be weighted against other risks and requirements. However, the recent catastrophic Tohoku earthquake and resulting tsunami have put a very different

⁵ <http://oneresponse.info/GlobalClusters/Water%20Sanitation%20Hygiene/publicdocuments/Cluster%20Minutes%20April%202007%20FINAL%2020070607.doc> (Accessed on May 12, 2011).

tone to the way tsunamis are now perceived. Nevertheless, coastal water supply systems are vulnerable to a wide variety of hazards that could potentially limit their ability to perform satisfactorily. Hence, it is important to assess the diversity and multitude of uncertainty sources present and prepare for a variety of risks, including that of tsunamis, in order to optimize water resource and water supply systems design, planning and management.

5. Conclusions

This paper analyzes, based primarily on experiences and research from the 2004 Indian Ocean tsunami, the short and longer term impacts of tsunamis on groundwater resources and water supplies derived from it. Groundwater pollution from a tsunami occurs at a relatively short time-scale, whereas the rehabilitation of these resources generally takes a much longer time. Though infrastructure around water supply may be rehabilitated relatively shortly after a tsunami, recovery of the aquifers may lag behind. This has to be factored into response, rehabilitation and recovery planning, in order not to compromise groundwater availability for extended times as groundwater is often the only available water resource for many human uses, sustaining health and livelihoods in coastal areas around the world.

Furthermore, the paper presents a framework for the integration of groundwater aspects into DRR strategies for tsunamis. This framework emphasizes the importance of integration of technical and scientific knowledge of groundwater into DRR and WASH cluster activities and is partly relevant for other coastal salinity flooding events as well.

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