Global Quick Scan of the Vulnerability of Groundwater systems to Tsunamis

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ABSTRACT

Major tsunami events have struck the coasts around the world with fatal consequences in terms of human casualties and material damage. While effects of a tsunami are clearly visible and well documented on the surface, little is known about the impacts on groundwater resources in the inundated areas. This study focuses on finding the most vulnerable areas to groundwater salinization caused by tsunami inundation. In our study, we present a Global Quick Scan of the vulnerability of the deltaic fresh groundwater resources to tsunamis. Two major steps were taken. As a first step, a vulnerability index is constructed. It is calculated using different types of topographical data. Regions with income below poverty line (1$/day per capita) are picked as the most vulnerable ones, due to no availability of alternative freshwater resources. Once these areas are selected, a search for parameter statistics is performed using a method of raster masking (overlay). Parameter statistics help to create ranges of values for relevant model parameters such as soil type and precipitation, which are then used in the second step. This step is a modeling process of salinization of fresh groundwater aquifers due to tsunami inundation. The severity of salinization is quantified as time necessary for a specific area to restore a freshwater concentration in more than 90% of its original extent.

INTRODUCTION

Fresh groundwater resources in deltaic areas are used for domestic, agricultural and industrial purposes. These resources in the coastal zone are threatened by salinization of the aquifers due to global change (increase of groundwater extraction due to population growth), climate change (including sea level rise), as well as natural disasters such as floods and tsunamis. Studies of how the coastal fresh groundwater resources are affected by the latter phenomena are often done a posteriori, especially the studies related to tsunami effects (e.g. the 2003 Sumatra Tsunami, Illangasekare, *et al.*, 2006). Then it is often too late to take appropriated measures to counteract the negative effects (e.g. on drinking water supply). These complex studies are time consuming, and need data which might not be available at the time of the disaster when a fast reaction of the water authorities is needed, e.g. to facilitate a quick and easy access to a fresh water supply system.

METHODS

We created a global database of relevant vulnerability indicators and model parameters. We collected SRTM90m data (Digital Elevation Model of the world), soil maps, gross domestic product and population density (step 1). We generated clustered data sets and used those to generate fast and simple variable-density groundwater flow and coupled solute transport models to simulate the salinization of groundwater systems in the coastal zone (step 2). These quantifications could give water managers a first approximation of the effects that a tsunami would have on the salinization of the fresh groundwater. The data collected in this database and the results of the models have been used to generate a map showing the areas with coastal groundwater systems vulnerable to tsunami effects and the magnitude of the possible impact of a tsunami. Python 2.7 scripts were used to transform the input data step by step, to extract parameter statistics (e.g. soil types), and to find the most vulnerable areas.

METHOD STEP 1 Vulnerability index

Information from the SRTM90m dataset is used to asses topographical parameters such as elevation, topographic slope and distance to coast (using GDAL and python scripts). The following equation is used to determine the vulnerability:

$$vulnerability\,index = 4 * ID_{elev} + ID_{dist} + ID_{slope} \tag{1}$$

where *elev* is topographic elevation, *dist* is distance to coast and *slope* is topographic slope. This formula is based on Rao *et al.* (2008) and has been tested in the northwestern coast of Japan (flood plains (Sendai and Minamisoma), V-shaped bays (Myiako, Rikuzentakata, Kesennuma) and a river estuary (Kitakami River), using historical 2011 data) and Spain (Murcia, Mallorca, being similar to the Japanese coastal zone). However, the threat of tsunamis is not the same throughout the world, and therefore, we selected only the areas with a high risk of tsunamis. For that, the global tsunami hazard study by Løvholt et al. (2012) was used to choose only areas with potential high risk of tsunami. In addition, regions with income below poverty line (1$/day per capita (Chen and Ravallion, 2007)) are picked as the most vulnerable ones, due to no availability of alternative freshwater resources.

METHOD STEP 2 Variable-density groundwater flow modeling

SEAWAT (Langevin et al., 2007) is used for the numerical simulations of variable-density groundwater flow and coupled solute transport. An adapted Henry concept is chosen to represent the impact of a tsunami on a coastal aquifer system, introducing constant head boundaries and recharge fluxes. SRTM90m data has been used to determine the different values of the inland constant head boundary. The conceptual 2D model is created with total length of 5km and depth of 50m; each model simulation has a unique combination of parameter values, see table 1. Number of columns and model layers are 5002 and 53, resp. The top soil layer has 4 model layers of each 0.25m thickness; longitudinal dispersivity is 1m (α_T/α_L=0.1); the MOC solver is used. The tsunami is conceptualized as follows; figure 1 shows the three different phases within such a disastrous event:

1. Phase 1: 500 years to determine the shape of the salt water wedge;
2. Phase 2: tsunami implemented as a head over the inundated area for a short duration;
3. Phase 3: the top layer of 1 m over 2 km length (X=2-4 km) is fully saturated with sea water (in terms of salt concentration) due to either a porous unsaturated medium, present top system (agriculture, ditches etc.) and/or local depressions where the sea water can stay after the wave retreat.

An important conceptual choice in the modeling process is the following: the severity of tsunami impacts in terms of head and thickness of the saturated top soil layer after wave retreat is the same for all 2D models. This is to be able to compare the response of different hydrogeological systems on a global scale, focusing on a-priori in-situ hydrogeological parameters. Basically, this means the initial starting concentration of phase 3 over X=2-4km in the top soil layer of 1m thickness is saline. As such, this 1m saline saturated thickness can be considered as a worst case scenario. We are aware that phase 2 has its effects (e.g. an unsaturated zone is probably present where the salt water could infiltrate) but in our vulnerability assessment this issue is assumed to be beyond our scope, for now. In addition, the direction of the tsunami hitting the coastline, the distance from the source (epicenter) and bathymetry are also not implemented in our approach).

These 2D models simulate among others the loss in fresh groundwater volume of the system after the tsunami. We have chosen for the zone below the inundated area of depth 7m (being a zone where often shallow groundwater is extracted in underdeveloped areas). In addition, the characteristic time of a groundwater system in the same zone is determined before it recovers 90% of the fresh groundwater that was available previous to the tsunami event.

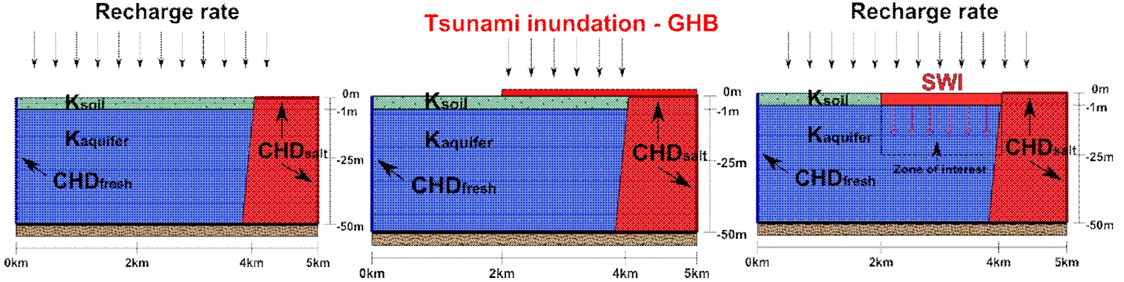


Figure 1: Schematisation of the conceptual model: three phases but basically only the phases 1 and 3 are modeled.

Variable parameters	Value			
	A	*B*	*C*	*D*
Recharge (fresh) (m/d)	0.0001	0.001	0.0025	0.005
CHD fresh (m)	1.0	5.0	15.0	-
K soil (m/d)	0.005	0.05	5.0	50.0
K aquifer (m/d)	1.0	100.0	-	-

Table 1: Variable hydrogeological parameters (4*3*4*2=96 model combinations).

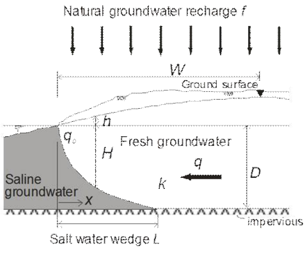
RESULTS

With the 2D models, two different times are characterized:

1. **Characteristic time** – time of zone recovery till 90% as before tsunami, and
2. **Reach time** – time necessary for the salt front to reach the deep zone (at least 10% of salt in the zone). This time determines how long it takes before deeper groundwater extraction wells could be contaminated with saline groundwater.

Figure 2 shows the 96 default ‘Henry’ salt water wedges (the end of phase 1). After modeling phase 3, differences in (fingered) plumes are detected, which are caused by difference in recharge rates, the constant head boundary at the hill site, and the hydraulic conductivities in the top soil aquifer of 1 m and the aquifer below it. Some characteristics are (keeping the traditional equation in mind):

$$L = -\frac{q_0}{f} - \sqrt{-(\frac{q_0}{f})^2 - \frac{k}{f} D^2 (1+\alpha)\alpha}$$



- the salt water intrusion wedge largely depends on the outflow flux; a large outflow flux reduce the length of the wedge,
- a low hydraulic conductivity in the aquifer reduces the length of the wedge,
- an increase in groundwater recharge can reduce the wedge length significantly.

On top, the characteristics of the tsunami event are:

- fingers do occur in most hydrogeological systems,
- high hydraulic conductivities in the aquifer fastens the flow of intruded seawater out of the drinking water zone,

- a large outflux from the inland area reduces the deep outflow of intruded seawater,
- a large groundwater recharge causes a deeper outflow of intruded seawater.

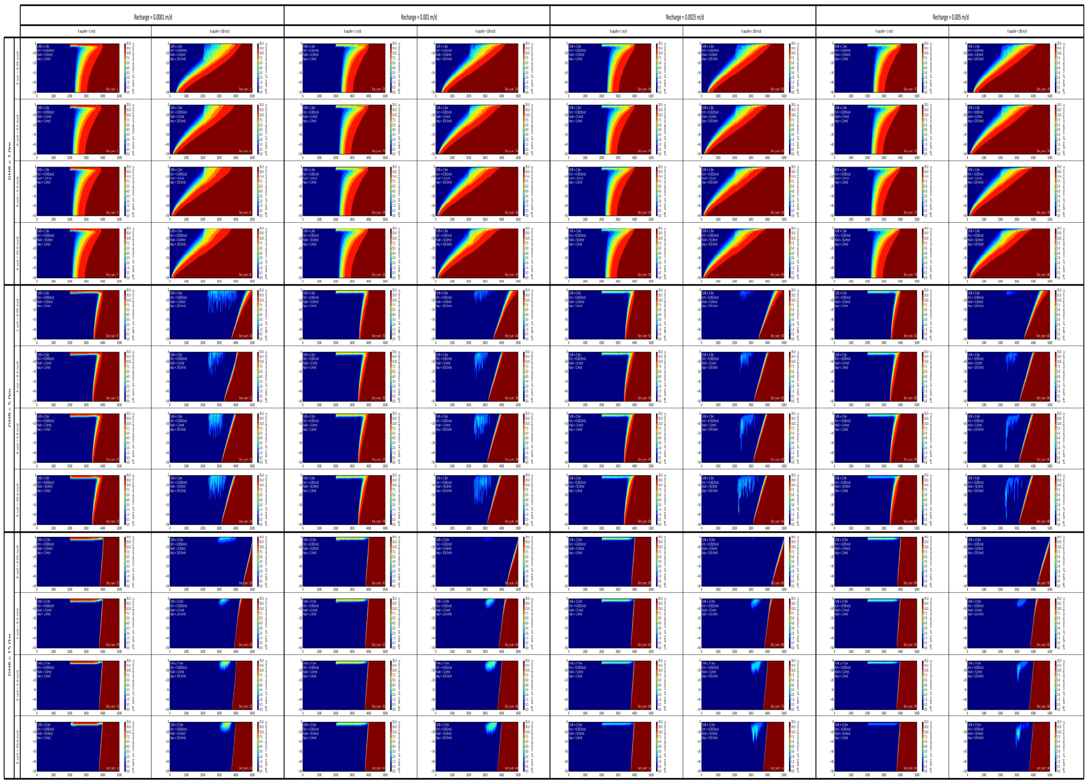


Figure 2: 2D profiles of all 96 adapted Henry cases, 2.5 yrs after tsunami event.

The method proposed in this study sets a framework for vulnerability assessments to different types of hazards of the groundwater system on a global scale. A similar approach could be adopted for assessing the effect of sea level rise and future increased groundwater extractions on vulnerable coastal groundwater systems worldwide.

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