Additional thesis project

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Global assessment of the potential effect of large sand replenishment on fresh groundwater resources

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Abstract

Sand replenishments, or nourishments, have been the prevalent strategy of the Netherlands for coastal protection since 1990. In consideration of the expected sea level rise and potential increases of storm surges as a result of climate change, an innovative pilot project known as the 'Sand Engine' has been implemented. In contrast with traditional replenishments that are repeated with 3 to 5 year intervals, this local mega-nourishment is expected to protect the coastline for a period of at least 20 years. As sand replenishments are a widely applied technique, the concept of the Sand Engine, if proven successful, could be an effective solution for other areas of the world as well. This study looks into the potential effects of a large-scale sand replenishment on fresh groundwater resources, on four coastal areas in different parts of the world where such a project could be applied. These effects were quantified using 2-D variable density groundwater flow and coupled salt transfer models, by simulating the fresh-saline water interface before and after the replenishment, and comparing the results based on the current sea level and weather conditions with those based on scenarios of climate change. The results show that a large sand replenishment can lead to a considerable increase in the fresh groundwater volume, offering an opportunity to combine coastal protection with an increase of freshwater availability for areas with limited water resources.

Keywords: Sand Engine, sand replenishment, fresh groundwater, coastal aquifers

Contents

1. Introduction

The Sand Motor, also known as the Sand Engine, is a pilot project in dynamic coastal management, which combines coastal protection and recreation with a sustainable and nature-friendly approach. It's an artificial peninsula consisting of 21 million m^3 of sand, placed on the coast of South Holland in 2011 and expected to be redistributed along the coast by wind, waves and currents, during its planned lifetime of 20 years (van Slobbe et al., 2013). Being the first sand replenishment of such large scale, it is an experiment whose long-term effects are still being investigated. Research is being conducted in various fields, such as the sand distribution, flora and fauna of the area, recreation and more. One of the other research areas of the Sand Engine is groundwater, where recent research showed that the Sand Engine could potentially lead to an increase of the local fresh groundwater availability (Huizer et al., 2016). This paper investigates the potential impact of large-scale sand replenishments on the volume of fresh groundwater, on various locations around the world where large-scale sand replenishments such as the Sand Engine could be implemented. This translates into two research questions: what are the suitable locations for mega-nourishments, and what are the possible effects on fresh groundwater resources at those locations?

2. Materials and methods

2.1. General

The study was carried out in the following steps:

1. A few locations were chosen out of a list of possible locations that were considered based on multiple criteria.
2. The necessary parameters were collected for each location, using available literature, global datasets and a few assumptions.
3. Using 2D models, which represent cross-sections of the coast, the groundwater systems were simulated using the computer code SEAWAT to simulate variable density groundwater flow and salinity transport.
4. For each case, the model was run for the initial condition – before the replenishment – until the system reached steady state (when the volumes of fresh, brackish and saline water were at equilibrium).
5. A sensitivity analysis was performed on the initial models in order to assess the impact of the model parameters on the system and to form scenarios based on the most significant parameters.
6. The sand replenishment was applied to each cross-section and the simulations were run until equilibrium was reached again.
7. Three climate change scenarios were applied on each case along with the sand replenishment.

2.2. Locations

The first step of this research is to look into possible locations where a large – scale sand replenishment could be applied. There is a large variety of factors that need to be taken into account in order to determine the suitability of a location. The most important factors are listed in Table 1.

Table 1: Factors that determine the suitability of a location for a sand replenishment

Parameter	**Conditions favourable for sand replenishment**
Type of material	Replenishments can only be applied on sandy beaches, which compose 20 to 40% of the world's coastlines. Up to 70% of these beaches are subject to erosion. (Bird, 1985).
Sand source location	A nearby source that can provide the required amount of replenishment material is necessary. The replenishment material can be either dredged from an underwater source or extracted from dry land. The choice of the source is based on the compatibility of the sand for replenishments, cost, removal and transportation, and environmental factors (Marchand et al., 2012).
Physical nature of the coast	The determination of the scale of the replenishment has to take into account the physical nature of the coast, as different sizes of replenishments are applicable for a continuous, uninterrupted sandy beach with uniform characteristics, and for beaches interrupted by bays and channels (Schasfoort & Janssen, 2013).
Grain size	The grain size of the replenishment sand is the most important parameter. It needs to be relative to that of the coast (preferably equal or larger) and fulfil certain criteria in composition, mechanical strength and abrasion. When the grain size is smaller than the original, it will lead to a flatter profile and larger amounts of replenishment will be needed, while larger grain sizes will lead to a steeper profile and smaller amounts of replenishment sand will be needed (Haney et al., 2007).
Sediment transport dynamics	Long-shore and cross-shore transport capacity of sediment, depending on wave climate and wind forces, determines the redistribution processes and the life expectancy of the replenishment. These dynamics vary significantly in different locations; there is still a knowledge gap about the reasons of these variations (Arens et al., 2012).
Erosion rate	The erosion processes also need to be taken into account, as high rates of erosion might make the beach replenishment technically or economically unfeasible. (*Beach nourishment and protection*, 1995)
Natural habitat	The potential impacts on the natural habitat need to be examined when the replenishment project is designed, as it may affect endangered species habitat or disrupt the life of aquatic animals and vegetation (Stronkhorst et al., 2010).
Maintenance	There needs to be a permanent organisation performing the required maintenance of the replenishment. In the case of the Sand Engine, Rijkswaterstaat is responsible for the maintenance (Schasfoort & Janssen, 2013).

There are numerous areas worldwide where smaller scale replenishments have been applied in the past, to prevent flood risk, compensate for coastal erosion, or to create or maintain beaches for recreation. Interest has been expressed of quite a few countries for a large – scale project too. The STW NatureCoast team, which investigates the general application of nature-driven sand replenishments, has looked into a few suitable areas. As a part of this study, a short research was made for areas that fulfil the main criteria and could be considered for a large replenishment and a list of suggestions was composed. All the suggested locations are depicted in the map of Figure 1 and a brief description of each one is given below. Out of those, the first four were chosen for further investigation.

Figure 1: Map of considered locations for a large -scale replenishment (Created with Google – *My Maps*)

- <u>Hoi An, Vietnam</u>
  Research has been conducted in the framework of a multidisciplinary project by TU Delft students on the recreation of the Cua Dai Beach, on the coast of Hoi An in Vietnam. Results show that a large - scale nourishment would be the best solution to prevent the coast from erosion, compared to solutions that suggested smaller nourishments combined with groynes or revetment. There are two options for the source of replenishment material, either the river deposit in front of the mouth, or further offshore dredging. The first choice appears to be preferable due to lower costs and grain size distribution closer to the original; however, the amount of material provided at that location would probably not be enough for a mega-nourishment. No negative effects are expected on to the local species natural habitat and vegetation (Fila et al., 2016).

- <u>Gold Coast, Australia</u>
  Australia's Gold Coast is another location where a mega-nourishment could be applied. Smaller scale beach nourishment projects have already been undertaken frequently in the past, on different sandy beaches along the 52 km coastline. So far, the nourishments have been proven successful in cases of severe storms, minimizing damage to the shoreward properties as well as protecting ecological communities on the dunes. The sand used as replenishment material in different parts of the coast originated from rivers and creeks near the beaches, although in case of a mega-nourishment offshore dredging would probably be required. There are more coasts suffering from severe erosion in Australia, such as the Byron Bay and the Collaroy –Narrabeen, where a large - scale nourishment could also potentially be implemented (Castelle et al., 2006; Strauss et al., 2009).

- Cancun, Mexico

  Cancun city, located on the South-East of the Yucatan Peninsula, is a long and narrow strip of land between the sea and a lagoon which behaves as an island, making it an interesting case for beach replenishment. For a long time, the Cancun beach had been affected by erosion processes that were intensified by touristic infrastructure and tropical cyclones. Two hurricanes accelerated the erosion processes, causing huge sediment loss and requiring strong measures to rehabilitate the beach. The biggest sand nourishment project in South America was carried out in Cancun in 2009 along a 10.5 km long beach, using 5.2 million m^3 of sand. The replenishment material was dredged from the two borrow sand pits and was completely compatible with the native sand. The project succeeded to restore original conditions and the environmental conditions were fully fulfilled on the deposition area and the sand borrow areas (Sanchez et al., 2011).

- Cape Henlopen, Delaware, USA

  Cape Henlopen is a thin peninsula located at the mouth of the Delaware Bay, which experiences erosion and shoreline retreat along its Atlantic boundary (Heiss et al., 2014) and has very high exposure to cyclones (CHW System, 2015). As part of a program of coastal damage reduction, the US Army Corps of Engineers has implemented a project than includes beach fill and periodic nourishments, located just north of the Delaware Seashore State Park. (US Army Corps of Engineers, 2016).

- Scania Province, South Sweden (NatureCoast)

  The coastline of the southern tip of Sweden consists of 25% sandy beaches, where coastal erosion has been observed in several places due to subsidence of 0.5 mm/year and sea level rise. Beach nourishment has not been a common method for coastal protection in Sweden, but recently a few areas have started to implement it. Ystad municipality, an area that experiences the most severe coastal erosion in Sweden, has completed two relatively small sand nourishments and is now opting for a larger one (340.000m^3). The proposed extraction area is an offshore large sand deposit in which eroded material from Ystad's coast accumulates. However, the permit for this project has not been given yet, as there are still concerns about the environmental impacts and the availability of sand resources. (Bontje et al., 2016)

- Poole Bay, UK (NatureCoast)

  During the winters of 2005-6 and 2006-7 a sand nourishment project successfully took place in the Poole Bay. In 2015, an experiment of near-shore seabed nourishment was conducted, which, contrary to the previous conventional nourishments, uses the Sand Engine's approach of taking advantage of the natural forces for the redistribution of the sand (The Poole Bay Partnership, 2015).

- Miraflores Bay, Lima, Peru (NatureCoast)

  Miraflores Bay is another location proposed by the NatureCoast team, where a mega-nourishment could solve the problems of coastal safety and environmental degradation. However, no additional information is available on this area (NatureCoast Newsletter, May 2015).

- Negril, Jamaica

  The sandy coasts of Negril town suffer from erosion, hurricanes and illegal beach activities. The government has authorized to build breakwaters, but the stakeholders are in favour of a sand nourishment (NatureCoast Newsletter, May 2015).

- Motril – Salobrena, South Spain

  The Spanish Mediterranean coast, which consists almost exclusively of sandy beaches, has performed small sand replenishments on more than 400 sites along the coast as a measure against erosion (Hanson et al., 2002). The chosen site does not have a particularly high erosion hazard; however, the coastal aquifer located between the cities of Motril and Salobrena is in high risk of saltwater intrusion due to increased freshwater extraction as well as decreased recharge (Dulque-Calvache et al., 2006). Keeping the saline wedge position under control is essential for the freshwater quality (Lopez-Chicano et al., 2010). It would therefore be interesting to examine the possibility of increasing the freshwater availability by expanding the coast between Motril and Salobrena.

2.3. Collection of model parameters

Out of the locations suggested in the previous paragraph, four were chosen for further investigation of the effect of a possible sand replenishment on fresh groundwater resources: Delaware, Cancun, Gold Coast and Hoi An. The main criterion of this choice was that all chosen sites differ in coastal morphology, aquifer characteristics and climate. Another important factor was the availability of previous related geohydrologic research in those areas that could provide the necessary data. The next step was to collect the parameters needed to build the models. Due to a few uncertainties, inability to find measured values or cross-reference resulting in contradicting data, assumptions were made for some of the model parameters. The main model parameters used for the 2-D groundwater model were:

Surface elevation / bathymetry: For the surface elevation and bathymetry several global gridded datasets were used, downloaded from various sources such as NOAA, Natural Earth and GEBCO (see Appendix) and processed with QGIS (version 2.12.3, 2016), as well as the GeoContext Profiler program (http://www.geocontext.org). Finally, the profiles created by the Geocontext Profiler were chosen to use for the models both for surface elevation and bathymetry, as they were the most accurate both for elevation and bathymetry. By cross-checking with profiles created by Google Earth, some adjustments had to be made, as in some cases there was a gap between the surface elevation and the bathymetry, resulting in an unrealistically long width of the beach.

Water level: The inland model boundaries consisted either of surface water or groundwater. The level and salinity of these boundary conditions were determined by observing rivers, canals or other draining outlets, and surface elevations in the area near the coast on Google Earth.

Storm climate and erosion hazard / suitability of nourishment: Using the Coastal Hazard Wheel (CHW) App, a tool that provides classification data of the hazards of coastal areas on a global level (see Appendix), the erosion hazard was assessed as “high” for Hoi An and “very high” for the other three locations, while all areas are influenced by tropical cyclones. Based on the CHW, beach nourishments are a suitable measure against erosion in all four locations. (Appelquist and Halsnæs, 2014)

Soil properties: For the determination of the porosity and hydraulic conductivity, a global dataset was used: GLHYMPS (Global Hydrogeological Maps) are high resolution global maps that provide permeability and porosity values, based on a previous global lithology map (see Appendix). Porosity values provided by GLHYMPS were used for the models; however, the hydraulic conductivity values that were calculated based on the corresponding permeability values of the maps were too low compared to values found in literature. Also, in all the locations the hydraulic conductivity seems to vary significantly within the aquifer, therefore an assumption of a mean horizontal hydraulic conductivity was used for each case. The vertical hydraulic conductivity was considered to be 10% of the respective value of the horizontal (anisotropy = 0.1). Different values of the hydraulic conductivities and the anisotropy were tested during the sensitivity analysis, further explained in the next chapter. Finally, for the specific yield and specific storage, the same values were used in all the locations as in the original Sand Engine model.

Precipitation, evaporation and recharge: Precipitation and evaporation are incorporated in the model as groundwater recharge. A range of values for recharge of each location was taken from global datasets PCR-GLOBWB (de Graaf et.al, 2015) and WHYMAP (World-wide Hydrogeological Mapping and Assessment Programme - see Appendix). The range was 100 – 300 mm/y for all four locations according to WHYMAP, which was chosen due to its higher resolution. An average of 200 mm/y was used in the models, as well as a maximum of 300 mm/y in the climate change scenarios.

Aquifer thickness: The aquifer thickness was estimated with a global map of soil layer thicknesses (Pelletier et.al, 2016), published by ORNL DAAC (Oak Ridge National Laboratory Distributed Active Archive Center), one of the data centres of NASA (see Appendix). As there was not enough available data on different soil layers, the models were simplified and one homogeneous aquifer was used for each location. The thicknesses of the aquifers used in the models were defined after cross-referencing the global map estimations with information found in literature (Heiss et al., 2014; Schafmeister and Van Hoang, 2001).

Salinity: For the concentration of salt in seawater, the general value of 35 ppt was used in all locations. For the Nichupte lagoon in Mexico, where the water is hyposaline but the salinity value varies spatially, an approximated value of 25 ppt was used (Leon-Galvan et al., 2007).

2.4. Model

The models were constructed using the computer code SEAWAT (version 4: Langevin et al., 2008) to simulate variable-density groundwater flow and coupled salinity transport. The same script was used for the four locations, adapted to each case based on the data and assumptions descripted above. First, the scripts were run until a steady-state condition was reached (amounts of fresh, brackish and saline water are at equilibrium). Second, a sensitivity analysis was performed by testing different versions of each script, alternately increasing or decreasing the values of several model parameters (hydraulic conductivity, anisotropy, recharge, groundwater level, sea level) in order to optimize the model and assess which factors affect the results the most. Finally, the coast was extended, using a copy of a cross-section of the Sand Engine as replenishment, and 3 scenarios of climate change were implemented along with the replenishment.

2.4.1. Delaware, USA (DL)

The DL cross- section is located on the west side of Cape Henlopen, approximately 4.5 km south of the tip. It has a total length of 5 km, with the land extending to approximately 2.3 km. There is one set of dunes of 9 m height just inland of the beach. There is a network of canals and creeks in the area, which are included in the model as drains and constant head boundaries. The model discretisation can be seen in Table 2; the horizontal cell resolution was 10 m, while the thickness of the model layers varied with depth. Denser layering was used close to the surface (model layers of 0.4 m), increasing to 1 m toward the bottom of the aquifer, in order to get higher accuracy of the simulation in the upper, most dynamic part of the model. The aquifer properties were taken from Heiss et.al (2014).

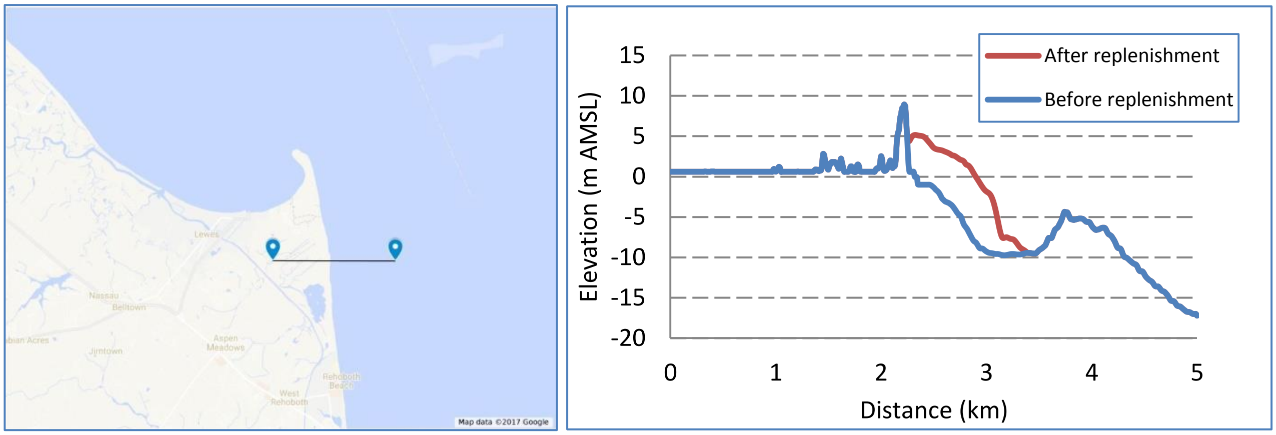


Figure 2: Cross - section at Delaware, USA (DL)

2.4.2. Gold Coast, Australia (GC)

The GC location is south of the city of Gold Coast, between the Bilinga and Coolangatta suburbs. The cross-section is 4.2 km long, with the land extending to the middle of this distance, and the model was discretized as described in Table 2, with horizontal cell resolution of 10 m and model layers with thicknesses varying from 0.7 to 1 m. A lake lies at the inland boundary, setting a boundary condition for the heads at that point. The aquifer properties were estimated from Pelletier et al. (2016) and de Graaf et al. (2015).

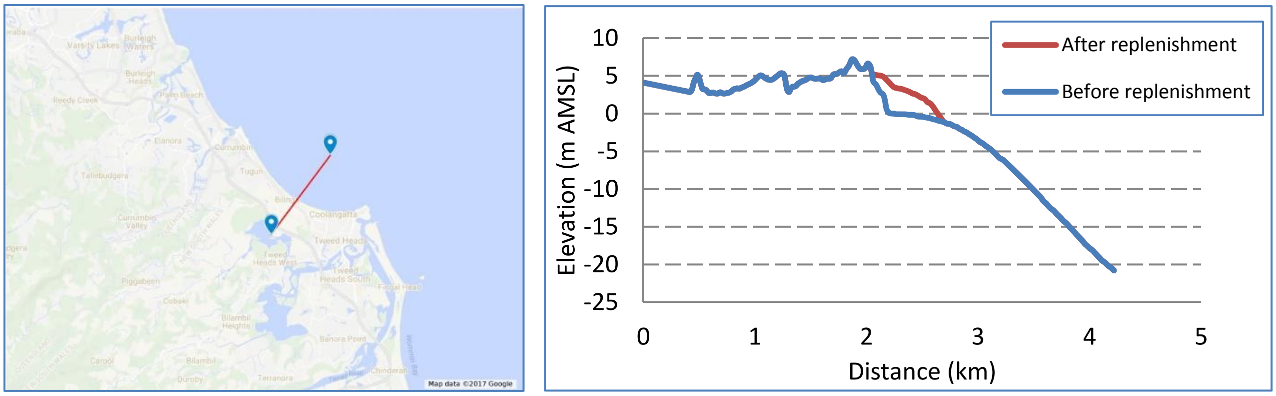


Figure 3: Cross-section at Gold Coast, Australia (GC)

2.4.3. Hoi An, Vietnam (HA)

Located between the cities of Da Nang and Hoi An in Vietnam, the HA cross-section is 3.4 km long with a high elevation of land of about 10-12 m and a small lake at the end of the line serving as a head boundary. In contrast with the other 3 locations where the aquifers reached a depth of 50m, the HA aquifer thickness is only 15m. The horizontal cell resolution of the model was 10 m and the layer thickness approximately 0.3 m. The properties used for this location were taken from Schafmeister and Van Hoang (2001).

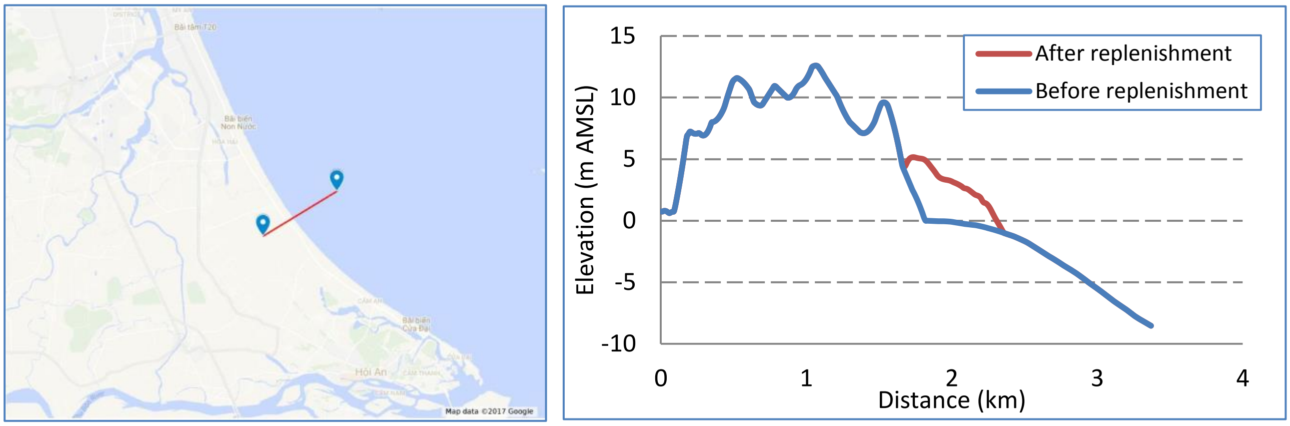


Figure 4: Cross - section at Hoi An, Vietnam (HA)

2.4.4. Cancun, Mexico (CN)

The CN cross-section is located on the Zona Hotellera of Cancun city, a 500 m wide strip of land reaching 10m of elevation between the Nichupte lagoon and the Caribbean sea. The cross- section is 7 km long, including part of the lagoon, for which an average salinity of 25 ppt and an average depth of 2 m were used (Leon-Galvan, 2007). The model was discretized to 234 columns of 30 m sized cells, and 100 model layers of sizes varying from 0.7 to 1 m. The aquifer thickness was taken as equal to that of the mainland, which is 50 m (Pelletier et al., 2016).

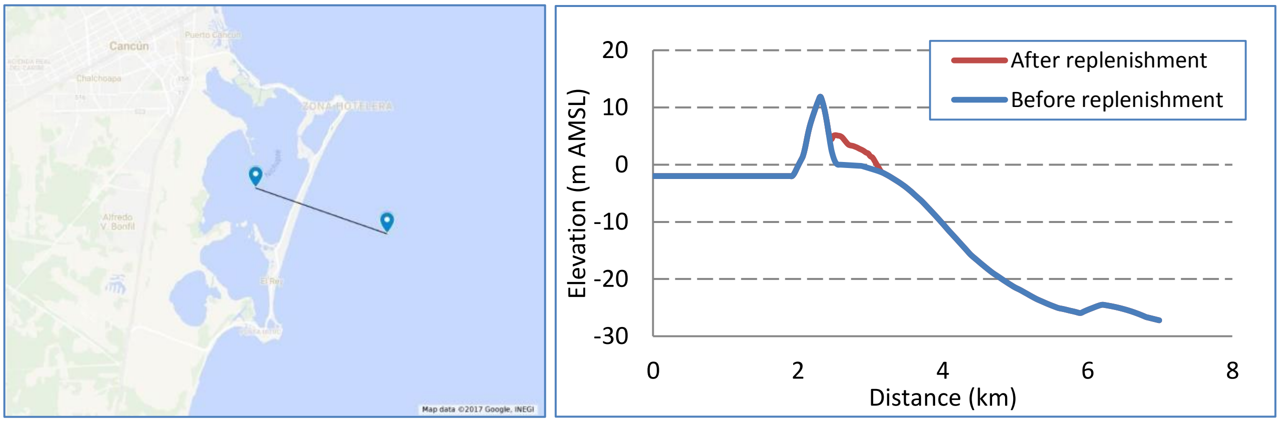


Figure 5: Cross - section at Cancun, Mexico (CN)

Table 2: Overview of locations and parameters of the reference cases

Locations **Model parameters**			**DL**	**GC**	**HA**	**CN**
Length of cross section		km	5	4.2	3.4	7
Model discretisation	Rows	(-)	1	1	1	1
	Columns	(-)	501	423	338	234
	Layers	(-)	100	70	90	100
	Cell size	m	10	10	10	30
Stress periods	Number of stress periods	(-)	6000	5000	2500	10000
	Length of each stress period	days	18.25	36.5	30	5
Hydraulic conductivity	Horizontal (K_H)	m/day	20	10	10	10
	Vertical (K_V)	m/day	2	1	1	1
Porosity		(-)	0.22	0.15	0.22	0.26
Aquifer thickness		m	50	50	15	50
Inland constant head boundary		m	-0.5	-0.5	-0.5	0
Sea level (AMSL)		m	0			
Specific storage (SS)		(-)	0.0002			
Specific yield (SY)		(-)	0.12			
Recharge		mm/year	200			

3. Results

3.1. Sensitivity analysis

The sensitivity analysis was performed thoroughly for the case of Hoi An, which is presented in this section, and more briefly for the other locations. The comments of this section are representative for all the locations, as there were no significant differences in the drawn conclusions. The tests and results are listed in Table 3 and the impact on the freshwater volume is depicted in Figure 6. The freshwater volumes are given per stretched meter of the coast.

Table 3: Hoi An (Vietnam): Sensitivity analysis

Case		Time until equilibrium (years)	Freshwater at equilibrium (10^3 m^3/m')	Freshwater volume increase or decrease	Maximum head (m)
0	**Reference case**	134.0	6.19	-	1.4
1	**Recharge = 55 mm/y**	705.2	4.76	-23.10%	0.4
2	**Recharge = 100mm/y**	354.2	5.96	-3.72%	0.6
3	**Recharge = 300 mm/y**	92.1	6.25	0.97%	2.1
4	**K_H=20 m/d, K_V=2 m/d**	134.0	5.97	-3.55%	0.7
5	**K_H=20 m/d, K_V=1 m/d**	151.2	5.97	-3.55%	0.7
6	**K_H=10m/d, K_V=0.5 m/d**	134.0	6.20	0.16%	1.4
7	**Sea level rise=0.5m**	134.0	6.13	-0.97%	1.6
8	**Groundwater head drop = 2.5m**	134.8	5.67	-8.40%	0.6

The main conclusions from the sensitivity analysis are:

○ *Recharge:* With a lower recharge rate (cases 0, 1, 2 and 3), the time until the model reaches equilibrium is longer, the total volume of fresh water is smaller and the groundwater heads are lower. For very low recharge (case 1) the freshwater lens does not reach the bottom of the aquifer, in contrast with all the other cases where the aquifer is filled with fresh water. On the other hand, a higher recharge rate (case 3) brings the system to equilibrium faster and increases the heads, but the total volume of freshwater only slightly increases, as the aquifer was already completely filled in the reference case.

○ *Conductivity:* Horizontal conductivity, vertical conductivity and anisotropy (K_H:K_V) were alternately changed (cases 5, 6, 7). The conclusion is that the system is most sensitive in respect to the horizontal conductivity (doubling the value of K_H leads to a decrease in heads and freshwater volume), while the vertical conductivity and the anisotropy don't have a significant impact on the results.

○ *Sea level rise:* Raising the sea level by 0.5 m (case 8) brings only a slight decrease to the freshwater volume and an increase to the heads.

○ *Groundwater level drop:* By decreasing the value of the constant head boundary condition at the lake, from -0.5 m to -3 m (case 9) brings a significant decrease to both the freshwater volume and the heads.

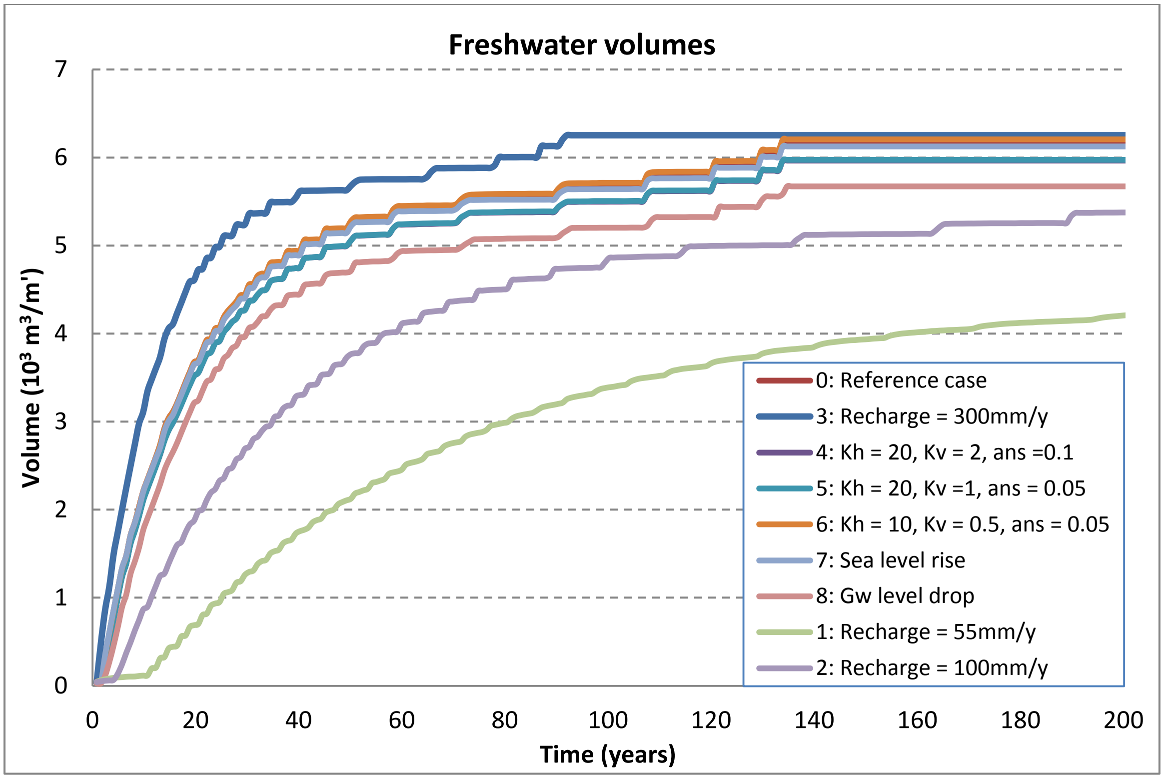


Figure 6: Hoi An (Vietnam): Graph of freshwater volumes for sensitivity analysis (cases 0-8)

3.2. Results before and after the sand replenishment

Presented in Figures 7 to 18 are the groundwater heads, salinity concentrations and fresh, brackish and salt groundwater volumes of each location. The top images of each location show the heads and concentrations at the equilibrium situation, before the sand replenishment is applied. The second set of images show the heads and concentrations long after the sand replenishment has been applied, when equilibrium has been reached again and therefore the growth of fresh groundwater has reached the maximum amount. The bottom graph and table of each location shows the change of fresh, brackish and saline water volumes before and after the replenishment. As a simplification, the sand replenishments were applied once and without morphological changes of the replenishment.

- **Delaware**

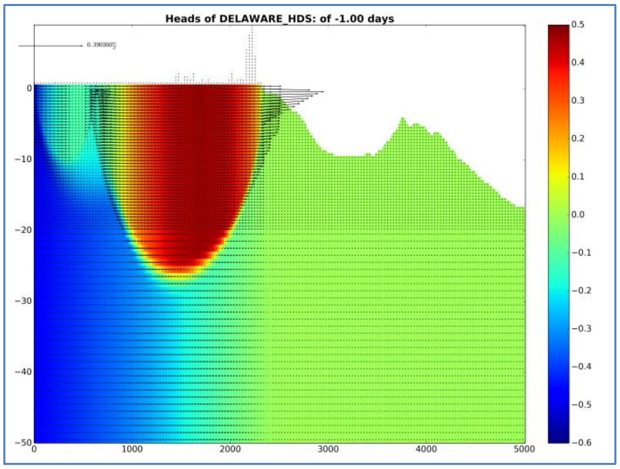


Figure 7a: Heads at DL before the replenishment

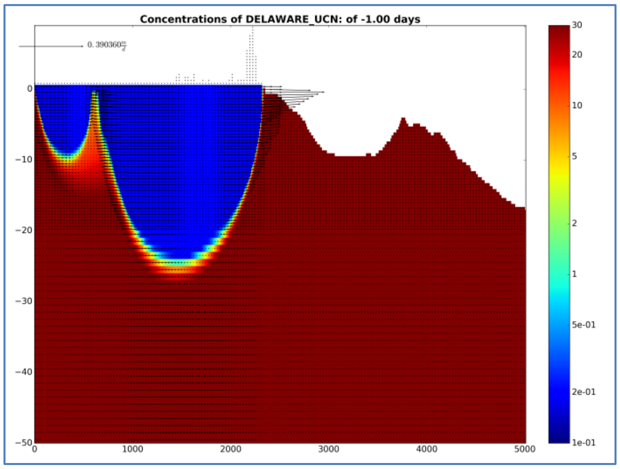


Figure 7b: Concentrations at DL before the replenishment

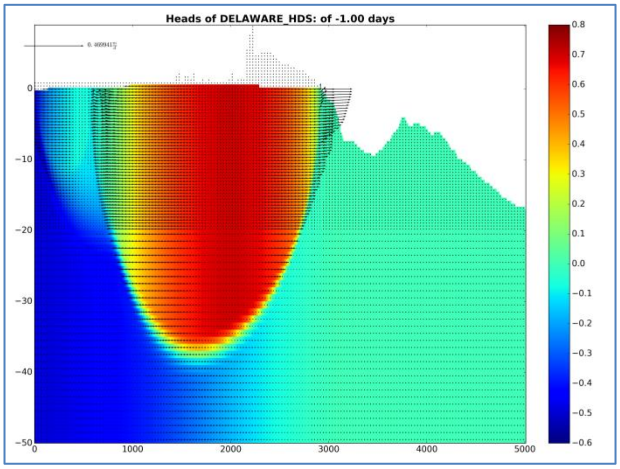


Figure 8a: Heads at DL after the replenishment

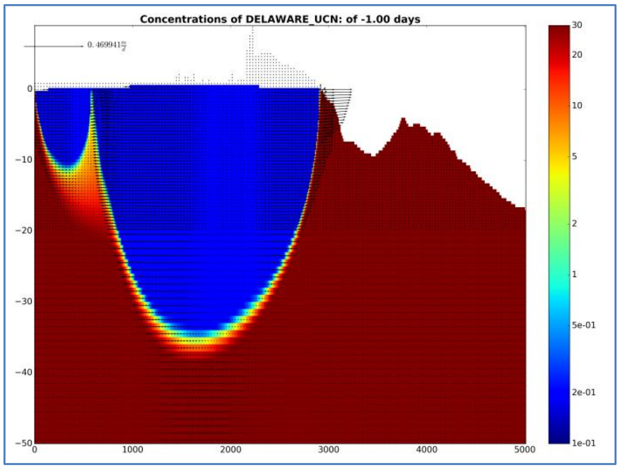
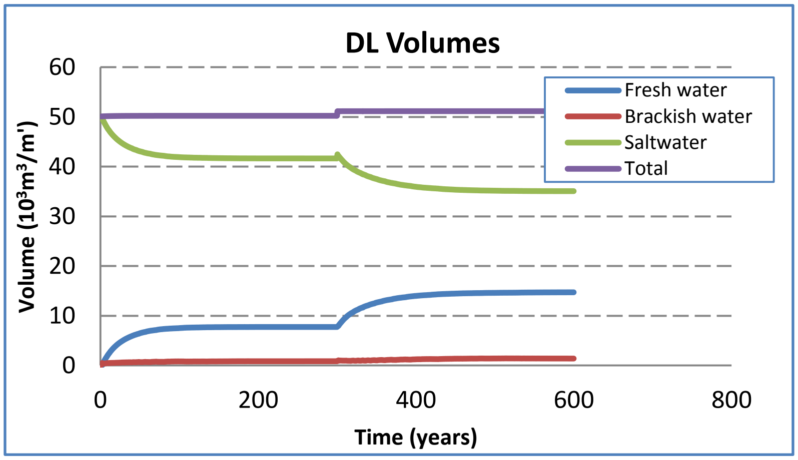


Figure 8b: Concentrations at DL after the replenishment



DL freshwater	
Volume at initial condition ($10^3 m^3/m'$)	7.73
Volume after replenishment ($10^3 m^3/m'$)	14.69
Increase in FW	***90.1%***

Figure 9: Changes in the fresh, brackish and salt groundwater volume at DL

- **Gold Coast**

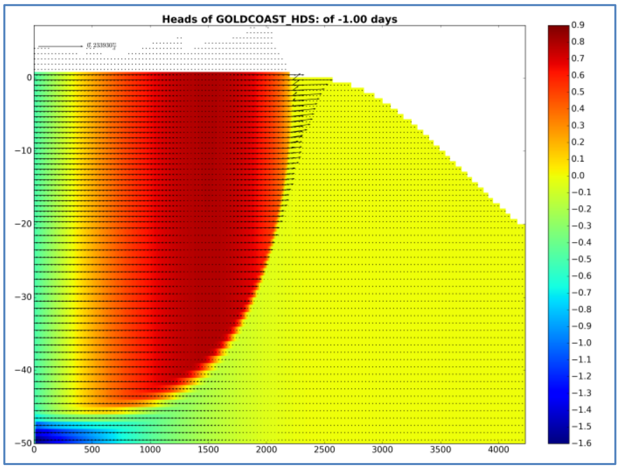


Figure 10a: Heads at GC before the replenishment

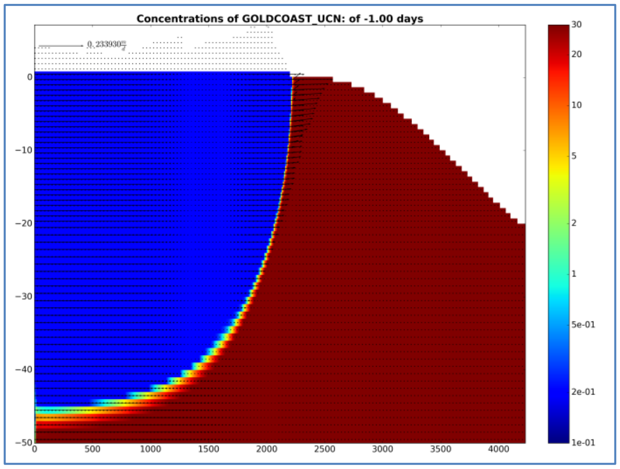


Figure 10b: Concentrations at GC before the replenishment

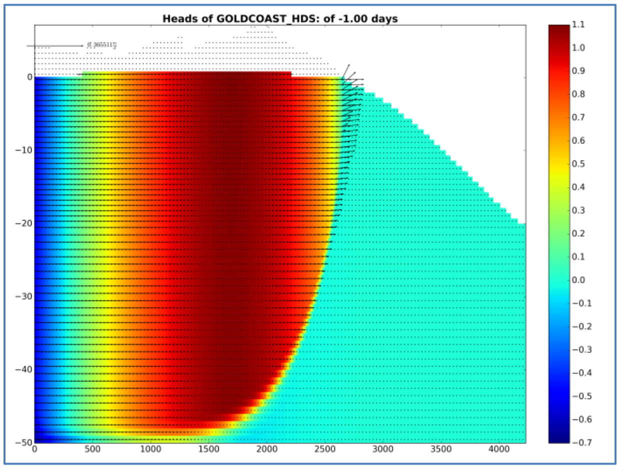


Figure 11a: Heads at GC after the replenishment

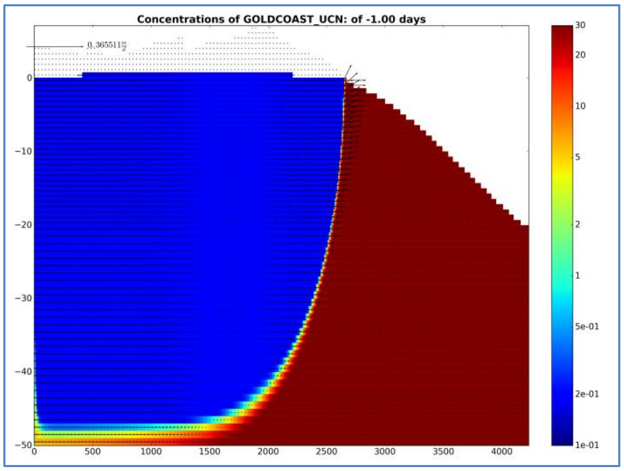
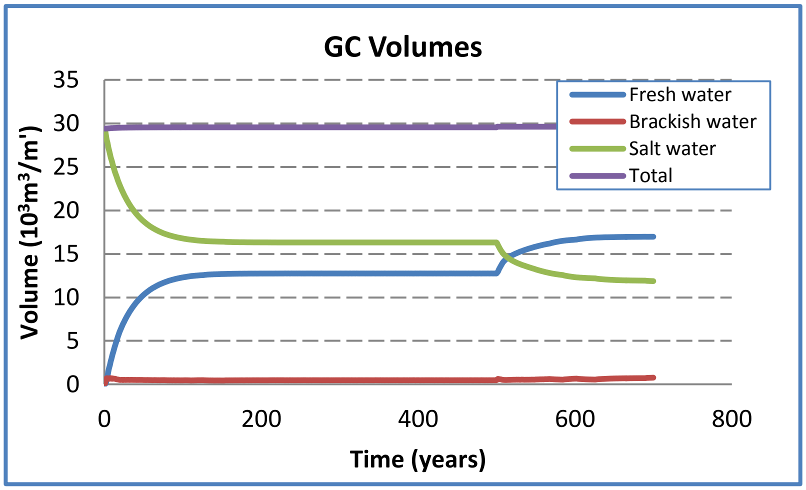


Figure 11b: Concentrations at GC after the replenishments



GC freshwater	
Volume at initial condition ($10^3 m^3/m'$)	12.74
Volume after replenishment ($10^3 m^3/m'$)	16.97
Increase in FW	***33.2%***

Figure 12: Changes in the fresh, brackish and salt groundwater volume at GC

- **Hoi An**

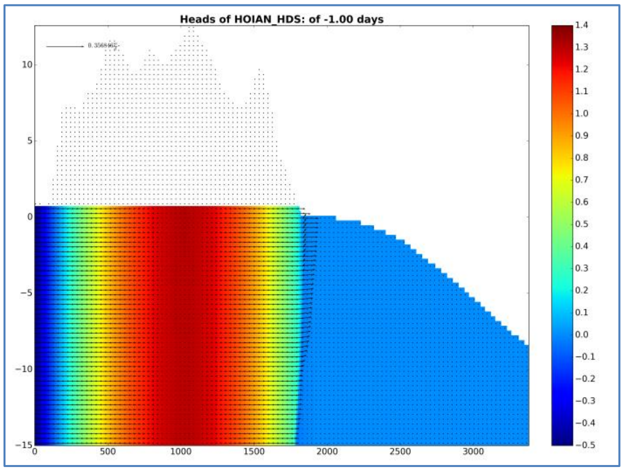


Figure 13a: Heads at HA before the replenishment

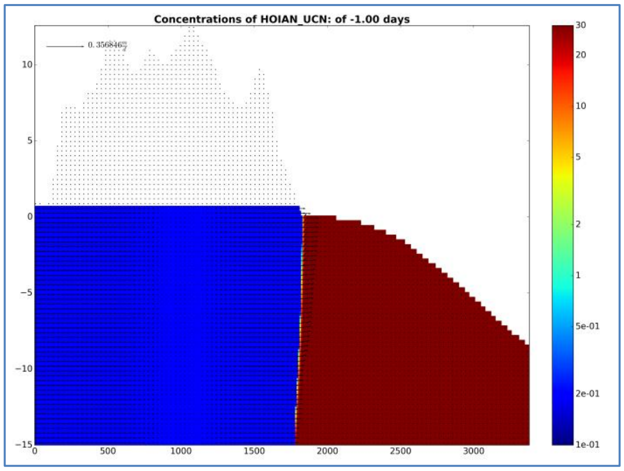


Figure 13b: Concentrations at HA before the replenishment

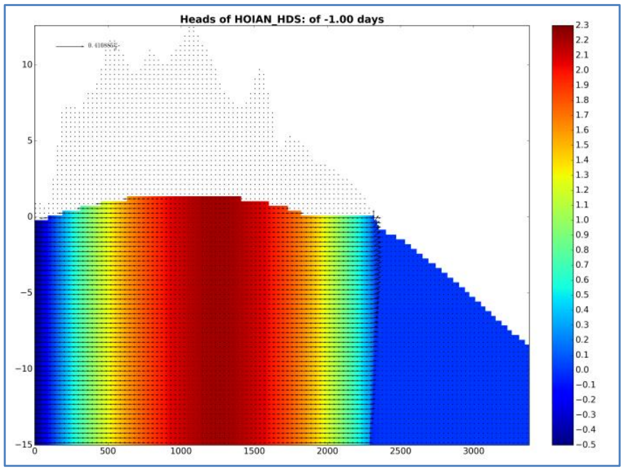


Figure 14a: Heads at HA after the replenishment

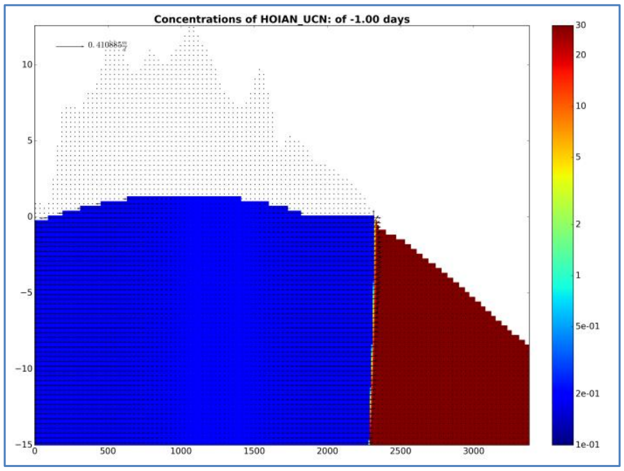
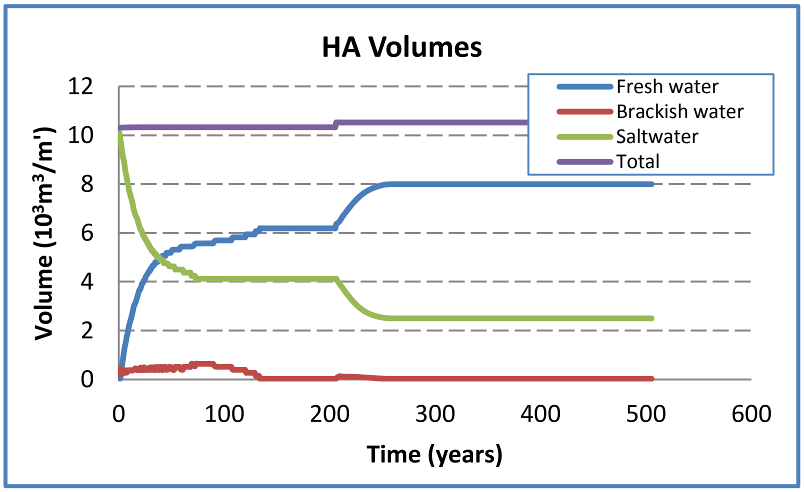


Figure 14b: Concentrations at HA after the replenishment



HA freshwater	
Volume at initial condition ($10^3m^3/m'$)	6.19
Volume after replenishment ($10^3m^3/m'$)	7.99
Increase in FW	***29.2%***

Figure 15: Changes in the fresh, brackish and salt groundwater volume at HA

- **Cancun**

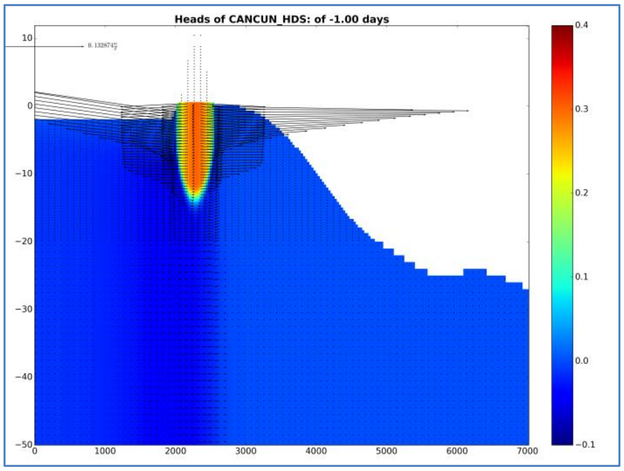


Figure 16a: Heads at CN before the replenishment

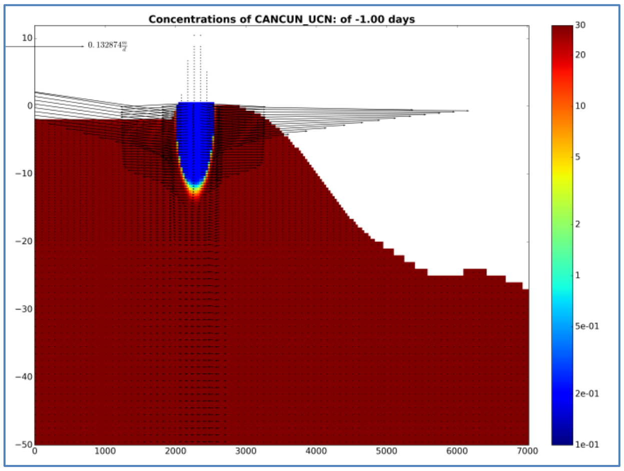


Figure 16b: Concentrations at CN before the replenishment

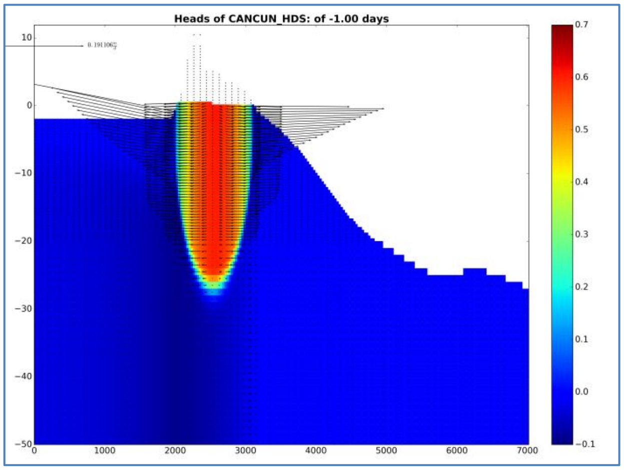


Figure 17a: Heads at CN after the replenishment

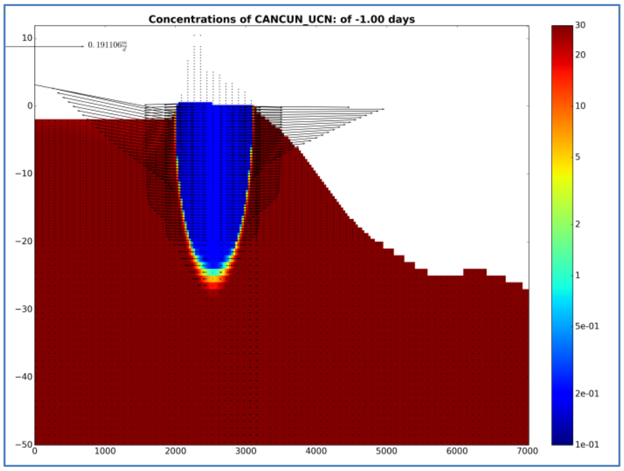
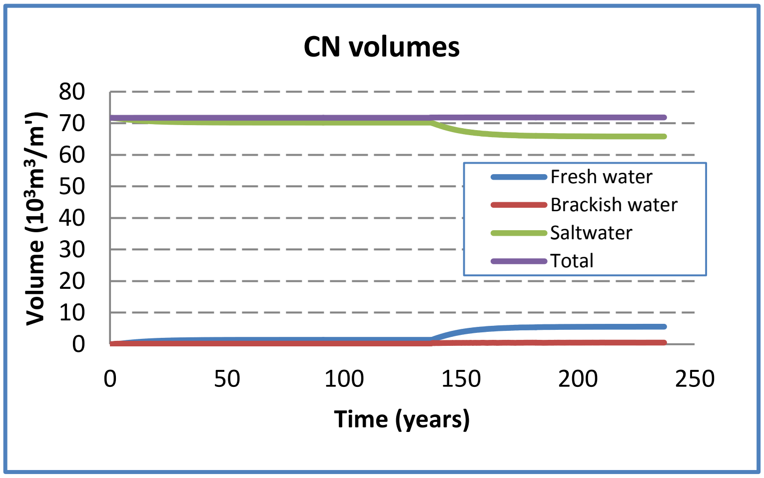


Figure 17b: Concentrations at CN after the replenishment



CN freshwater	
Volume at initial condition ($10^3 m^3/m'$)	1.38
Volume after replenishment ($10^3 m^3/m'$)	5.53
Increase in FW	***301.3%***

Figure 18: Changes in the fresh, brackish and salt groundwater volume at CN

3.3. Climate change scenarios

Three climate change scenarios consisting of sea level rise (B), increased precipitation (C), and a combination of both (D) were applied along with the sand replenishment (**Error! Reference source not ound.**). The assumed sea level rise was 0.5 m, which is within the IPCC's estimations for the year 2100 (Church et.al, 2013). For the increase in precipitation, the maximum value of recharge within the range given by WHYMAP dataset was used, which was 300 mm/year for all locations. For simplification reasons, the changes in the parameters happen instantaneously, together with the replenishment.

Table 4: Climate change scenarios

Scenario		**Sea level rise at 0.5m AMSL**	**Recharge increase at 300mm/y**
A	*Reference case*	–	–
B	*SLR*	+	–
C	*RCH*	–	+
D	*SLR + RCH*	+	+

The impact of the three climate change scenarios on freshwater volume growth, in comparison with the reference case, is presented below.

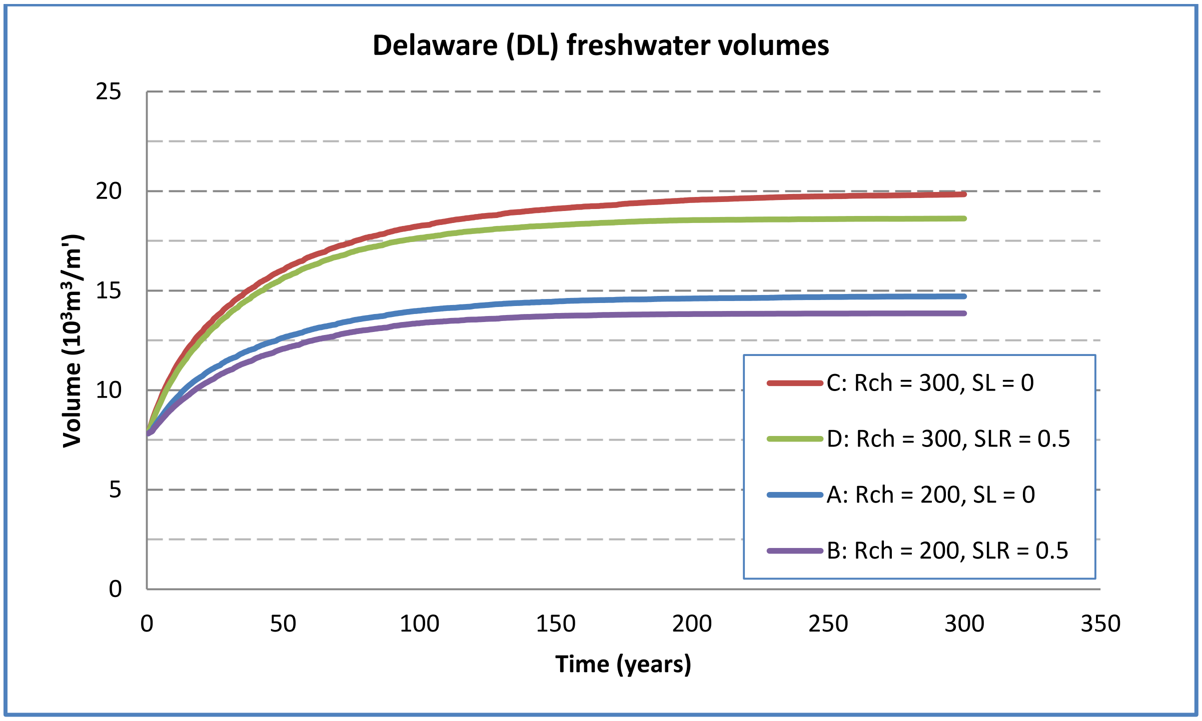


Figure 18: Delaware: changes in fresh groundwater for different climate scenarios

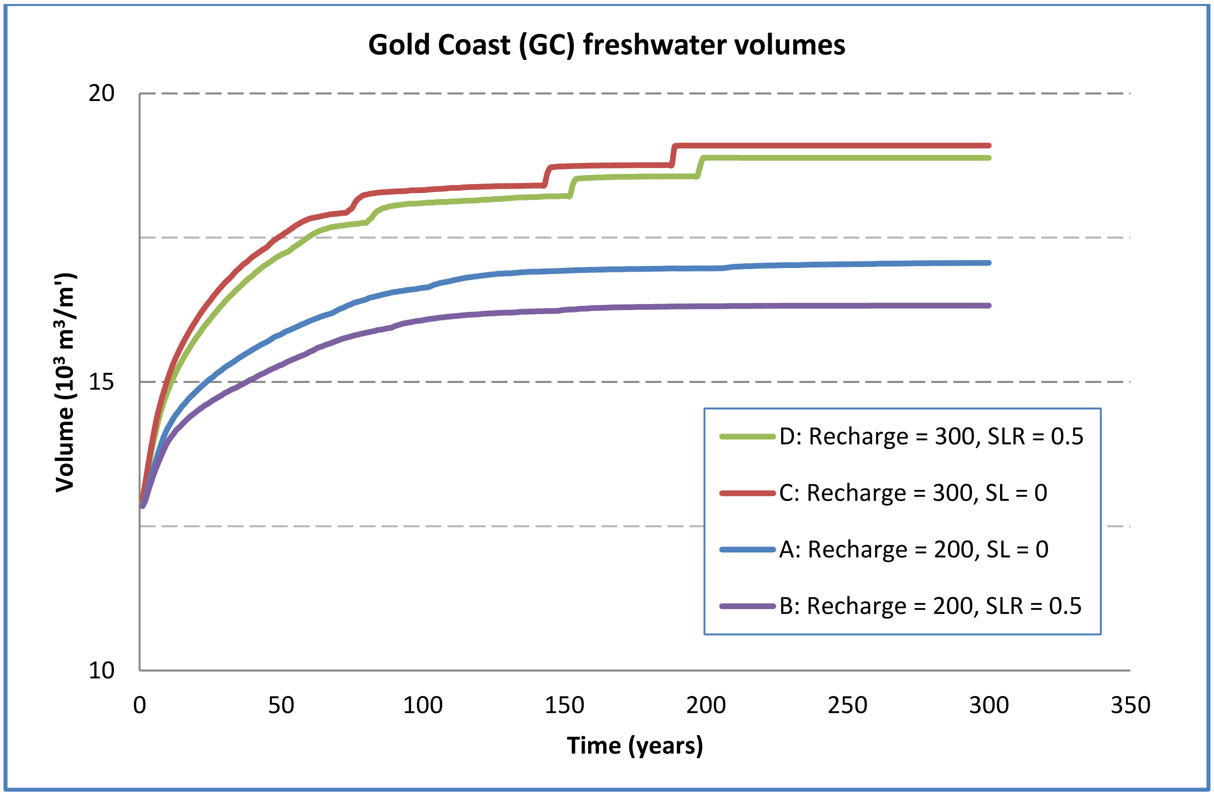


Figure 19: GC changes in fresh groundwater for different climate scenarios

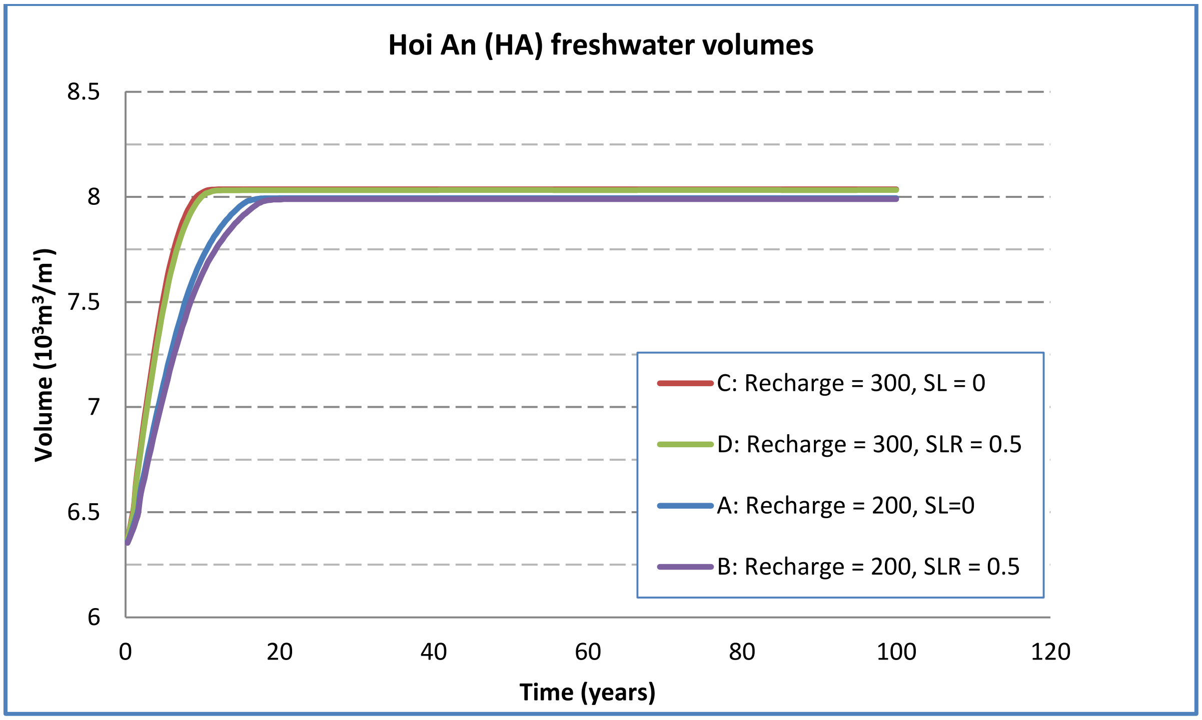


Figure 20: HA changes in fresh groundwater for different climate scenarios

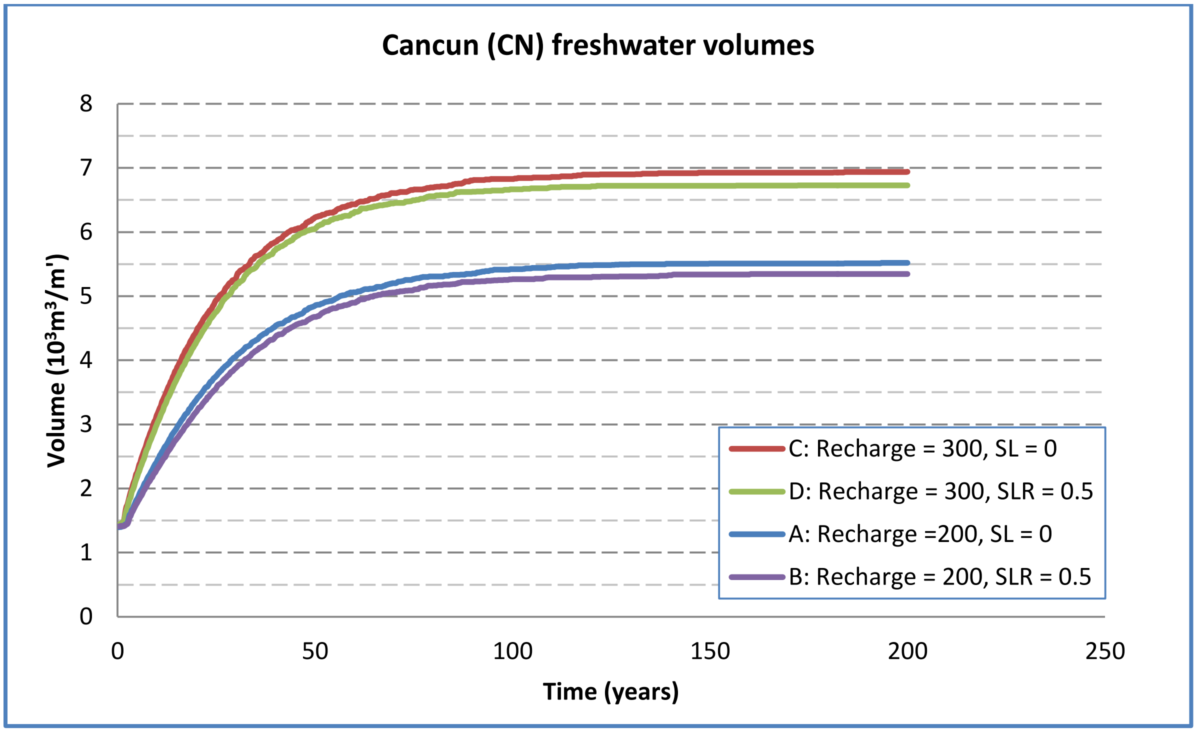


Figure 21: CN changes in fresh groundwater for different climate scenarios

Table 5: Fresh groundwater volumes for different climate scenarios

Scenarios		Freshwater volumes			
		DL		GC	
		Volume (10^3 m^3/m')	Increase/ decrease*	Volume (10^3 m^3/m')	Increase/ decrease
A	*Reference case*	14.69	-	16.97	-
B	*SLR*	13.85	-5.7%	16.31	-3.9%
C	*RCH*	19.82	34.9%	19.10	12.5%
D	*SLR + RCH*	18.6	26.6%	18.74	10.4%
Scenarios		**Freshwater volumes**			
		HA		**CN**	
		Volume (10^3 m^3/m')	**Increase/ decrease**	**Volume (10^3 m^3/m')**	**Increase/ decrease**
A	*Reference case*	7.99	-	5.51	-
B	*SLR*	7.99	-0.1%	5.34	-3.0%
C	*RCH*	8.04	0.5%	6.93	25.8%
D	*SLR + RCH*	8.03	0.5%	6.72	22.1%

(*increase/decrease compared to reference case A)

4. Discussion and conclusions

The model simulations show that a large-scale sand replenishment could lead to a growth of fresh groundwater volume by thousands of m^3 per meter of coast, in various locations around the world. The increase of the fresh groundwater volume varies significantly for each location, from 1.8 thousand m^3/m' in the shallow aquifer of Hoi An to almost 7 thousand m^3/m' in Delaware, leading to the conclusion that the increase depends highly on the characteristics of the replenishment site. The depth of the aquifer, the groundwater head, the existing amount of freshwater and the position of the fresh-saline water interface before the replenishment affect the results of each location significantly. The most defining factor is the amount of recharge, which has the biggest effect on the results, as it can be clearly seen both in the sensitivity analysis and in the climate change scenarios. The sea level rise scenarios bring a relatively small reduction of the freshwater, compared to the scenario with no changes, in all four locations.

Of course, this study has used a few simplifications. The real system is much more complex and there are quite a few parameters that have not been taken into account in this study which would have an impact on the results. For example, an average value of recharge was used; to obtain more accurate results, the exact pattern of precipitation, evapotranspiration and groundwater extraction would have to be measured and simulated. Other parameters that were not included are storms, waves and beach erosion. Inundation of the land caused by storm surges would lead to salinization of the fresh groundwater. Finally, the models assume a steady-state situation will be reached, while in reality the replenishment will have disappeared long before that, unless it's maintained.

The conclusion is that large-scale sand replenishments such as the Sand Engine can combine coast recreation and protection with a substantial growth of fresh groundwater resources. Despite the fact that the replenishment sand is supposed to be redistributed along the coast, gradually bringing it back to its original form, it could lead to a fresh groundwater growth that would last for decades, making it an appealing solution for coastal areas with limited water resources. The results of this study should be combined with research on sustainable ways to take advantage of the fresh groundwater increase while avoiding saltwater intrusion. Horizontal wells are generally preferred, as they don't cause saline groundwater upconing as easily as vertical wells do, but further investigation would be required in each location in order to determine the optimal positions and extract rates of wells in a way that salinization of the fresh groundwater is avoided.

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6. APPENDIX

Several global datasets were used to extract the data required for each location. A short overview of those sources is provided in this section.

A. GEBCO_2014

General Bathymetric Chart of the Oceans (GEBCO) is a digital bathymetric model of the world ocean floor, merged with land topography from publicly available digital elevation models (DEMs). The 2014 version, which was used in this study, incorporates regional bathymetric compilations from various bathymetry data sources as well as large amounts of collected multibeam data (Weatherall et al., 2015).

B. ETOPO1 and CRM

ETOPO1 is a 1 arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry. US Coastal Relief Model (CRM) is a 3-arc second model that also integrates topographic and bathymetric data and provides a detailed representation of the coasts of USA. Both are created by the National Centers for Environmental Information (NCEI) of the U.S. National Oceanic and Atmospheric Administration (NOAA), using data provided by various institutions (https://www.ngdc.noaa.gov/). The gridded datasets were downloaded and processed with QGIS to provide cross-sectional profiles.

C. CHW

The Coastal Hazard Wheel (CHW) is a system developed for multi-hazard assessment and management of coastal areas around the world under a changing climate. It can be used for classifying a particular coastal location, determining its hazard profile, identifying relevant management options and communicating coastal information (Appelquist and Halsnæs, 2014). Using the CHW App (http://chw.openearth.eu/) useful information can be obtained for any chosen location, such as the storm climate, sediment balance, tidal range, erosion hazard, as well as proposed measures suitable for the location, including beach nourishments.

D. WHYMAP

The World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) (BGR/UNESCO, 2008) is a joint programme of a consortium consisting of 8 organizations, with the objective of compiling global data on groundwater from various sources, and visualising them in maps, web map applications and services. The organizations participating in the WHYMAP programme are:

- UNESCO - United Nations Educational, Scientific and Cultural Organization (http://en.unesco.org/)
- UNESCO - International Hydrological Programme (IHP) (http://en.unesco.org/themes/water-security/hydrology)
- UNESCO - International Geoscience Programme (IGCP)

(http://www.unesco.org/new/en/natural-sciences/environment/earth-sciences/international-geoscience-programme)

- IAH - International Association of Hydrogeologists (https://iah.org/)
- International Groundwater Resources Assessment Centre (IGRAC) (https://www.un-igrac.org/)
- CGMW - Commission for the Geological Map of the World - Subcommission on Hydrogeological Maps (SCHYM) (http://ccgm.org/)
- International Atomic Energy Agency (IAEA) (https://www.iaea.org/)
- BGR - Federal Institute for Geosciences and Natural Resources (http://www.bgr.bund.de/EN/Home/homepage_node_en.html)

The WHYMAP available products include global and continental maps that classify groundwater resources, precipitation, groundwater recharge, river discharge, flood vulnerability and more. The continental maps of groundwater recharge, which were used in this study, depict the mean annual groundwater recharge in mm/year classified in 5 ranges (very low, low, medium, high and very high). All the chosen locations fall within the range 100-300 mm/y, characterized as high. The maps were retrieved from: http://www.whymap.org/whymap/EN/Downloads/Continental_maps/contimaps_node_en.html

E. GLHYMPS

The Global Hydrogeology Maps (GLHYMPS) (Gleeson et al., 2014) are the first set of high resolution maps that depict near-surface permeability and porosity on a global scale, by synthesizing and modifying existing databases. They are based on a global lithology map that differentiates fine and coarse-grained sediments and sedimentary rocks and categorizes the soils into 10 hydro-lithological categories. The values of porosity applied on this study were all extracted from the GLHYMPS.

F. Thickness of Soil, Regolith, and Sedimentary Deposit Layers

The Global 1-km Gridded dataset is provided by the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) is one of the Earth Observing System Data and Information System (EOSDIS) data centres sponsored by NASA. It provides estimated of the thickness of the permeable layers above bedrock, based on the landform type, within a global 30-arc second grid. The aquifer thickness values used in this study were all extracted from this dataset (Pelletier et al., 2016).