UTRECHT UNIVERSITY

Securing freshwater supply with measures to diminish the effect of sea-level rise by climate change

Literature review on state-of-art SWI research and a case study on SIDS in the Pacific

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Abstract Climate change will have a significant negative impact on fresh groundwater quantities in every area of the globe. A literature review of the Salt Water Intrusion Meetings (SWIM) papers was conducted to survey the state of research into water security issues where saline groundwater affects freshwater resources. From this literature review a lack of research relating to SIDS (Small Island Developing States) in the Pacific Ocean was uncovered. We therefore undertook a study is set up of SIDS. Deltares have been conducting research into the topic of securing fresh groundwater resources, and have found a possible solution; the seepage provision. Several models were created using PMWIN, representing the following scenarios; a reference scenario; a scenario accounting for sea-level rise; and a scenario accounting for the introduction of the seepage provision system. Further models were also created to investigate the outcomes of applying alternative measures. The results show that the provision system requires a water extraction rate that is too great for application to these islands. We therefore advise the use of other measures such as beach nourishment and ASR.

Keywords: groundwater, fresh water resources, climate change, measures, SWIM, sea-level rise, variable-density groundwater model, SIDS, Pacific, Deltares

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1. Introduction

This report has been written as the Bachelor thesis of the study Earth Sciences at Utrecht University. The aim of this research is to test one possible technical solution to the water security problems that climate change poses to fresh groundwater quantities found in Small Island Developing States (SIDS).

Before commencing with this research, first a literature review has been performed of the Salt Water Intrusion Meetings (SWIM) papers that have been published since 1968, because it was necessary to get acquainted with water security issues in coastal zones where saline groundwater affects freshwater resources. Since this date 1968, experts have come together to exchange ideas and discuss problems relating to saline groundwater. A database has been compiled with key features of each paper listed at the SWIMs. If possible, geological information was extracted, because it is of particular interest for fresh saline groundwater issues. The database clearly indicates that to this date there exists a lack of research on the fresh-saline groundwater conditions of islands; particularly of SIDS in the Pacific Ocean. We have therefore established a study focusing on SIDS with the aim of attempting to diminish the problems related to water security that these islands face due to climate change and global change. Now that the population is also growing, even extra extraction of fresh groundwater is needed. The database itself will be discussed in further detail in the section, “Literature review”.

Climate change will have a significant negative impact on fresh groundwater quantities in every area of the globe. SIDS are particularly vulnerable to the threats that CC poses, since there are little to no actions executed to prevent this threat sea-level rise will have on the freshwater reservoirs. There are approximately 50,000 islands located in the Atlantic, Indian and Pacific Oceans. These islands have a total population of 18 million people, whilst the land area that they occupy is very small, amounting to less than 100 km^2, often with a maximum island width of 3 km. Many of these islands have relatively high rainfalls but with evaporation increasing rapidly due to global warming, these islands are often already experiencing severe droughts (Ian White et al. 2006), let alone in future circumstances. Current climate models (GCMs – Global Climate Models) are too inaccurate to estimate the real effect that climate change has on these islands, since the models are based on grid-like division of 240 by 210 km. This makes these small islands disregarded by the calculations (K. B. Karnauskas et al. 2016).

In this research the focus will lie on the SIDS of the Pacific Ocean in particular (figure 1). These islands are very diverse in their geography and all belong to some of the most remote countries in the world. There are 1000 inhabited islands with a combined population of 2.3 million people. This is 12.8% out of the overall 18 million people living on SIDS around the world. Most of these islands are extremely small indeed, comprising a land area of less than 10 km^2 and with widths of 1 km or less. As population density can be as high as 12,000 people/km^2, the lack of freshwater becomes a major issue (White and Falkland, 2010).

Rising sea-levels will place pressure on both the extent of fresh groundwater reservoirs as well as on its quality, posing risks to health, including an increase of insect-borne diseases (The World Bank, 2016 & Kelman & West, 2009).

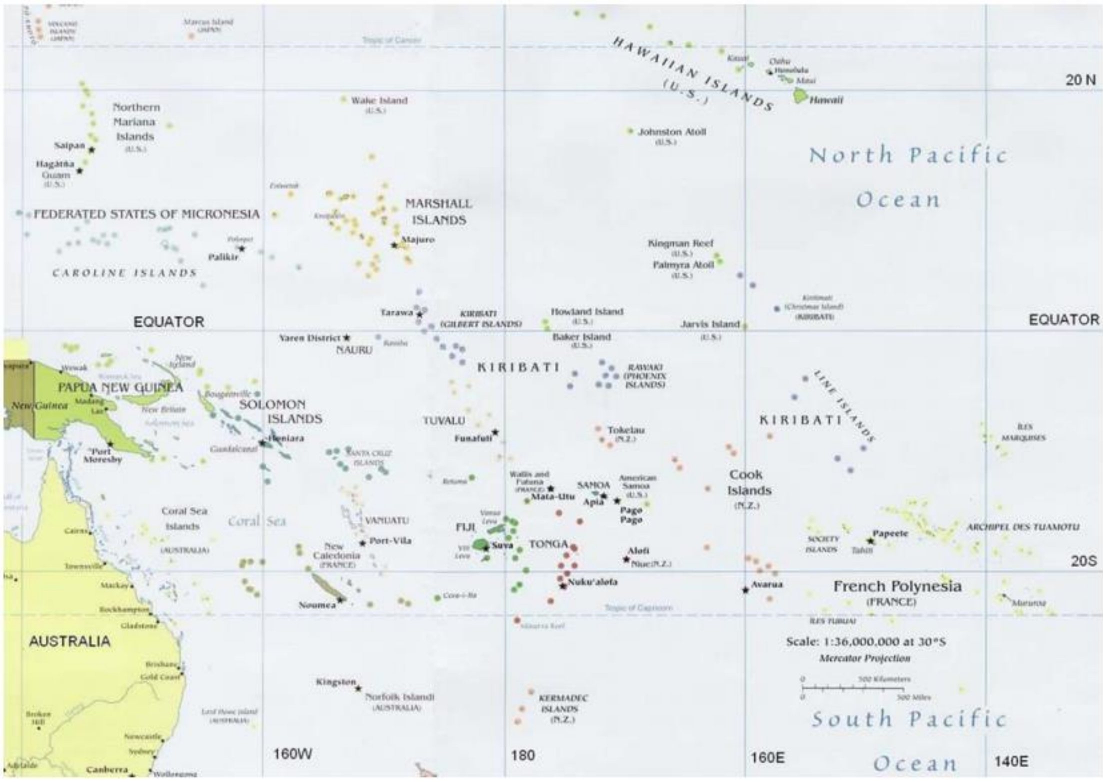


Figure 1 Small island countries in the central and southern Pacific Ocean (White & Falkland, 2009)

As people living on SIDS rely on fresh groundwater as the source for all domestic purposes, as these island do not have excess to fresh surface water at large extent, further research is therefore needed of what we consider the impact that these water sources will suffer due to climate change. Water scarcity, which will increase in the future, is capable of threatening the very survival of these peoples (Bailey et al. 2009).

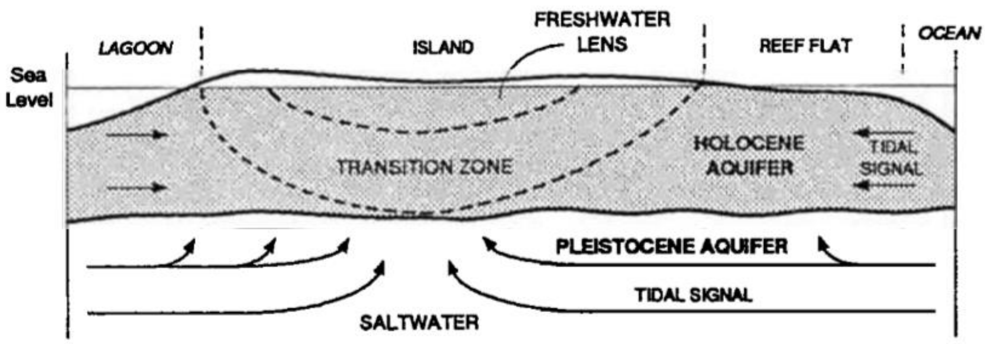


Figure 2 Cross-section groundwater lens on two-layer atoll island (Underwood et al., 1992)

Though regular continental islands exist in the Pacific Ocean (e.g. New Guinea, Solomon), a significant proportion of Pacific Islands consist of low-lying atolls, which reach only a few meters above sea-level (United Nations, 2009). Overall there are 294 atoll islands in the Pacific, which are defined by a set of unique geological features. These islands are composed of circular chains of small coral islands which enclose shallow lagoons, and possess thick sedimentary sequences accumulated on top of a submerged seamount of volcanic origin (Bailey et al. 2009). Especially the uppermost few tens of meters of the sedimentary sequence are of hydrogeologic significance, constituting the Holocene aquifer. Beneath these atoll islands, fresh groundwater accumulates as a lens, which is separated from the underlying seawater by a thin transition zone of mixed water (figure 2). The upper aquifer is often composed of 20 to 30m of unconsolidated sands, gravel and silts and possesses a moderate permeability (Underwood et al. 1992).

Deltares (a Dutch independent institute for applied research in the field of water and subsurface) have been conducting research into this topic of securing fresh groundwater resources on SIDS, and have tested a potential technical solution in the Netherlands, Zeeland. This solution is capable of diminishing the effects of rising sea-levels on fresh groundwater. Their results are promising. The technique appears to work effectively. This method, which is called "Kwelvoorziening" (translates to: "seepage provision") will be quantified to calculate the effectiveness of this method on SIDS. This will be performed using the PMWIN (processing MODFLOW) software. Our methodology will be further explained in section "Modelling method".
Then the results will be presented. In the Discussion, problems or inaccuracies of the models and the input data that have been chosen will be given with suggestions for improvements for further studies. Finally, some conclusions with the focus on the effectiveness of the method are stated. The circumstances that affect the freshwater volume will be discussed. Should the model demonstrate results which correspond to those that are measured in the field at the seepage provision, then this technical solution will be communicated at this year's SWIM in Australia.

2. Literature Review and Modelling Method

2.1 Literature Review

SWIM-database

The literature review that has been performed took a period of around 5 weeks out of 12 weeks. In this time, all 600 published SWIM proceedings papers (up till the year 2008) have been analysed with the aim of extracting key summary information. Most papers are digital available on www.swim-site.org. Such information includes: the country where the investigation took place; year of publication; topic; geological information; and, where present, the type of model that is used. The topics are: Descriptive, Modelling, Calculations, Geophysical, Chemical, Study and Survey methods, Prevention and Climate Change.
The geological information includes aquifer type, aquifer layers, and number of clay layers if present. The complete database can be found in Appendix 1.
The geological information was of particular interest, as researchers require this data in order to understand the geological structure of an area in order to better understand its hydrogeological system within the context of salt water intrusion.
In figure 3 the locations are indicated with coloured dots where the research from each paper was conducted on. Green dots represent papers which I have reviewed, whilst red dots represent the papers reviewed by Eleni Bampalouka (research intern at Deltares) and Daniel Zamrsky (PhD student at Utrecht University), in collaboration with whom this database was compiled.

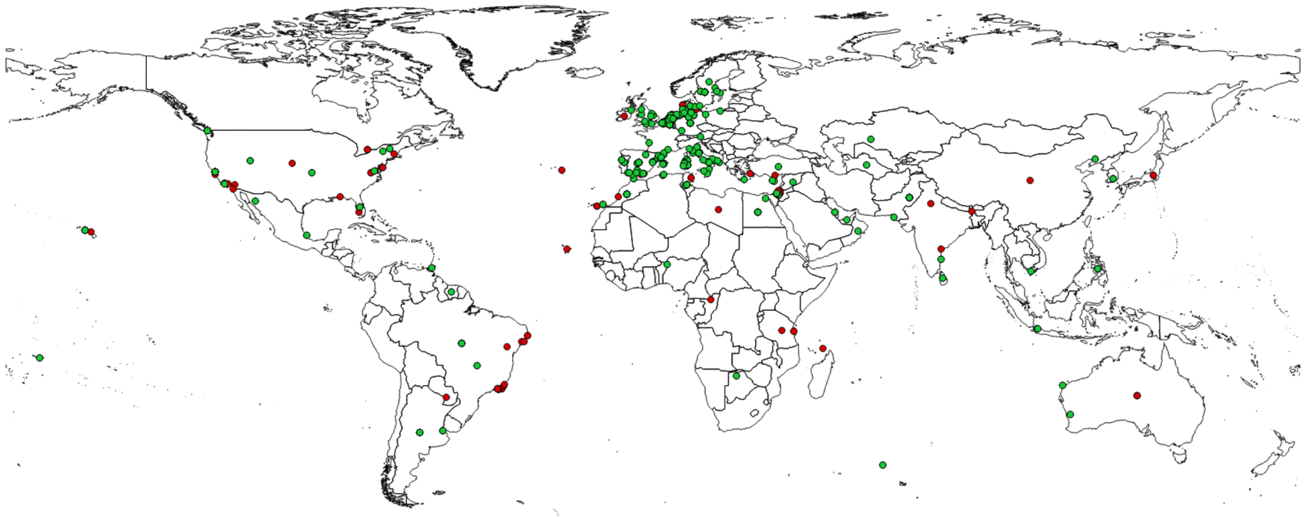


Figure 3 Map with research area of each paper in the database. I started with the first 400 SWIM proceedings papers, in which most studies were conducted in Europe, thus ending up with most green dots in Europe.

From the map it is visible that there have been only a very limited amount of papers published on salt water intrusion problems of islands, especially the Pacific. Therefore it is decided to set up a study on SIDS in the Pacific, also as they appear to be the most vulnerable areas prone to sea level rise.

For this case study several scenarios and alternatives will be created. Two scenarios will be set up to get an idea of how much fresh groundwater is available now, and to see the effect of sea-level rise on the fresh groundwater reserves. Another scenario is when the provision system has been applied. Also some alternative models will be created, which will give more insight in what the effects will be of several measures on the fresh groundwater reservoir. As this is important for drinking water purposes, the most effective measure would be considered to apply to these islands. The method of the modelling will now be explained.

2.2 Modelling Method

The research was conducted over a period of 7 weeks using the variable-density groundwater flow and coupled solute transport code SEAWAT within the PMWIN modelling software.

<u>Scenarios</u>

Three future scenarios were created; Scenario A, a reference scenario with no sea-level rise; scenario B, which incorporates increasing sea-levels; and scenario C, with sea-level rise and the seepage provision, as being an effective measure against the impact of sea-level rise, accounted for. Each different scenario has been modelled with two different values for each of the variables: hydraulic conductivity, recharge and height of the island; giving a total of 8 (2^3) models per scenario. The width of the island remains constant across all scenarios, so effects of erosion is left out. Based on the paper of White and Falkland, 2010, an average of width of 1 km has been applied.

<u>Model concept</u>

In figure 4 below, an image is shown of what the model looks like. The boundary conditions of the models are given in table 1. This will also be given in the factsheet (Appendix 2). The pixels are 10 meters wide and 2 meters in length. So to indicate the island in the model, which is 1 km wide, the cells from 251 to 350 are made inactive with '0' for the 'General Head Boundary'. This is the setup of each model. Although, in figure 4, the wells are shown in red, this is not present for the scenarios A and B.

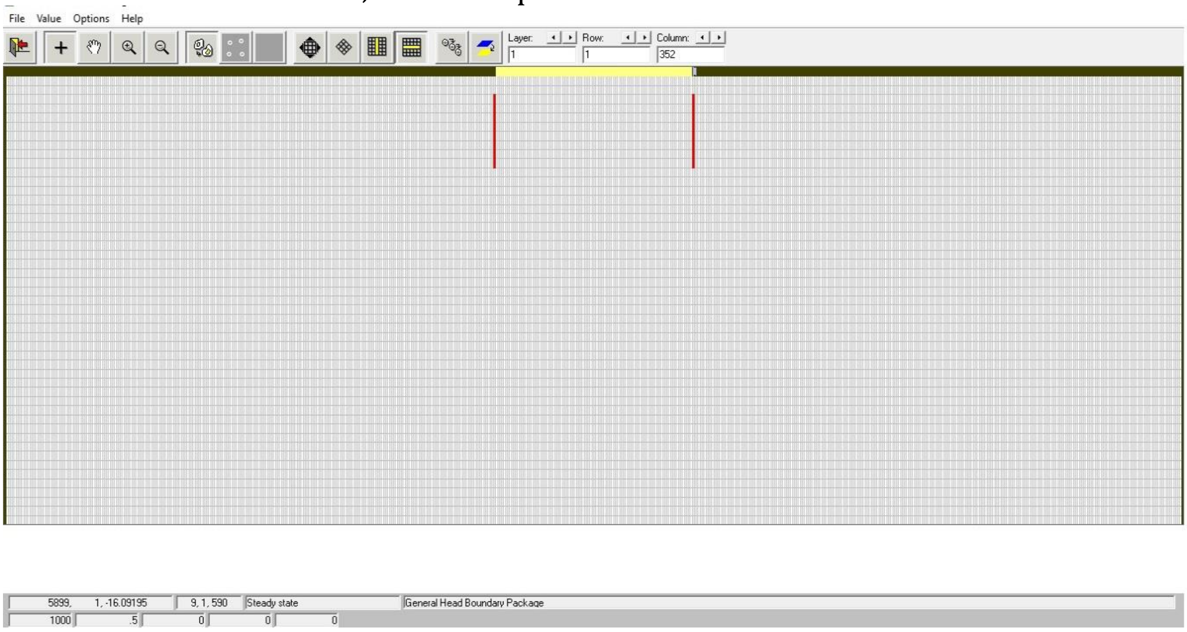


Figure 4 Image of view the model. The colours indicate; Red: the wells of scenario C, yellow: the island, Black: the sea

Model		**MODFLOW**			
General information		General Head Boundary Package			
Width:	6 km	Boundaries:	1000 L^2/T		
Depth:	100 m	251-350:	0 L^2/T		
		MT3DMS/SEAWAT			
Simulations setting		**Advection**		**Dispersion:**	
Salt (TDS g/l)	Density On	Max. Particles	6000000	0.1	
DRHODC:	0.7143	NPL	16	**Diffusion coefficient:**	
		NPH	27	0.0000864	L^2/T
		NPMIN	16		
		NPMAX	27		
Width:	**1 km**	**Effct. Porosity:**	**0,2**	**Drain HC:**	1000 L^2/T

Table 1 Boundary conditions of each model (where T = day)

Further to these three main scenarios, we have also created additional conceptual models. In these additional models we have only applied a single set of variables, with the same aim of calculating what effect a combination of different measures would have on the fresh groundwater volumes. This is explained in more detail under the subsection, “Alternative models”.

The parameters that are chosen for the models are explained here.

- In all the models, the horizontal (K_h) and vertical hydraulic (K_v) conductivity are distinguished. Considering a sandy island, K_h is chosen as 5 m/d and K_v is 0.5 m/d. And for an island in a coral setting, with no fine sand nor clay is present in the soil K_h would be 50 m/d and K_v 1 m/d. These values are based on the paper of Bailey et al. (2009). However the values for the sandy island have been estimated based on the general characteristics of sandy soils.

- Two different natural groundwater recharge values are chosen to represent the variation in recharge over the two different climates: a dry climate and a wet climate setting. The papers of Bailey et al. (2009) and Underwood et al. (1992) give more information on the degree of recharge on these islands and present an annual rainfall ranging from 0.5 m to 3.75 m. Values of 1m and 2m a year are chosen to represent the difference between the two climate settings. However these values have been reduced by 3.98 mm/d to 4.73 mm/d since evapotranspiration has a significant effect on decreasing the amount of natural groundwater recharge. In the end we have settled on values of 1.5 mm/d and 0.75 mm/d for the purpose of our models.

- Furthermore, calculations have been performed using ArcGIS to find the elevation distribution in SIDS (figure 5). This is important as when sea-level rise occurs, the piezometric head and groundwater level want to follow. However, if the DEM is not high enough this will severely hinder the adaptation of the freshwater lens to a new dynamic equilibrium, and thus significantly reduces the size and volume of the lens. The most frequent elevation lies between 0 to 120 m. The complete list with the elevation data of these islands is included as Appendix 3. In figure 6, there is also map with the DEM of several islands that we have zoomed in to. For an island with a width of 1 km, a height of 1.5 and 3 meters would be most likely to occur. Therefore these values are applied. The shape of the DEM (digital elevation map) of

the island is created as a parabola. The formulas for the island are:
$y = -0.0006(x-50)^2 + 1.5$ (For the 1.5 m height)
$y = -0.0012(x-50)^2 + 3$ (for the 3.0 m height)
A drain package is included where these values are inserted. From this height the water will be drawn off. The conductance of this 'synthetic' drain is very high and the level of the drain is equal to the DEM parabolic shape.

Table 2 provides all the parameters that have been used for each model (also given in Appendix 2).

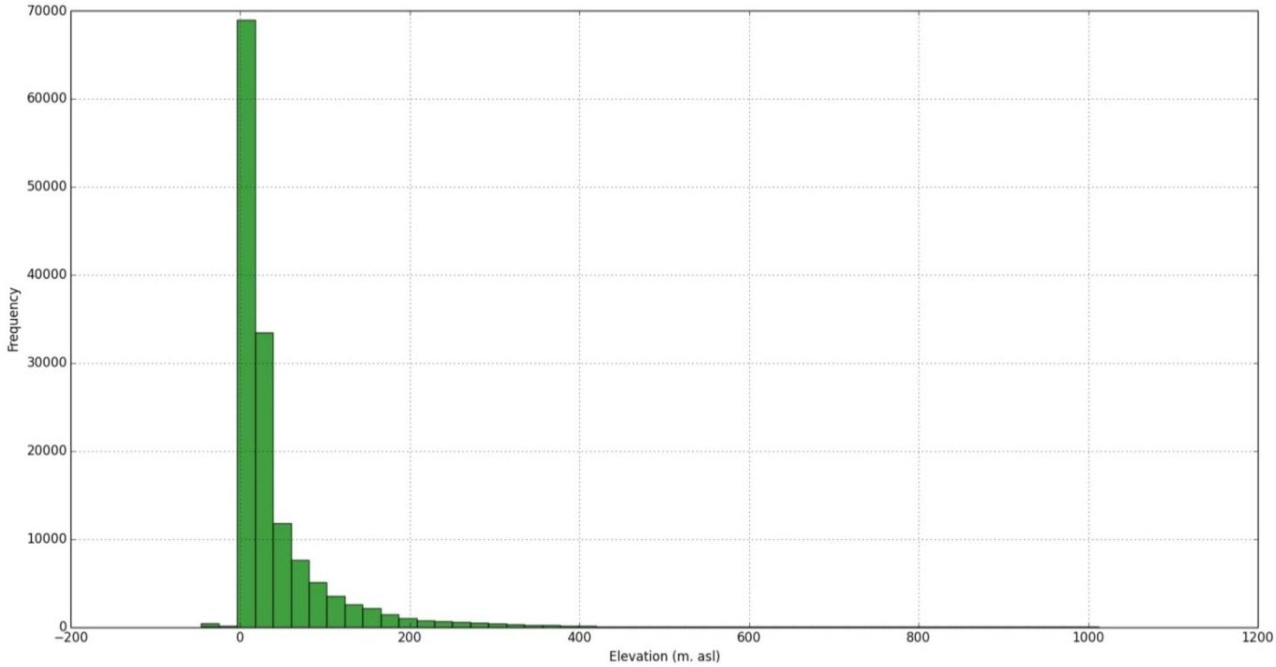


Figure 5 Elevation value distribution in SIDS which are smaller than 10 km^2 in the Pacific Ocean.

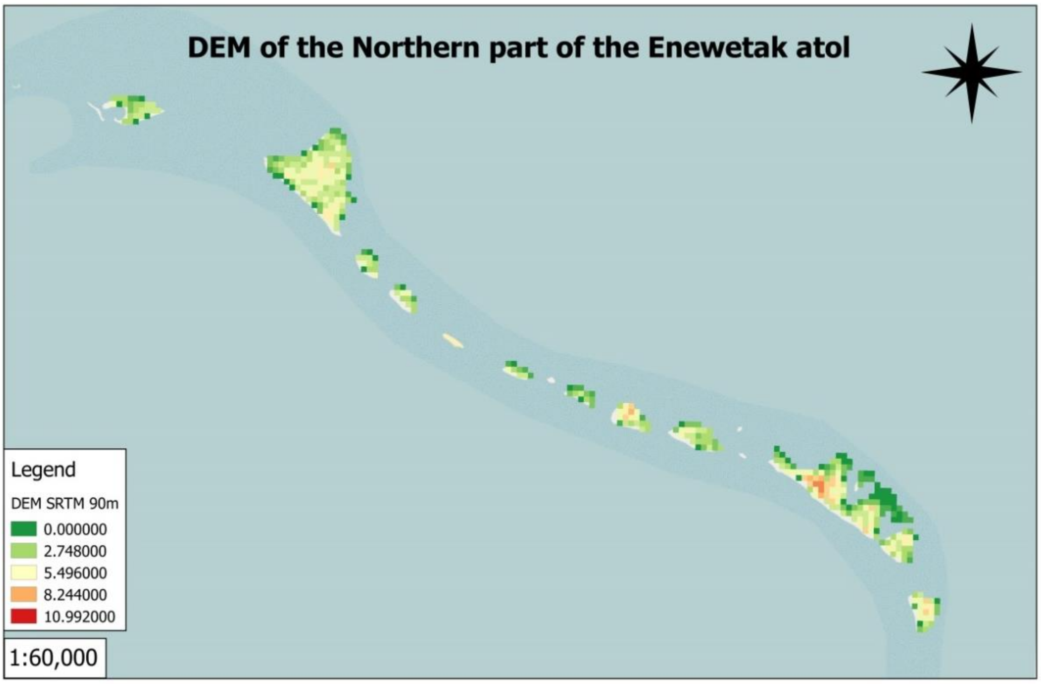


Figure 6 DEM of the Northern part of the Enewetak atoll. For most these islands the elevation lies between 0 to 5 meters.

The different scenarios that are created will now be further discussed.

- **Scenario A** is the reference situation. This scenario gives an indication of how long it takes for the freshwater lens to develop until it eventually stabilises: the so-called dynamic equilibrium. This depends on the parameters that have been used for the model; the periods are variable from 100 to 250 years. The concentration distribution of the equilibrium situation will then be used as the initial concentration for the models of scenarios B and C.
- For **scenario B** a sea-level rise of 0.5 meters is applied, to calculate what effect this will have on the freshwater volume.
- **Scenario C** is when there is a sea level rise of 0.5 meters whilst also the seepage provision method of Deltares is active. This will be further explained.
  Commissioned by Rijkswaterstaat (agency of the ministry of Infrastructure and Environment), 75 ha of land is added to the outer dike area of the Westerschelde (Zeeland, the Netherlands), called 'Perkpolder'. On the 25th of June in 2015, an entrance has been created in the existing dike. From that moment on the water from the Westerschelde is influenced by tides, the water will therefore stream in and out of Perkpolder.
  This unique and innovative method, which is the seepage provision system, is able to protect the fresh groundwater in the aquifer from getting affected by the saltwater intrusion. The excessive amount of saltwater is removed through pipes that have been drilled into the ground. Figure 7 gives an illustration of how this system works. In Perkpolder there are 61 pipes installed, which reach a depth of 17 meters and are connected to each other with horizontal pipes that lead to several control wells. These wells are used for regulating the operation of this provision system. After a period of intensive testing, it proved that it works very efficiently.
  It is able to diminish the effect of sea-level rise, and may even increase the freshwater amount (Deltares, 2016).

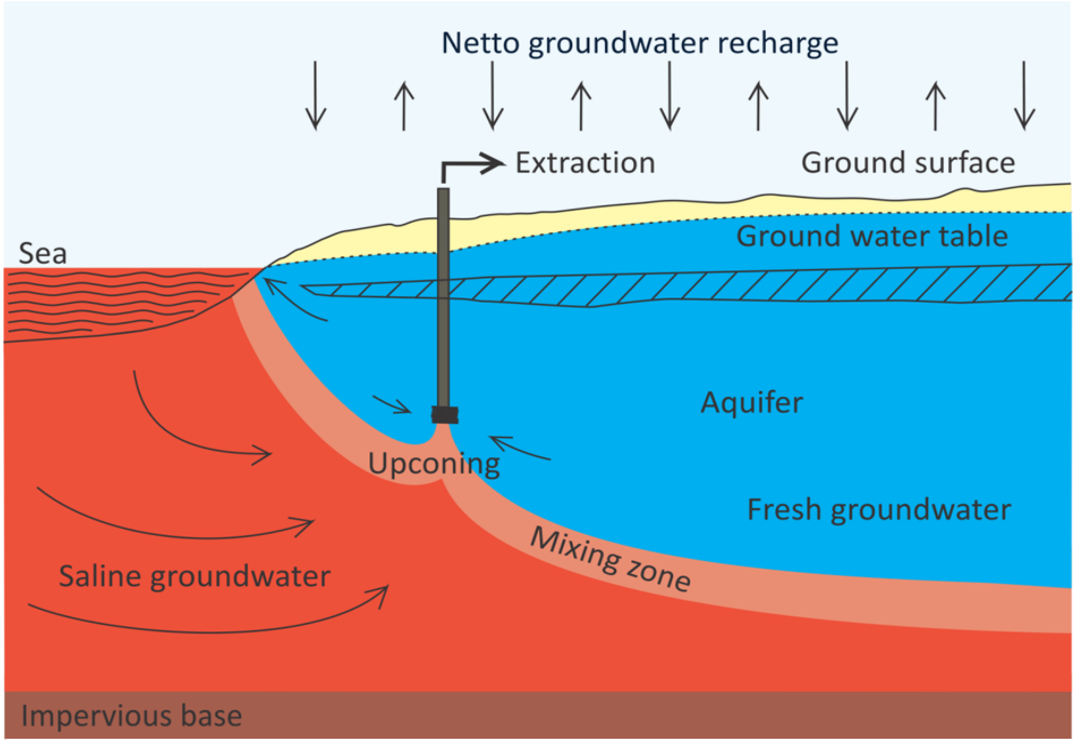


Figure 7 Illustration of the working of the Seepage Provision system of Deltares (Oude Essink, 2016)

In the model itself, this provision system has been inserted as wells that extract the saltwater from the subsoil. The exact amount and position where they have been placed can be found in table 2. The codes that have been given to these models, which represent the parameters that have been applied, can also be found in the same table and Appendix 2.

		Parameters		**Models**					MT3DMS/SEAWAT
		Parameters		MODFLOW (flow packages)					Output frequency
Code	**Topic**	Kh (m/T)	Kv (m/T)	Elevation (m)	Recharge (m/d)	Max. el of the Drain (m)	Wells	*Depth (m) & position*	*Years*
sidsA110	Reference	5	0,5	0	0,00075	1,5			200
sidsA111	Reference	50	1	0	0,00075	1,5			100
sidsA120	Reference	5	0,5	0	0,0015	1,5			200
sidsA121	Reference	50	1	0	0,0015	1,5			100
sidsA210	Reference	5	0,5	0	0,00075	3			250
sidsA211	Reference	50	1	0	0,00075	3			100
sidsA220	Reference	5	0,5	0	0,0015	3			250
sidsA221	Reference	50	1	0	0,0015	3			100
sidsB110	SLR	5	0,5	1	0,00075	1,5			200
sidsB111	SLR	50	1	1	0,00075	1,5			100
sidsB120	SLR	5	0,5	1	0,0015	1,5			200
sidsB121	SLR	50	1	1	0,0015	1,5			100
sidsB210	SLR	5	0,5	1	0,00075	3			250
sidsB211	SLR	50	1	1	0,00075	3			100
sidsB220	SLR	5	0,5	1	0,0015	3			250
sidsB221	SLR	50	1	1	0,0015	3			100
sidsC110	SLR+M	5	0,5	1	0,00075	1,5	16; -0,6	4 - 11 at 250 & 351	200
sidsC111	SLR+M	50	1	1	0,00075	1,5	16; -0,6	4 - 11 at 250 & 351	100
sidsC120	SLR+M	5	0,5	1	0,0015	1,5	16; -0,6	4 - 11 at 250 & 351	200
sidsC121	SLR+M	50	1	1	0,0015	1,5	16; -0,6	4 - 11 at 250 & 351	100
sidsC210	SLR+M	5	0,5	1	0,00075	3	16; -0,6	4 - 11 at 250 & 351	250
sidsC211	SLR+M	50	1	1	0,00075	3	16; -0,6	4 - 11 at 250 & 351	100
sidsC220	SLR+M	5	0,5	1	0,0015	3	16; -0,6	4 - 11 at 250 & 351	250
sidsC221	SLR+M	50	1	1	0,0015	3	16; -0,6	4 - 11 at 250 & 351	100

Table 2 The codes and parameters that are used for each model

2.2.1 Alternative models

For model A110 there are four different alternative models created.

- **X:** The first conceptual model is when the sides of the island will get submerged by the sea-level rise of 0.5 m. This would cause the island width to decrease to the point where the elevation will exceed the 0.5 m.

- **ASR:** The second alternative is “Aquifer Storage and Recovery” (ASR) is the re-injection of freshwater back into an aquifer for recovery and use. The GO-FRESH project (www.go-fresh.nl), is a project where certain measures are taken to restore the aquifer by inserting freshwater into it.
  One method is CARD (controlled artificial recharge and drainage), where fresh surface water as artificial extra rainfall is added to increase the freshwater storage in the aquifer (Pauw, P.S et al., 2015).
  So in this alternative the rainfall will be increased with 80% from 0.00075 m/d to 0.00135 m/d.

- **WIDTH:** The third model is when beach nourishment is applied; widen the island by adding sand along the beaches. The width of the island in the model is estimated to increase with 100 m. A new formula has therefore been applied to create the parabola shape again, which is: $y = 0.00049587*(x-55)^2 + 1.5$

- **Z:** The fourth model is actually the same method that has already been applied to the scenario C models. But this time, the aim is to find a certain location and amount of extraction that will increase the freshwater volume with 10% relative to the reference situation.

So there are three alternative measures undertaken in the cases AL110-ASR, AL110-WIDTH and AL110-z, except AL110-x, where there has been no any influence of humans. In table 3 the legend of the alternative models is provided.

Model	Description
AL110-x	Decrease island width till the elevation lower than 0.5 m
AL110-ASR	ASR – Increase recharge with 80%
AL110-WIDTH	Increase island width with 100 m
AL110-z	Increase freshwater volume with 10% relative to the reference level using extraction wells.

Table 3 Legend alternative models for 110.

3. Results

The results of the modelling will be presented in the observation part. In this section the graphs of the total amount of freshwater will be given and the differences that is found between the scenarios and the alternatives in tables. In the interpretation, the observations will be shortly explained and a conclusion will be drawn. Also the total amount of people that are able to live on the island will be calculated regarding to the freshwater amount that is present from the rainfall. To calculate the volume it is necessary to multiply the values given by the model to the length of the island. There is little information available on the length of islands from articles, but it has been estimated to be around 3 km for our 1 km width island concept.

3.1 Observations

The observations from the results of the modelling will be divided into three parts; the first two parts are the two heights which are chosen for the islands. The third part would be the alternative models. The first part gives the values of the freshwater amount for a height of 1.5 meter. The second part gives the values for a height of 3 meter. Eventually, the differences between both parts will be discussed.

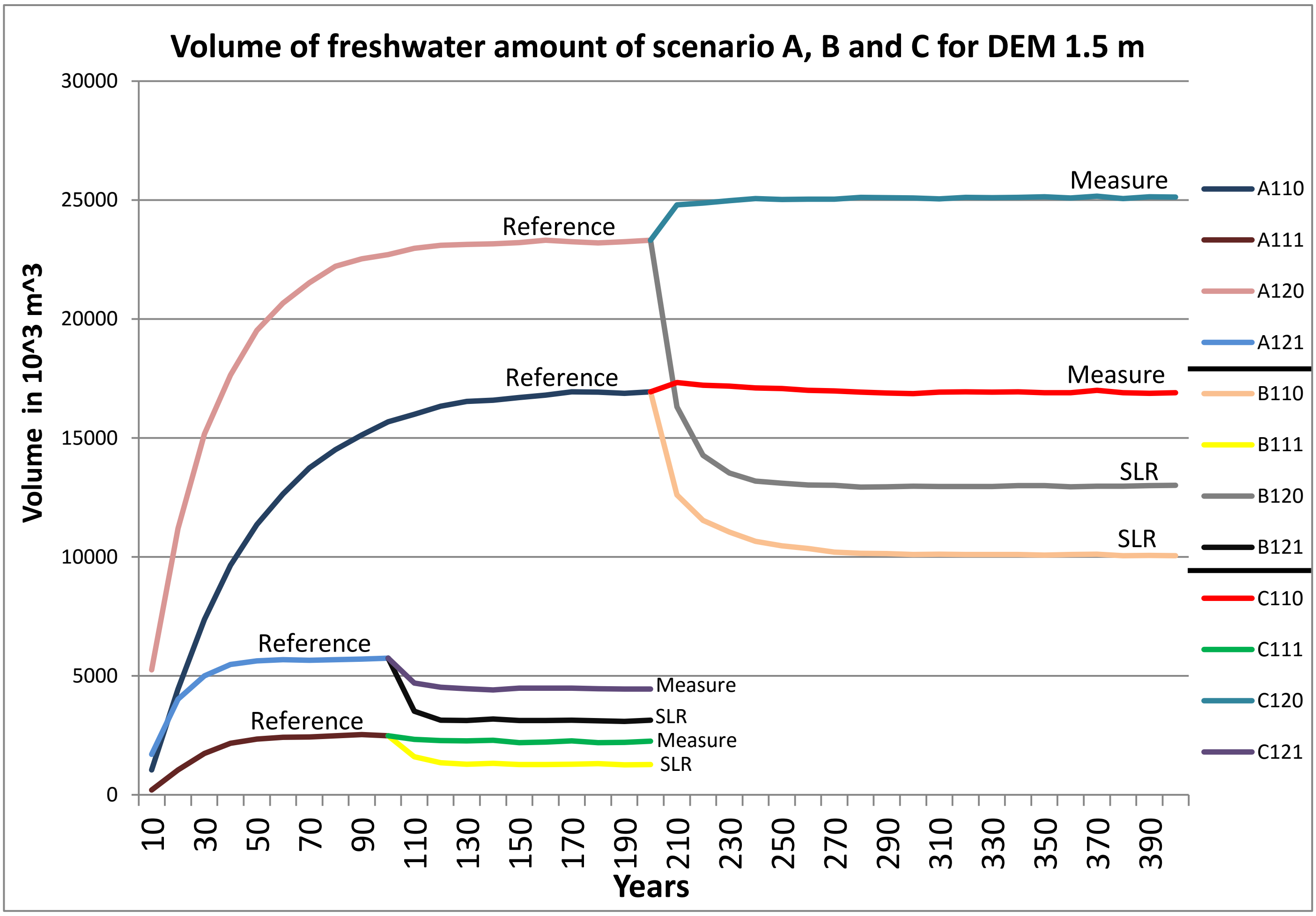
The model gives results in 10^3 m^3/m' for the freshwater amount; per stretched meter or m' represents the volume as a cross-section (2D view). Therefore, as mentioned earlier, to calculate the total volume of freshwater on the island, the length of the island (3 km) is multiplied by these values.

For each different conceptual model of the reference situation, depending on the parameters, it takes a certain amount of time till it reaches a stabilization of the freshwater lens. The model will run till it reaches this stabilization (the dynamic equilibrium), with time steps of 10 years. As mentioned earlier, the concentration distribution at the final stage of stabilization of the reference situation will then form the initial concentration for the scenarios B and C.

For model C, wells from which groundwater is extracted are included in the model. 16 extraction wells have been placed in each model which extracts each 0.6 m^2/d, which is a total of 16*0.6 = 9.6 m^2/d. Tables will be given with the ratio between the recharge and the discharge of the extraction of each model of scenario C. This will make it possible to conclude on the possibility of applying this system on the islands.

3.1.1 Part 1: 1.5 meter height

The results include a graph with the total amount of freshwater volume, and how it developed through time. Also a 2D view of the concentration distribution at the final stage of the cases B and C are provided. Also table 4 is given with the legend of the models, to make it easier to understand the case codes seen in the graph.



Graph 1 Volume of the freshwater amount of Scenario's A, B and C for DEM 1.5 m

Scenario	DEM (m)	Recharge (mm/d)	Kh/Kv (m/d)
A = Reference situation	100 = 1.5	10 = 0.75	0 = 5/0,5
B = SLR	200 = 3	20 = 1.5	1 = 50/1
C = SLR + measure			

Table 4 Legend for numbering models for the scenarios A, B and C

The first general observation from graph 1 is that for the reference situation, it takes the models A111 and A121 some 100 years to stabilize, while the models A110 and A120 needed some 200 years. After this stabilization, the sea-level rise causes the volume to drop down quite rapidly, within some tens of years, till it also reaches its stabilization. For the scenario C graphs, it is visible that it reaches its dynamic equilibrium quicker and lies closer to the reference situation, and for C120, it even reaches above the reference level.

In figure 8, the freshwater lens is visualised in the images for the cases B110, B111, B120 and B121. This can be compared with figure 9, where the freshwater lenses of the cases C110, C111, C120, and C121 are presented.

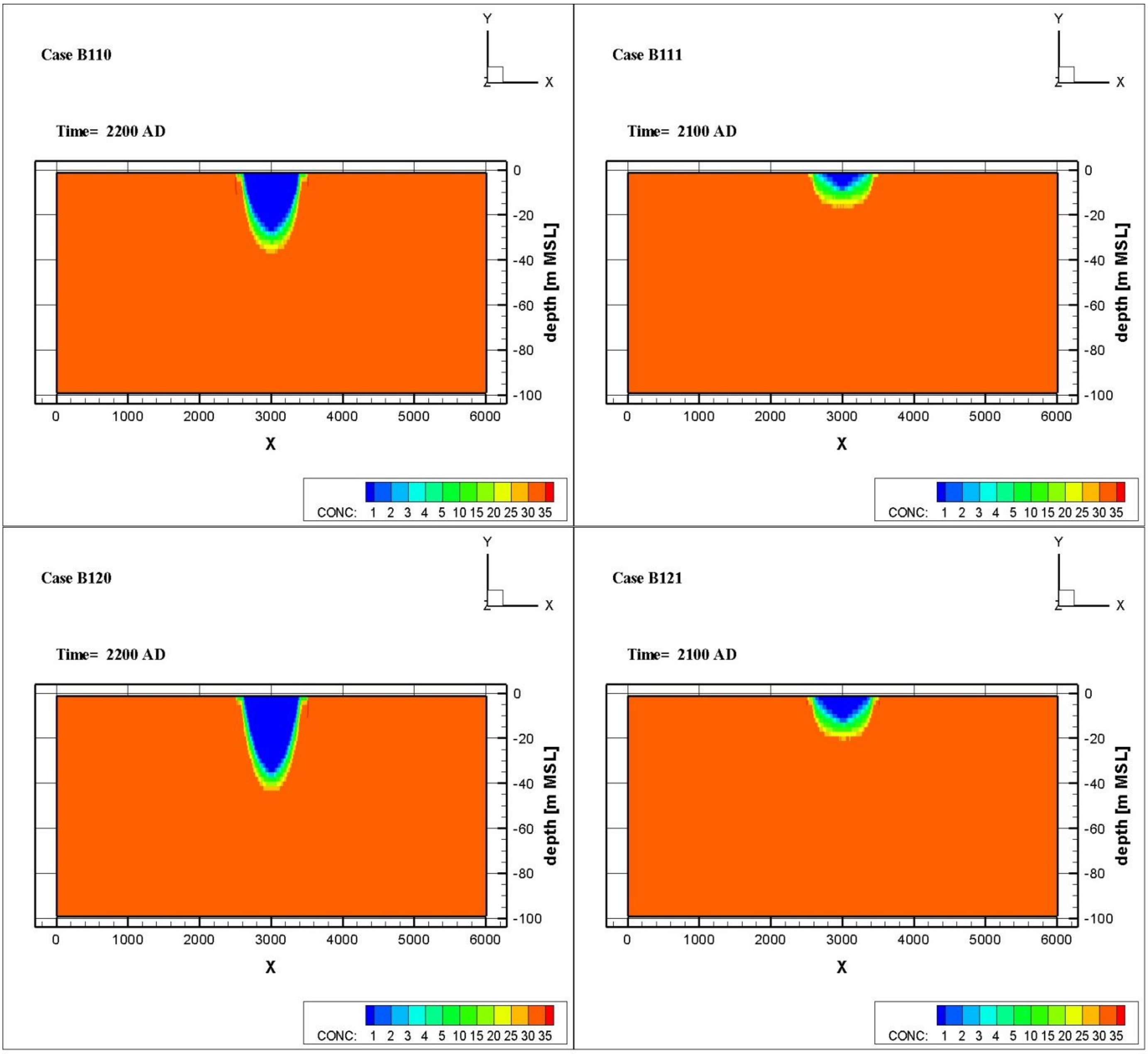


Figure 8 2D view of the final stage of each case with an elevation of 1.5 m for scenario B

Figure 8 also shows that the largest freshwater amount is found for the cases with small hydraulic conductivities (B110 and B120). These lenses reach a depth of around 25 to 38 meters deep, when only looking at a concentration of around 1 to 2 g TDS/L. Whilst for the cases with large hydraulic conductivities (B111 and B121) it will not exceed the 20 meters. The transition zone seems to be relatively larger for these cases, and the lens developed more in width rather than in length.

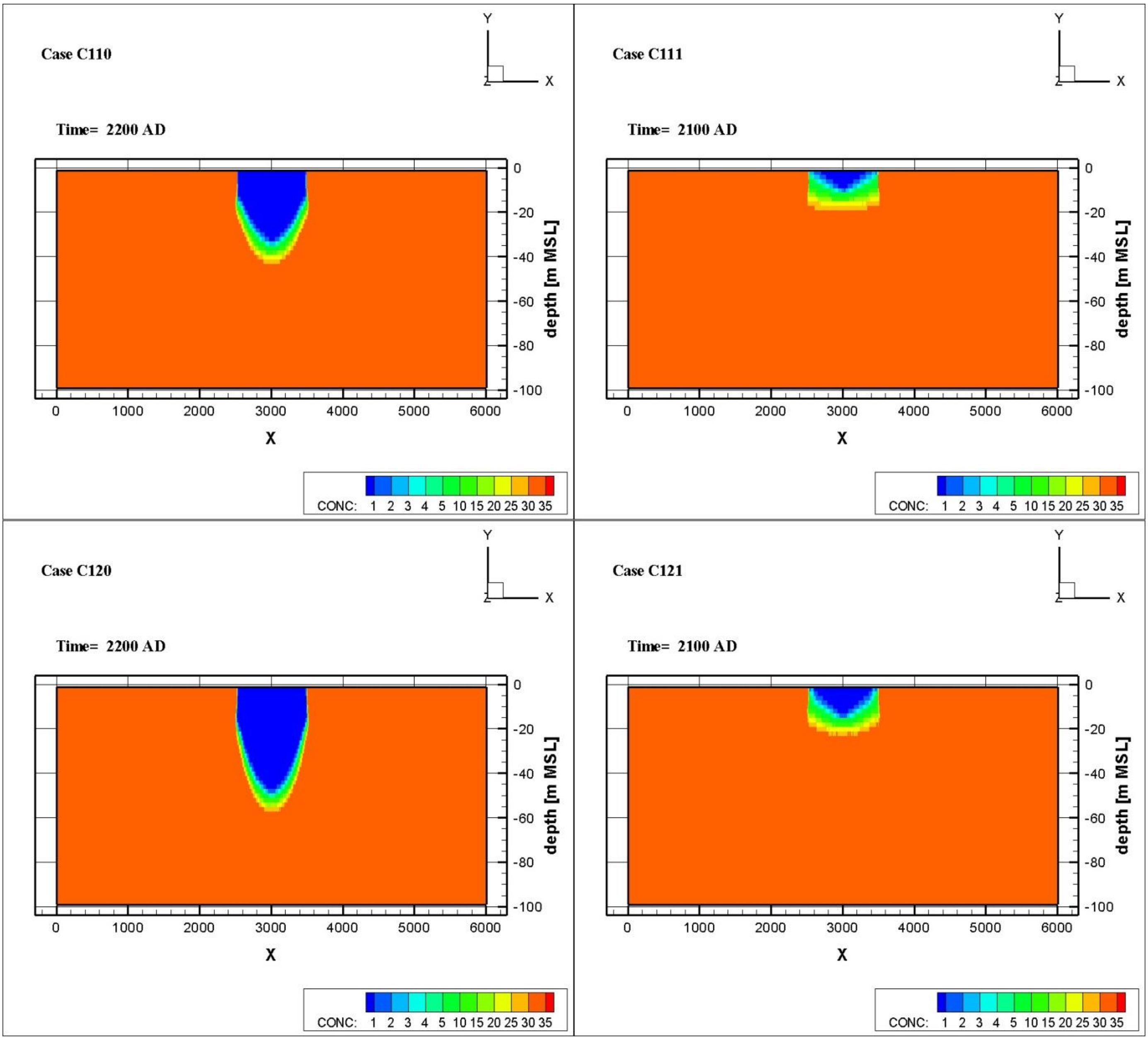


Figure 9 2D view of the final stage of each case with an elevation of 1.5 m for scenario C

From figure 9 an overall increase in the fresh groundwater amount is shown for all the cases compared to figure 8. This time C110 and C120 are able to reach a depth of 30 to 50 meters. The cases C111 and C121 still aren't able to exceed the 20 m, but have increased in depth with around 5 meters. The transition zone also increased in all the cases; especially in the last two cases it is still very dominantly present. The lens also increased in width for all the cases.

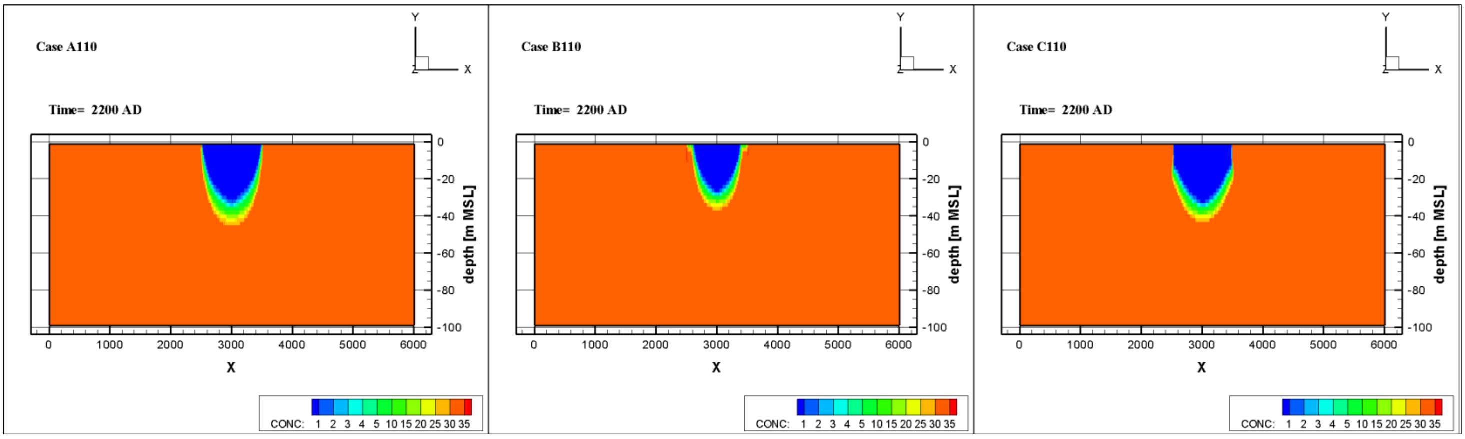


Figure 10 Comparison between the freshwater lens of the models A110, B110 and C110

In figure 10, the cases of 110 have been picked just to make it easier to compare each scenario. From this figure, it is clearly visible that the freshwater lens shrinks because of SLR and increases and widens by the provision system.

In table 5, the total amount of fresh groundwater is given for each case. Also the difference between the scenarios is calculated in percentage.
Notable is that the percentages are quite similar for the models where the sea-level rise added. The largest impact is found for the case B111, where the volume decreased with -48.5%.
However when the extraction wells are added in scenario C, the percentages show more variation. This time the biggest impact is found for model C120, where this measure has even increased the freshwater amount with 7.8% compared to the relative freshwater amount. The least effect is noticed for case C121, where the volume still decreased with 22.7%. But compared to the scenario B, where there was a decrease with 45.4% it is still a significant improvement.

	Volume (x 10^3) m^3		Volume (x 10^3) m^3	ΔA-B%		Volume (x 10^3) m^3	ΔA-C%
A110	16935	**B110**	10050	-40,7%	**C110**	16395	-3,2%
A111	2475	**B111**	1275	-48,5%	**C111**	2250	-9,1%
A120	23310	**B120**	13005	-44,2%	**C120**	25125	+7.8%
A121	5745	**B121**	3135	-45,4%	**C121**	4440	-22,7%

Table 5 Volume, and difference in volume of scenario A, B and C.

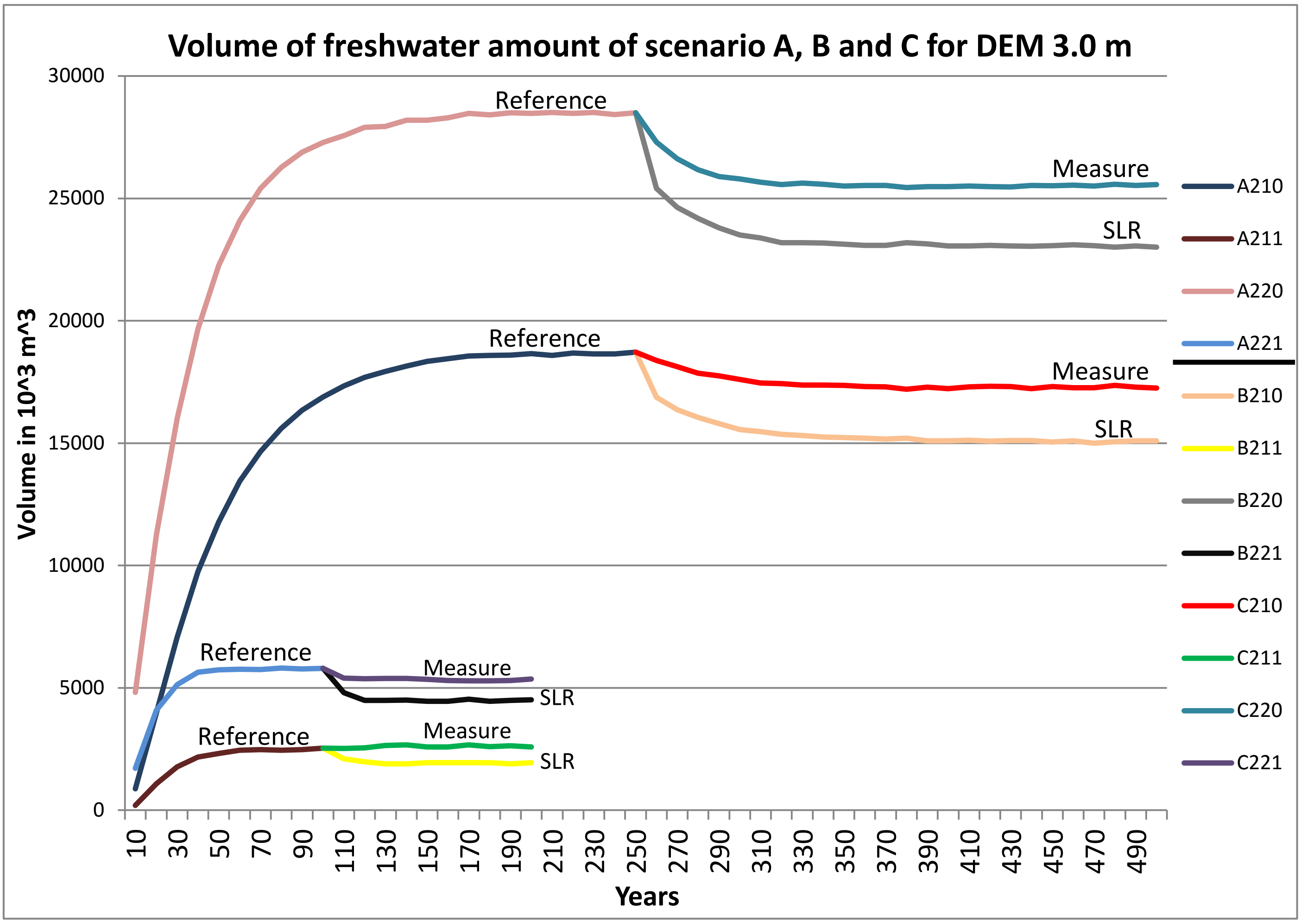
However, to see these improvements in scenario C, it is important to note that the amount of extraction does exceed the recharge greatly. In table 6, the ratios between the recharge and wells have been given. For the first 2 models, where the recharge is 0.75 mm/d, the extraction is 13 times greater. And for the last 2 models, with a recharge of 1.5 mm/d, the extraction is around 6.5 times greater.

Model	Recharge (kg)	Wells (kg)	Ratio
C110	0.7500536	9.818692	1/13.09
C111	0.7500536	9.8306361	1/13.1
C120	1.5001071	9.8016501	1/6,53
C121	1.5001071	9.8270589	1/6.55

Table 6 Ratio between the recharge and the extraction of wells for scenario C with a DEM of 1.5 m

3.1.2 Part 2: 3.0 meter height

The results of the models will now be presented for an island with an elevation of 3.0 meters. Table 7 provides the same legend seen before (table 4) to read the graph.



Graph 2 Volume of the freshwater amount of Scenario's A, B and C for DEM 3.0 m

Scenario	DEM (m)	Recharge (mm/d)	Kh/Kv (m/d)
A = Reference situation	100 = 1.5	10 = 0.75	0 = 5/0,5
B = SLR	200 = 3	20 = 1.5	1 = 50/1
C = SLR + measure			

Table 7 Legend for numbering models for the scenarios A, B and C

Graph 2 shows some interesting differences compared to the graph of part 1. One of the differences is that sea-level rise has a far less significant impact on the cases A210 and A220. These cases also need 250 years to stabilize, compared to the 200 years of part 1. Furthermore, the impact of scenario C is less effective, since instead of exceeding the reference level for case A220, it still lays beneath it. However, in general the difference between scenario B and C is still clearly noticeable. For the cases A211 and A221 they seem to be impacted more positively compared to part 1.

In figure 11, the freshwater lens is visualised in the images for the cases B210, B211, B220 and B221. This can be compared with figure 12, where the freshwater lenses of the cases C210, C211, C220, and C221 are presented.

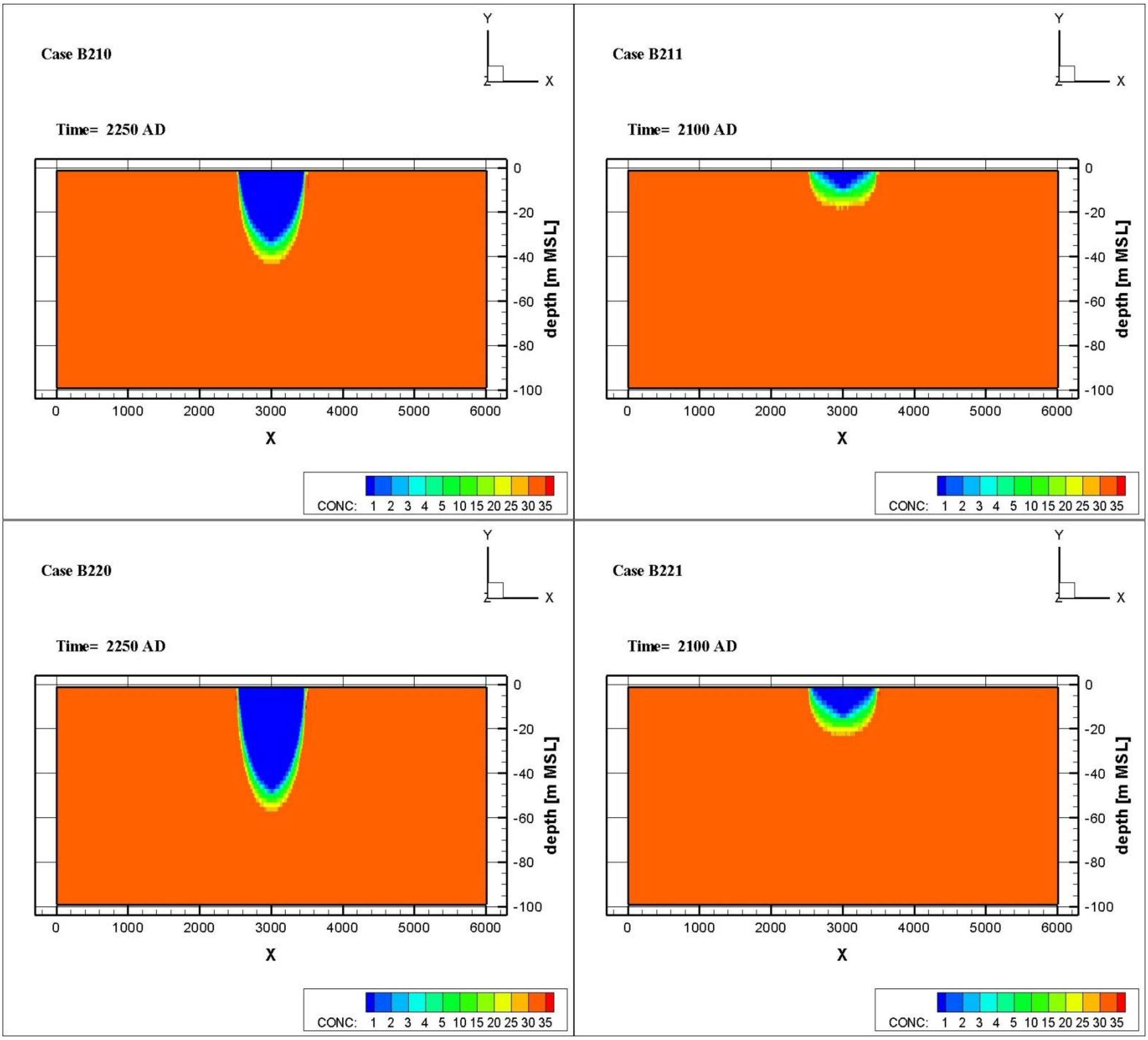


Figure 11 2D view of the final stage of each case with an elevation of 3.0 m for scenario B

Figure 11 also shows that the largest freshwater amount is found for B210 and B220. These lenses reach a depth of around 30 to 46 meters deep. The depth of the cases B211 and B221 lies between 10 to 18 meters deep. In these images it is also clear that the transition zone is the greatest for the last to cases that were mentioned. These results are quite similar to what was seen in part 1.

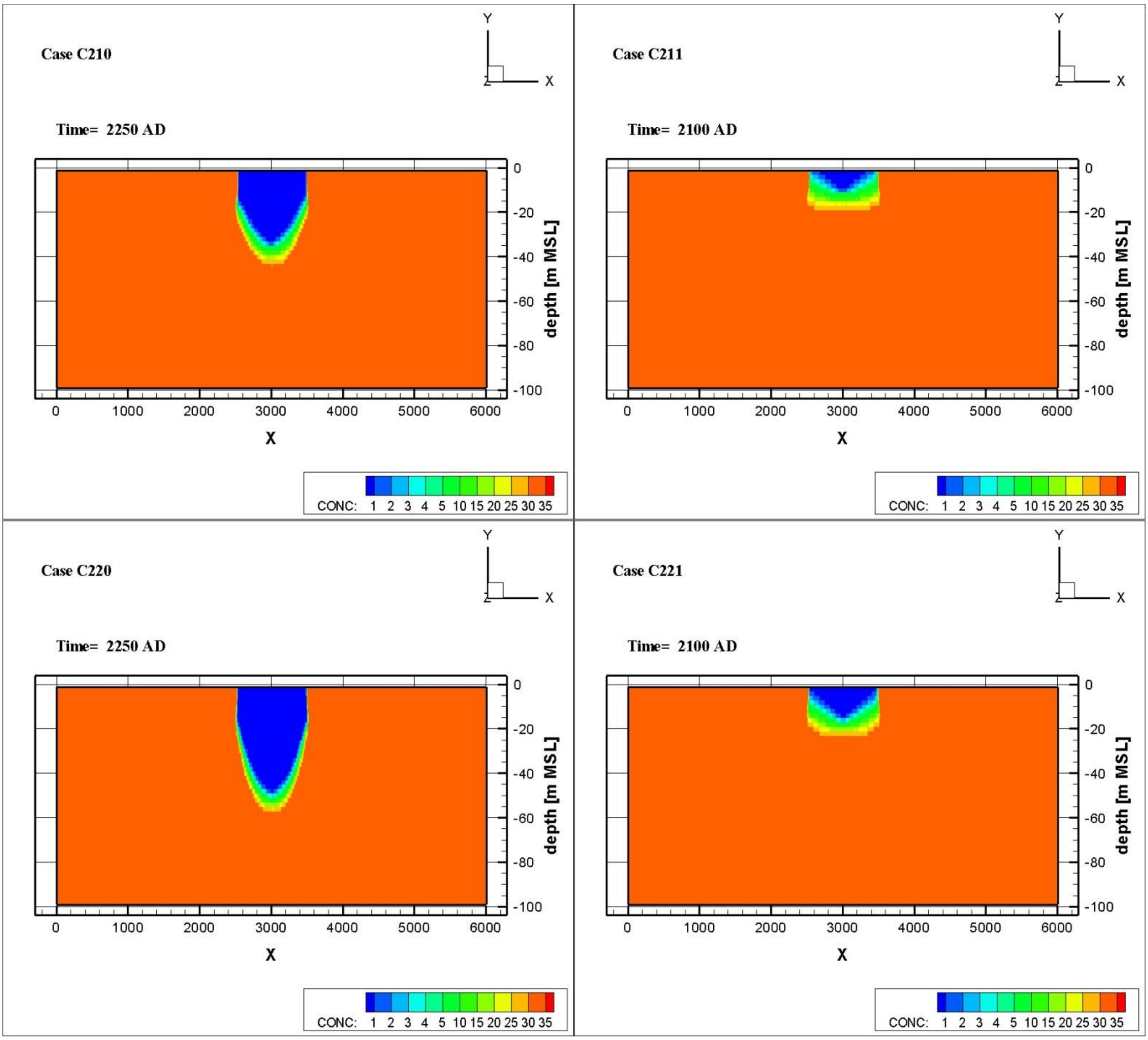


Figure 12 2D view of the final stage of each case with an elevation of 1.5 m for scenario C

Figure 12 also shows a clear growth of the freshwater amount compared to figure 11. This time the depth of C210 reaches 30 meters and C220 48 meters. The cases C111 and C121 show a large transition zone, and this time C221 is coming close to a depth of 20 meters. However, the transition zone also increased for C210 and C220.

In table 8, the total amount of freshwater is given for each case. Also the difference between the scenarios is calculated in percentage.
Notable is that the percentages are also quite similar for the models where the sea-level rise is added. The largest impact is found for the case B211, where the volume decreased with 23.7%.
However when the extraction wells are added in scenario C, the percentages show more variation. This time the biggest impact is found for model C211, where this measure has increased the freshwater amount with 1.8% compared to the relative freshwater amount. It had the least impact on case C220, where the volume still decreased with 10.3%.

	Volume (x 10³) m³		Volume (x 10³) m³	ΔA-B%		Volume (x 10³) m³	ΔA-C%
A210	18720	**B210**	15090	-19,4%	**C210**	17250	-7,9%
A211	2535	**B211**	1935	-23,7%	**C211**	2580	+1,8%
A220	28500	**B220**	23010	-19,3%	**C220**	25560	-10,3%
A221	5790	**B221**	4515	-22,0%	**C221**	5355	-7,5%

Table 8 Volume, and difference in volume of scenario A, B and C

In table 9, the ratios between the recharge and amount of extraction have been given. The ratio for the first model is the greatest with an extraction discharge that is 13 times larger than the recharge. For the second model (C211) the extraction is 11 times larger and the last to models are around the 6.5 times as large as the recharge. This is more like the ratios given of the first part (table 6).

Model	Recharge	Wells	Ratio
C210	0.7500536	9.9011491	1/13.2
C211	0.7500536	8.3564969	1/11.1
C220	1.5001071	9.8057612	1/6.54
C221	1.5001071	9.8206768	1/6.55

Table 9 Ratio between the recharge and the extraction of wells for scenario C with a DEM of 3,0 m

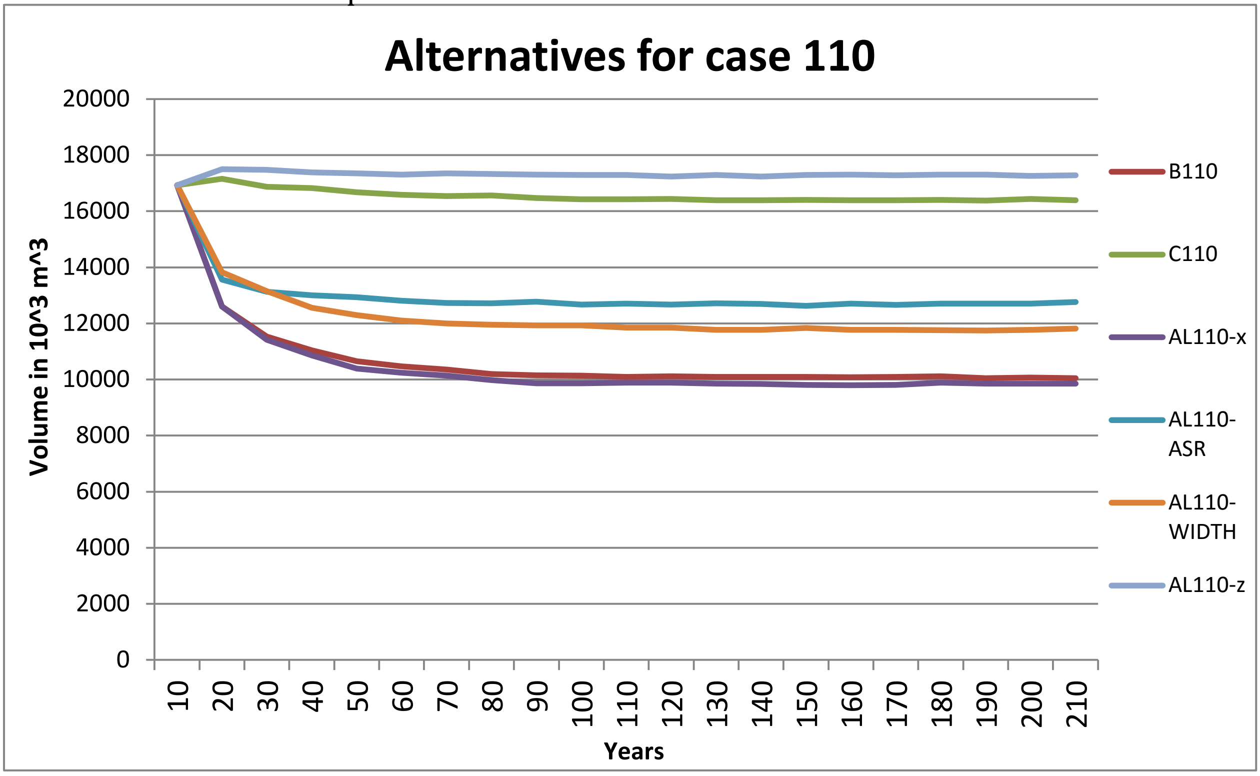
Comparison between part 1 and part 2

When looking at the tables 5 and 8, and the observation made from the graphs, there are some differences found in the impact the sea-level rise and the seepage provision has on the amount of freshwater.
For a height of 1.5 meters, the sea-level rise had a much more significant impact, in some cases reducing the volume with more than 45% relative to the reference situation. This dramatic decline in volume is not witnessed for the second part (with a height of 3.0 meters). In this case, the amount did not decrease more than around 24%.

When comparing the effectiveness of the seepage provision, it appeared to have been more significant for the first part, especially for case C120.
The second part shows the largest improvement for case C211, where it increased from -23.7% to +1.8%. This time it was the least effective for C220, with still a decline of 10.3%.
However, this effectiveness can only be reached when the discharge of the extraction is around 6.5 to 13 times greater than the recharge. This questions the possibility of applying the seepage provision on these islands.

3.1.3 Part 3: Alternative models

Besides the scenarios, the results for the alternative models that have been created for the cases of 110 are now presented.



Graph 3 Alternative situations applied on case 110 with B110 and C110 added for comparison

As explained before in the section "Modelling Method", there have been several measures applied to calculate the effects it would have on the freshwater amount in the aquifer. This is also were the legend of the graph (table 3) can be found. Each graph starts from the last point of the reference level of case A110, which is at a volume of 16935 x 10^3 m^3.

In table 10 the volume of each case has been provided, including the difference given in percentage between each alternative and the reference level of A110. The difference between A110 and B110, which has already been given before in table, is -40.7%. That means that every measure has been able to increase the freshwater volume, except case AL110-x. This is the situation where there are no human involvements, and the sides of the island were submerged by the rising sea-level.

The difference between A110 and C110 is -3.2%. AL110-z has proved to be more effective when the extraction wells are placed more carefully and the right amount of extraction has been searched for. The aim was to increase it with 10%, but it was even possible to achieve 15%. However, when looking at the ratio between the recharge (0.7500536) and the amount of extraction (24.5794657) for this case it is 1/32.8. This difference is very large, and would most likely not be applied to these islands.

Case AL110-ASR, where the GO-FRESH method is applied, shows a great improvement for diminishing the sea-level rise in comparison with the other measures, bringing it up to -24,6%.

Model	Volume (in 10^3 m^3)	ΔA-AL%
AL110-x	9855	-41,8%
AL110-ASR	12765	-24,6%
AL110-WIDTH	11820	-30,2%
AL110-z	19530	+15,3%

Table 10 Total amount of freshwater resulting from the alternative models, and the difference in percentage with the reference level A110.

3.2 Interpretation

The results from the observation clarified that the largest freshwater lens can be found for A220, so when K_h = 5 m/d and K_v = 0.5 m/d, with a recharge of 0.0015 m/d and an elevation of 3 meters. However, if the seepage provision has been applied it has a significant improve to the freshwater amount in all the cases.

The dramatic response that has been seen for the first part of the results can be explained due to the low elevation level of the island. If the island is 1.5 meters high and there is a sea-level rise of 0.5 meters, it will influence the aquifer more significantly. The low elevation also limits the freshwater lens of growing very deep.
However, this also implies that when the seepage provision is provided, it will also be able to reduce this effect very efficiently.

The transition zone is relatively the greatest for the cases where the hydraulic conductivity has a high value; K_h = 50 m/d and K_v = 1 m/d. This corresponds with the formula given in the paper of White and Falkland, 2009, which is:

$$\frac{\delta_u}{H_u} = \frac{K_0}{R}\left(\frac{D}{\alpha\, WK_0}\right)^{1/2} \quad \text{(Equation 1)}$$

where D (m^2/y), is the dispersion coefficient. Equation 1 predicts that the thickness of the transition zone will increase if K increases and the recharge decreases.
This seems to correspond with the cases that have been discussed.

The alternatives showed that the seepage provision has the most significant impact in restoring and even increasing the amount of freshwater in the aquifer. This could reach a growth of 15% relative to the reference level. Besides the seepage provision, the ASR measure, where the recharge is increased with 80% has diminished the effect of sea-level rise the most of the remaining alternatives. The beach nourishment result also proved effectiveness.

However, the ratios show a very large extraction rate compared to the recharge as is seen in the tables 6 and 9. This makes it unlikely to be able to apply on the islands, especially because of the high costs.
Therefore, it suggested that it would possibly be more advised to combine effective measures, such as the beach nourishment and ASR. This would have a very significant improvement that could maybe bring the freshwater amount back to the reference level. This would have a long-term positive effect for the inhabitants of the islands.

Population density based on rainwater catchment

It is interesting to calculate what the maximum amount of people is, that would be able to live on the island. By only using rainwater, it is possible to provide freshwater for a significant amount of people.

So there are two climates distinguished in the models, a dry and wet climate. The dry climate has a rainfall of 0.75 mm/d and the wet 1.5 m/d.
The surface of the island is 3 km^2, multiplying 1 km (width) by 3 km (length).

People living on an island are estimated to waste around 25-50 L/water a day.

So the total amount of volume available from the rain has been divided by the amount that would be wasted by each individual. 50 L/day is chosen, to calculate the maximum amount of people that are able to live there. However, since the rainfall catchment would not be 100% effective, the total amount of volume has been divided by 2 suggesting an effectiveness of 50%.

In table 11, the results of the calculations are provided. This suggests that during the dry season 22 500 people are able to live on the island and in the wet season 45 000 people. This implies a population density of 22 500/3 km^2 = 7 500 people/km^2 to 15 000/km^2. In the paper of White and Falkland, 2010, a population density of 12 000 people/km^2 is mentioned, which corresponds with this calculation. And since in the wet season double the amount of people is able to live, it will be more likely that eventually there will be more people living on these islands than 22 500 or 45 000. Therefore, it would be necessary to provide freshwater to these people by extracting it from the aquifer.

Rainfall (m/d)	Volume (x 10^3) m^3	People
0.00075	2250	22500
0.0015	4500	45000

Table 11 Amount of people provided by rainfall catchment

4. Discussion

The problems that SIDS faces which have been discussed in the Introduction will now be answered with possible responses or a solution. After performing this modelling research, the seepage provision system of Deltares proved to have the most effective results. Not only is it able to diminish the effect of sea-level rise, but it could even increase the freshwater amount in the aquifer of the island with 15%.

This provision system however shows some problems. It won't be possible to extract up to 13 times more water than the recharge, since it will be too expensive, and demands a lot of supervision and control. Therefore it is not advised to use this on the islands.
A better option would be to combine ASR and beach nourishment. Since it won't always be possible to provide the freshwater for an increased recharge of 80%, the beach nourishment will help with keeping the fresh groundwater reservoir more protected and stable.

However, there are still improvements to make for further researches about this subject. Since this paper has been written as a bachelor's thesis, time was limited. Therefore certain choices have been made that would make it possible to benefit the most of the available time. For example, Python was not used for the modelling, although it is more preferable, because there was not enough time to learn this first. Instead, an easier program is used for the modelling, namely PMWIN. Python is believed to have a higher accuracy with more possibilities. However, the PMWIN software provides sufficient quality of results and information for this research.

The time limit also withholds other possible additions to the models, such as modelling the effects for variations in the width, sea-level rise or placing wells at different locations whilst changing the amount of extraction. So, there surely are plenty more possibilities of variables to use.

Furthermore, the alternative models have only been applied to the models of other hydraulic conductibility's (110), but it would be interesting to apply these different measures to the islands with the other variables. Also, as mentioned before in the results, combining different measures together could have a greater improvement of the freshwater amount of the aquifer. This has not been proved yet with modelling, but it is expected, and would be interesting for further researches to perform.

When calculating the amount of people that could live on these islands, it was limited by the amount of rainfall and an effectiveness of 50%. However, if there is evidence of an improved effectiveness for the rain catchment or the freshwater from the aquifer would be extracted, then more freshwater can be provided to the people who live on these islands. But this has to be performed in a sustainable way. There is not enough information known about this yet to make it possible to perform the right calculations, but it is something to keep in mind for further calculations on this topic.

The variables that have been used for the modelling are based on the papers that are available, however since there is a knowledge gap about SIDS in the Pacific Ocean, it was sometimes necessary to make our own estimations. Therefore, this could be improved in the future, when there has been more researches performed on SIDS.

The effect of sea-level rise on the freshwater amount in SIDS and finding a solution for this problem is of particular interest nowadays. It is therefore, inevitable that more researches will be performed on this. Deltares will proceed with improving the research and this paper will contribute to this project.

5. Conclusion

The most important conclusions gained from the research are:

- The seepage provision system offered by Deltares as a solution to the problems SIDS are facing, does diminish the effects of sea-level rise. For sandy islands with a low elevation it is the most effective.
- However, the provision system is not advised to install in these islands, since the extraction rate is too large relative to the recharge, for it to have a significant improvement.
- With the alternative models, an idea is proposed for a combination of the ASR (GO-FRESH) method and beach nourishment. This would be a better option for these islands to diminish the effects of sea-level rise.
- A maximum of 45 000 people could live on an island of 3 km^3 when the only freshwater source would be rainfall of 1.5 mm/d, or 22 500 people for a rainfall of 0.75 mm/d. Both with a rainwater catchment of 50%.

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