Internship Project Report

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1. Introduction

Groundwater is one of the main water resources that is used widely for domestic and agriculture purposes. The point is not only to locate the groundwater resources but also to know the quality of these resources and how to extract sustainable fresh groundwater. In coastal zones, the quality of the groundwater is affected by many factors such as human activities, sea-level rise, coastal erosion and extreme events which lead to the shortage of fresh groundwater in these zones (Oude Essink, 2001). However, these coastal areas are still important due to many human activities such as fisheries, agriculture and other industrial activities. As a result, groundwater resources in the coastal aquifers highly need proper monitoring and manging for providing sustainable freshwater mainly for domestic and agriculture purposes.

1.1 Variable Density Groundwater Flow

The presence of the salt in the groundwater needs to be considered when studying the groundwater flow. The freshwater has a density of about 1000 kg/m^3 while the seawater has a density of about 1025 kg/m^3. This difference in the density will affect the interface between the fresh and the saltwater. Field observations had shown that this change in density can have a significant impact on the groundwater flow rates and patterns (Langevin, et al., 2008). Therefore, considering the difference in the groundwater density is critical especially in cases of extracting the groundwater resources from the coastal aquifers. Modelling a case with variable density groundwater needs two models to work together. The first one is a groundwater flow model and the second one is a groundwater transport model. MODFLOW is the widely open-source model code for simulating the groundwater flow system. While MT3DMS is the widely open-source code used for simulating solute transport (advection, dispersion, and chemical reactions) (Zheng & Wang, 1999). MODFLOW and MT3DMS were compromised together to simulate a groundwater system with a variable density such as SEAWAT code (Langevin et al., 2008).

1.2 Case Study: Province of Zeeland, Netherlands

Zeeland is a province located in the south-west of Netherlands bordered from the east direction by the North Sea. Post, (2003) had provided a group of maps which indicate that a large part of Zeeland is below sea level with shallow groundwater depth (less than 20m). In Zeeland, farmers use the groundwater for irrigation, especially in summer when the natural resources (recharge) are limited. These conditions of pumping shallow groundwater in a coastal aquifer lead in many cases to the rise of the brackish or saline groundwater beneath the extraction source (Oude Essink & Pauw, 2018). Therefore, it is fundamental to control the groundwater extraction in such cases to avoid groundwater salinization. Moreover, it is essential to understand the interaction between the fresh and the salt groundwater and define the transition zone.

1.3 Related Work

The main approach to evaluate groundwater resources is groundwater modelling. Groundwater modelling provides a simulation of a part of a real hydrological system in a cheap and quick way (Oude Essink, 2000). Using groundwater modelling help the researchers and the local water sectors to make important decisions for sustainable management plans. Some related studies were done before in Zeeland with the use of groundwater modelling and the focus of analysing the groundwater resources in different aspects. First, Oude Essink & Pauw, (2018) had provided a detailed study to evaluate the groundwater resources and investigate the groundwater rules in Zeeland. They also study the effect of the sea level rise and the climate change on the groundwater replenishment. Another study is still going on to study the effect of spatial and temporal discretization in modelling density-dependent flow (Schoonderwoerd, n.d.). As a forward step, this research will continue studying the groundwater resources in the same area but with different objectives.

2 Research Objectives and Questions

2.1 Research Objectives

The main objective of this research is to test the effect of changing different model parameters on the system response using a variable density 3D model.

2.1.1 Sub-Objectives

The main objective will be split into sub-objectives. Each specific objective will be considered as a separate task to define the following:

- The effect of different temporal discretization of the recharge data. Task 1
- The effect of different extraction rates. Task 2
- The effect of different total model depth. Task 3
- The effect of lumping the thickness of the model layers. Task 4
- The effect of using different numerical solvers. Task 5

All these specific objectives will be linked at the end to the system response (the effect of these changes on:

- Fresh groundwater volume.
- Freshwater lens (interface between the fresh and saltwater).
- Run time of the model.
- Water concentration at the well location (in cases of extractions).

2.2 Research Questions

- What is the effect of changing the temporal discretization of the recharge data on the system response?
- What is the effect of assigning different extraction rates on the total freshwater volume and the water concentration at the extraction source?
- What is the effect of changing the vertical discretization of the model on the system response?
- What is the effect of using different numerical solvers on the system response?

3 Methodology

3.1 Conceptual Model

The conceptual model provided by Oude Essink & Pauw, (2018) will be followed. This model is a reference case that represents the groundwater system in Zeeland with relatively large creek ridges and drains on top. Due to the symmetry of the solid edges of the reference case, only a quarter of the actual domain needs to be simulated (Figure 1). The model has a horizontal dimension of 550 x 650 m and a total thickness of 41 m. The top level of the model is 2m above sea level. As shown in figure 1, the north and east sides of the model represent constant boundaries with head = 0 and concentration = 16.394 kg Cl^-/m^3, while the west and south sides represent no-flow boundaries. The (0,0) point represent the location of the well while a ditch is located 200m away from the (0,0) point with total length equal to the model length (650) m and level = 0.5m above sea level.

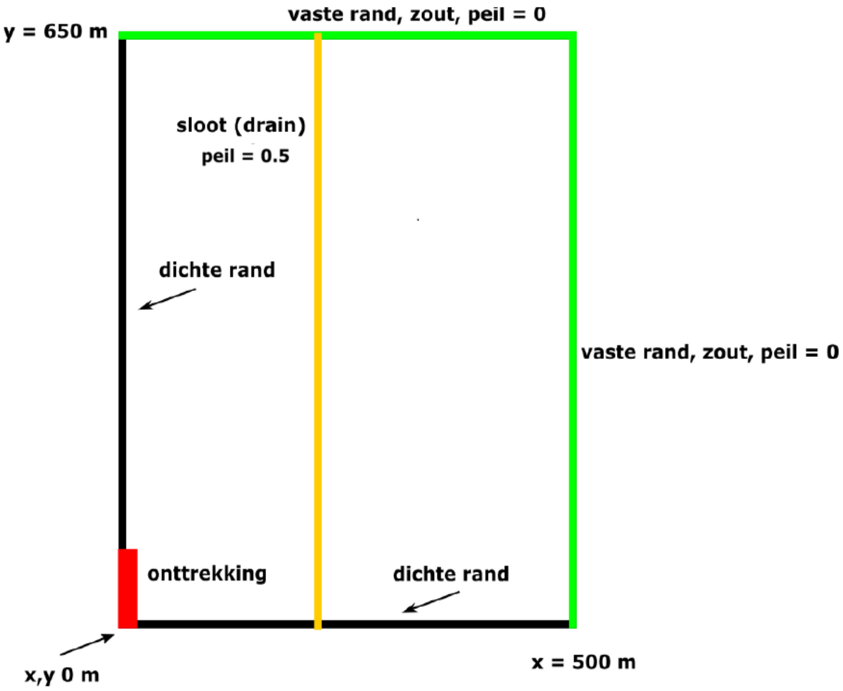

Figure 1: Model Domain and its Boundary Conditions, reference: (Oude Essink & Pauw, 2018)

3.2 Numerical Model (MODFLOW 6)

Recently the U.S. Geological Survey had developed the latest version of MODFLOW which is called MODFLOW 6 (Langevin et al., 2017). MODFLOW 6 is an object-oriented framework which supports the use of multiple models within the same simulation (Hughes et al., 2017). MODFLOW 6 includes most of the functions of the previous MODFLOW versions (MODFLOW-2005, MODFLOW-USG, MODFLOW-NWT and MODFLOW-LGR). It is based on a generalized control volume finite-difference which a grid cell can be connected to any number of surrounding cells. It has high flexibility to use any cell shape (rectangular, triangular, hexagonal or unstructured) using one of three different discretization packages. The main advantage of MODFLOW 6 is that multiple models can be incorporated and solved numerically within the same simulation. The official MODFLOW 6 releases only the groundwater flow model (GWF). However, in this study, the solute transport model will be also used (GWT). The unofficial version of MODFLOW 6 which include the transport model was retrieved from the USGS but it is still under development (Schoonderwoerd, n.d.). Together, the GWF and GWT can simulate the variable-density groundwater system but with the advantage of the MODFLOW 6 new capabilities. However, the documentation for the input and the output of the transport model is still so limited that some explanations about the transport model were not provided.

3.3 Original Model (Base Case)

The original model is a 3D variable density model that was implemented by Oude Essink & Pauw, (2018) using SEAWAT. This SEAWAT model had already used the needed packages to define all the model inputs such as driving forces, soil parameters, initial and boundary conditions. Therefore, this model inputs will be used again for creating a new MODFLOW 6 model. All the SEAWAT model packages will be converted to the MODFLOW 6 readable format except the spatial discretization package which will be different from the SEAWAT model. This conversion process was done using a group of Python scripts for all the tasks following the documentation of MODFLOW 6 input and output.

3.4 Model Spatial Discretization

For the model spatial discretization, the model of Schoonderwoerd, (n.d.) will be followed. It is basically a MODFLOW 6 model with an unstructured grid for the same study area. The grid cells had the rectangular shape with using the octree refinement option to change the grid cell size in areas of interest. The refinement option was used starting from the origin (0,0) point with the smallest grid cell and coarser cells as far as moving away from the origin point in both x and y directions (Figure 2). The DISU discretization package was used in all the tasks except in (Task 3 and 4), where the DISV package was used for simplicity (easier to change the number or the thickness of the model layers).

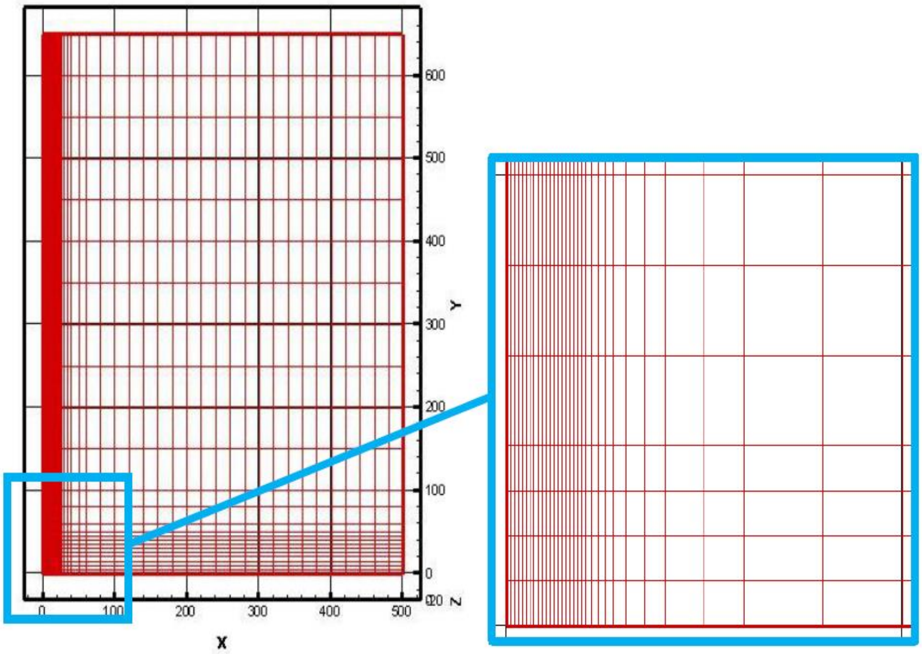

Figure 2: Model Horizontal Discretization, reference: (Schoonderwoerd, n.d.)

4 Task-1: Different Temporal Discretization of Recharge data

The original SEAWAT model of Oude Essink & Pauw, (2018) had a total time period of 200 years with weekly stress periods (length of each stress period = 7 days). The main driving forces (model stresses) in this model are the recharge (net groundwater recharge) and the evapotranspiration (groundwater evapotranspiration). The data for these driving forces were retrieved in (mm/day) on a daily basis of total period = 20 years. Then for each stress period length (7 days), the data was lumped to have an average value for recharge and an average value for evapotranspiration. In this task, the daily recharge data will be used with different lumping criteria for the different models. The main change between task-1 models will be the temporal discretization of each model. The following sub-sections describe the implementation of different temporal discretization for each model.

4.1 Weekly Stresses Model (Base Case)

The weekly stresses model is the model which the period of a week (7 days) is the representative length of each stress period. So, for each week, only one value for recharge and evapotranspiration will be assigned. As it was mentioned, the recharge data is a daily data for 20 years. The total time period of all the models in task-1 is 100 years, so the data will be repeated 5 times. This model is considered to be the base case for all other models in task 1, so all the models will be compared to the weekly stresses model. The following table shows the temporal discretization of the weekly stresses model and the criteria for assigning the recharge data.

Table 1: Temporal Discretization of Weekly stresses model

Model Name	Weekly stresses model
Total time period	100 years
Length of the stress period	7
Number of time steps per stress period	1
Total number of stress periods	5200
Total number of time steps	5200
Original recharge data	Daily data
Assigning recharge data in the model	For each stress period: $$Lumped\ recharge\ value = \frac{\sum daily\ recharge\ values}{stress\ period\ length = 7}$$ If lumped value = (+ve), assigned as a recharge rate using recharge package. If lumped value = (-ve), assigned as an evapotranspiration rate in the evapotranspiration package.

The output expected from the model is the distribution of the Chloride concentrations. Figure 3 shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

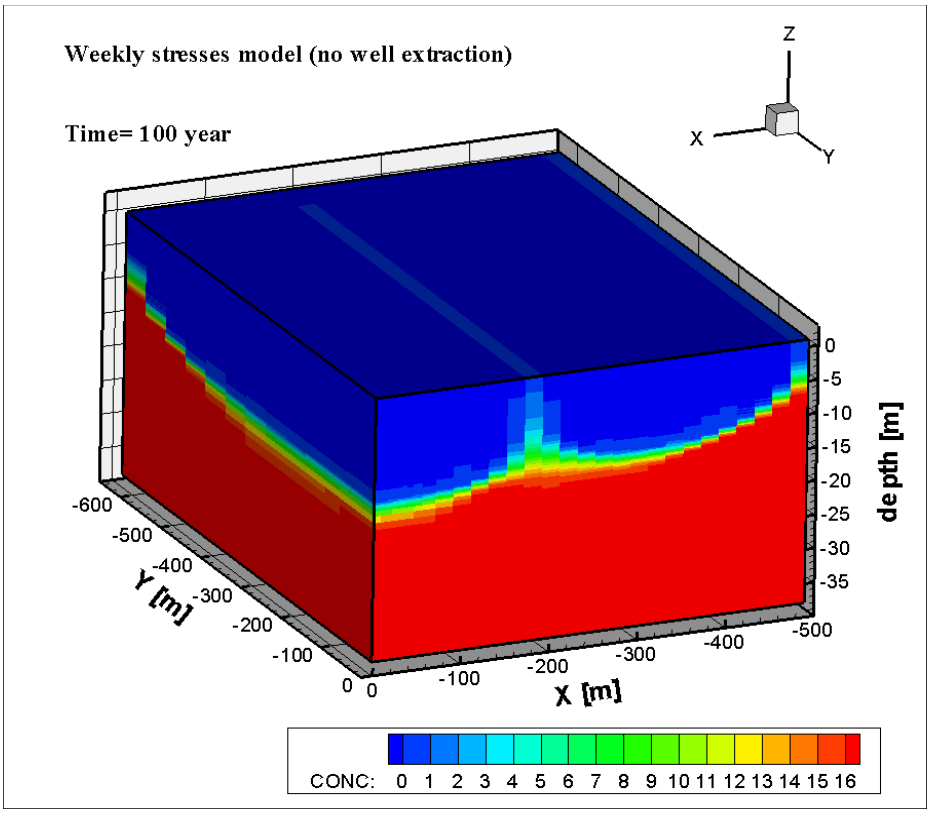

Figure 3: 3D Plot of Chloride Concentrations for Weekly Stresses Model

4.2 Daily Stresses Model

The daily stresses model is the model which the period of a 1 day is the representative length of each stress period. The daily stress model uses the original daily recharge data without any lumping. The following table shows the model temporal discretization and the criteria for assigning the recharge data.

Table 2: Temporal Discretization of Daily stresses model

Model Name	Daily stresses model
Total time period	100 years
Length of the stress period	1
Number of time steps per stress period	1
Total number of stress periods	36400
Total number of time steps	36400
Original recharge data	Daily data
Assigning recharge data in the model	If recharge value = (+ve), assigned as a recharge rate using recharge package. If recharge value = (-ve), assigned as an evapotranspiration rate in the evapotranspiration package.

Figure 4 shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

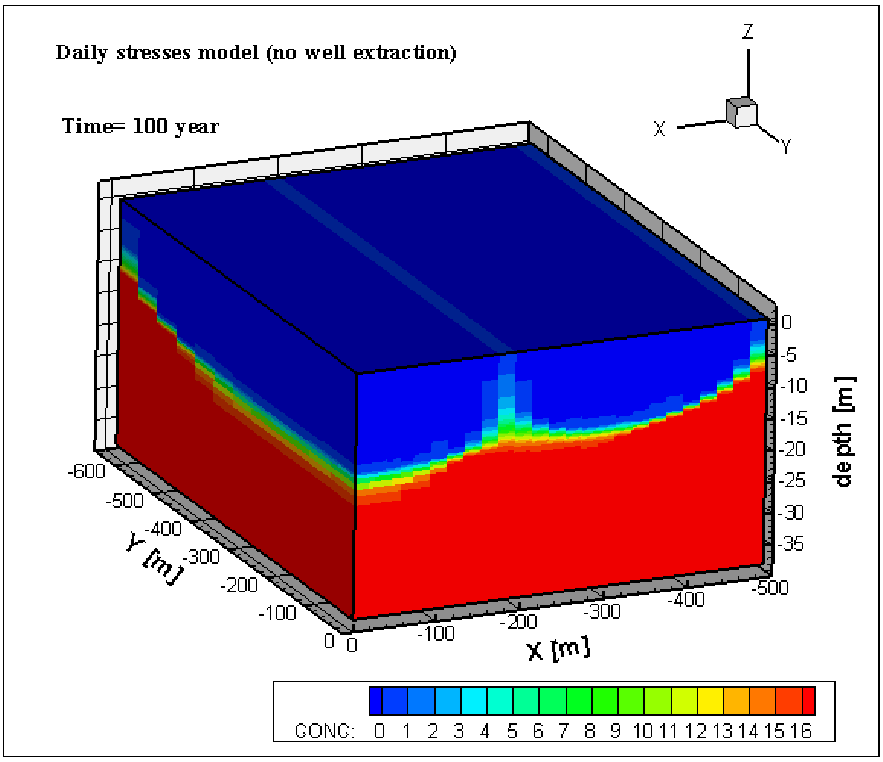

Figure 4: 3D plot of Chloride Concentrations for Daily Stresses Model

4.3 Monthly Stresses Model

The monthly stresses model is the model which the period of a month (28 days) is the representative length of each stress period. The following table shows the model temporal discretization and the criteria for assigning the recharge data.

Table 3: Temporal Discretization of Monthly stresses model

Model Name	Monthly stresses model
Total time period	100 years
Length of the stress period	28
Number of time steps per stress period	1
Total number of stress periods	1300
Total number of time steps	1300
Original recharge data	Daily data
Assigning recharge data in the model	For each stress period: $Lumped\ recharge\ value = \frac{\sum daily\ recharge\ values}{stress\ period\ length = 28}$ If lumped value = (+ve), assigned as a recharge rate using recharge package. If lumped value = (-ve), assigned as an evapotranspiration rate in the evapotranspiration package.

Figure 5 shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

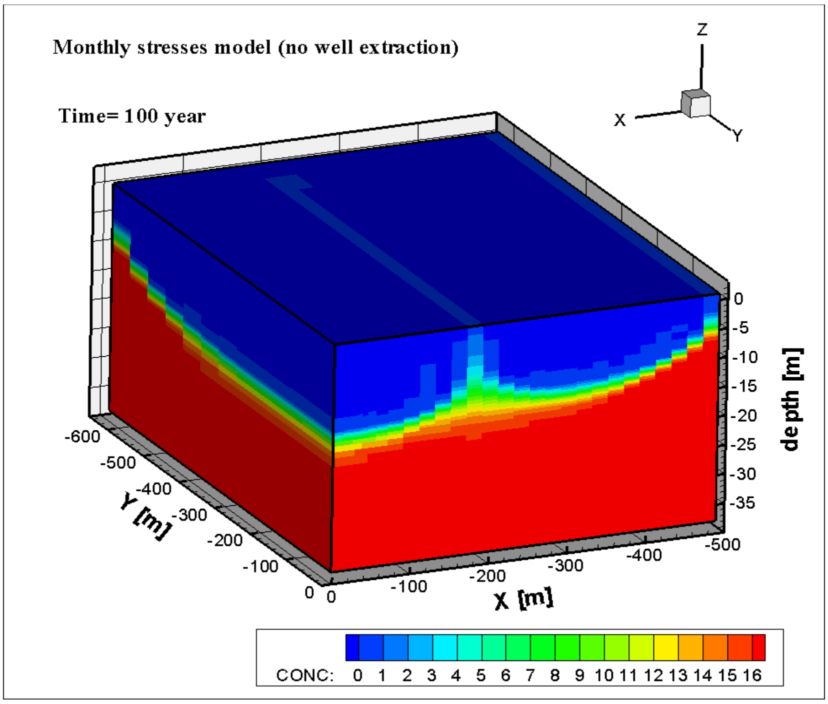

Figure 5: 3D plot of Chloride Concentrations for Monthly Stresses Model

4.4 Half-Yearly Stress Model

The half-yearly stresses model is the model which the period of a half year (182 days) is the representative length of each stress period. The following table shows the model temporal discretization and the criteria for assigning the recharge data.

Table 4: Temporal Discretization of Half-Yearly stresses model

Model Name	Half-year stresses model
Total time period	100 years
Length of the stress period	182
Number of time steps per stress period	1
Total number of stress periods	200
Total number of time steps	200
Original recharge data	Daily data
Assigning recharge data in the model	For each stress period: $Lumped\ recharge\ value = \frac{\sum daily\ recharge\ values}{stress\ period\ length = 182}$ If lumped value = (+ve), assigned as a recharge rate using recharge package. If lumped value = (-ve), assigned as an evapotranspiration rate in the evapotranspiration package.

Figure 5 shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

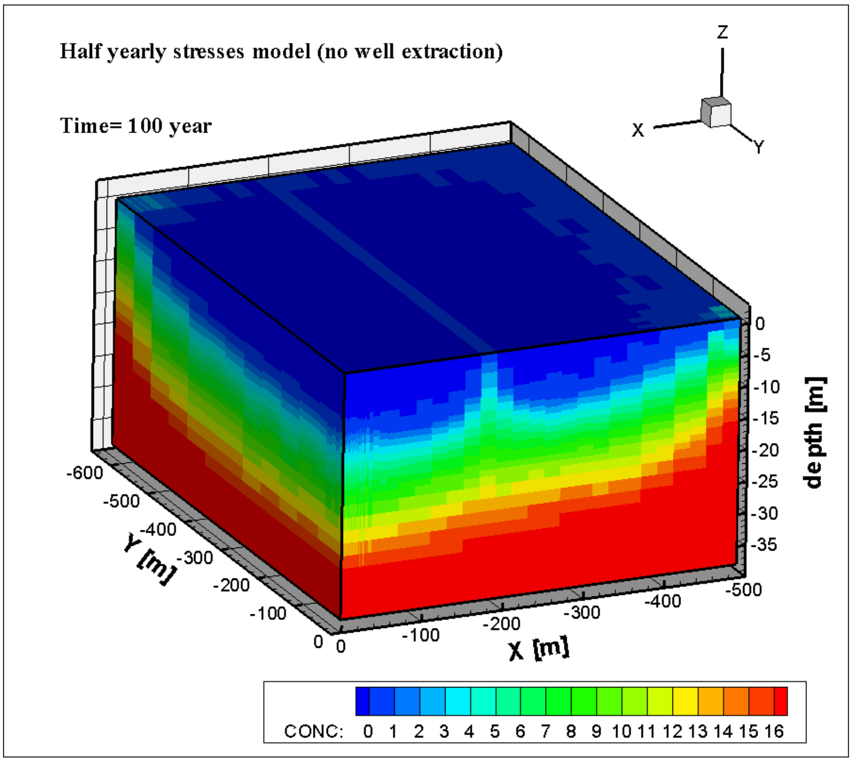

Figure 6: 3D plot of Chloride Concentrations for Half-Yearly Stresses Model

4.5 Effect of Different Temporal Discretization on the System Response

The main objective of task 1 is to understand how the temporal discretization of the recharge data can affect the response of the groundwater system particularly the fresh-salt water interface and the total freshwater volume. In addition, it is important to know how this different temporal discretization affects the total run time of the model.

4.5.1 Effect on Fresh-Salt water Interface

For results comparison, the fresh-salt water interface was exported from the models at Y = 0 m at the end of the model (after 100 years). The following figures show the fresh-saltwater interface for each model and the difference of the interface position.

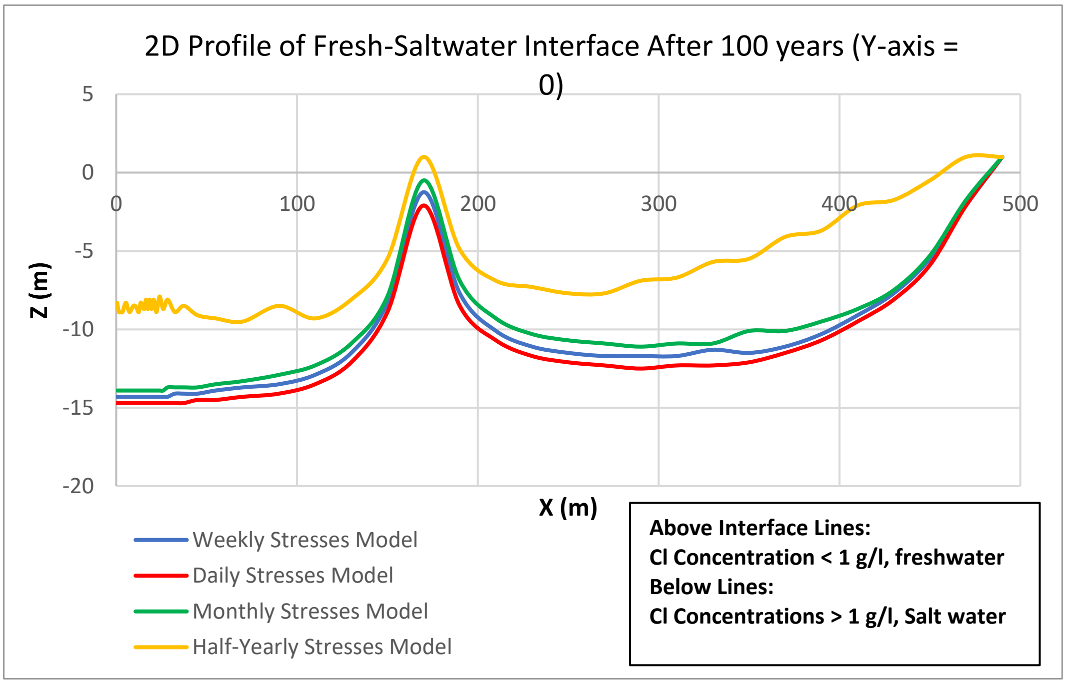

Figure 7: Fresh-Saltwater Interface for Different Models

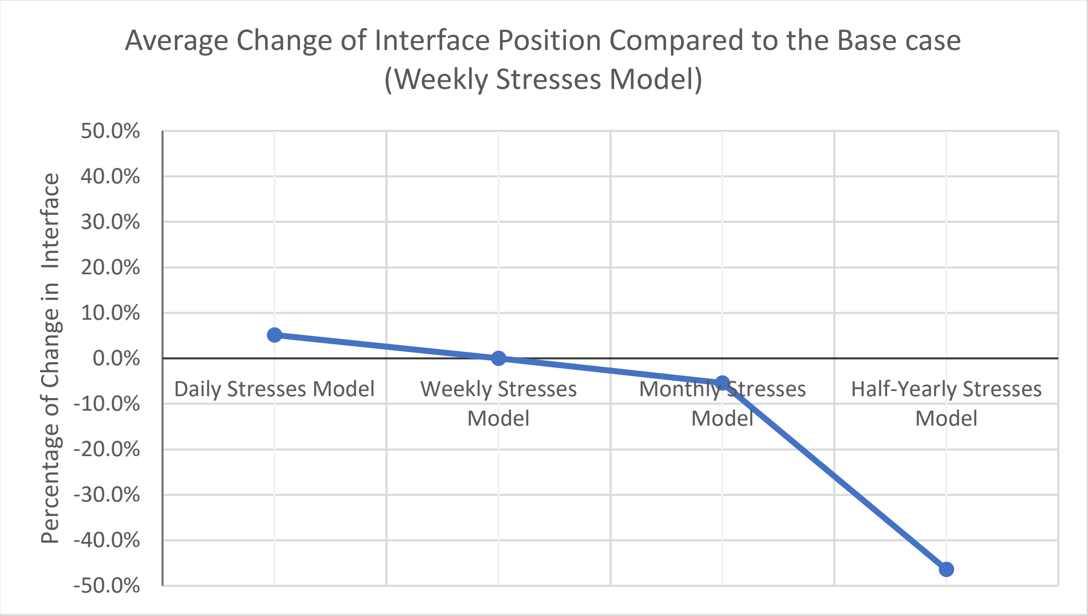

Figure 8: Change of Fresh-Salt water Interface

It can be noticed that the relative change of the fresh-saltwater interface for the daily and monthly models compared to the weekly model are not significant (+5%, -5% respectively). However, the half-yearly model had significantly underestimated the fresh-salt water interface (less than the weekly stresses by an average change = -46%).

4.5.2 Effect on Freshwater Volume

The total freshwater volume was calculated for each model as shown:

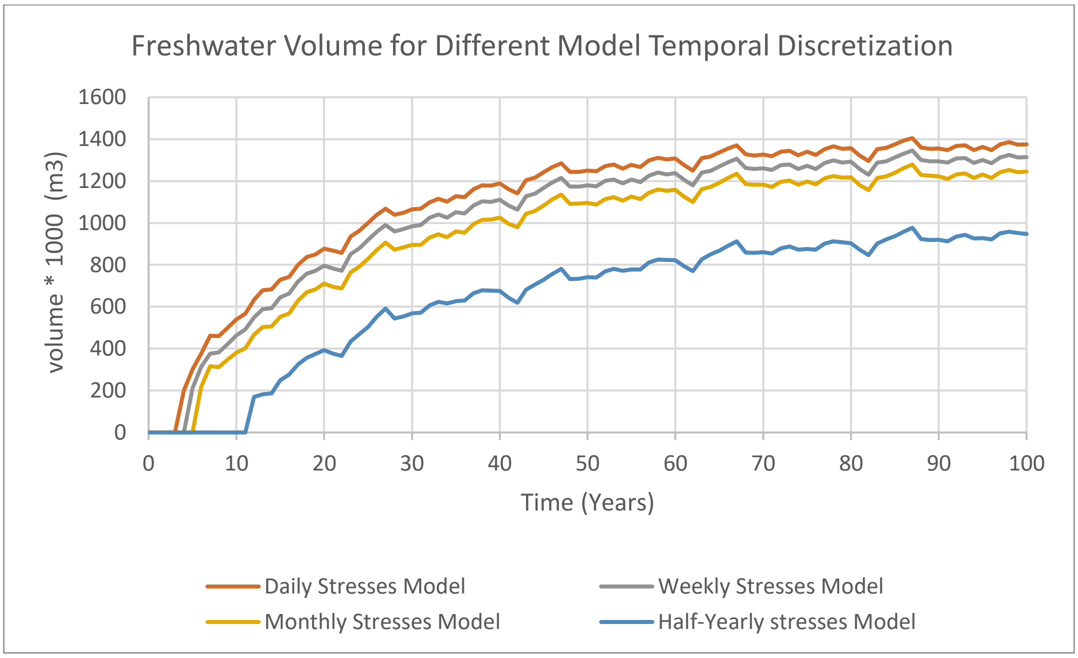

Figure 9: Freshwater Volumes for Different Models

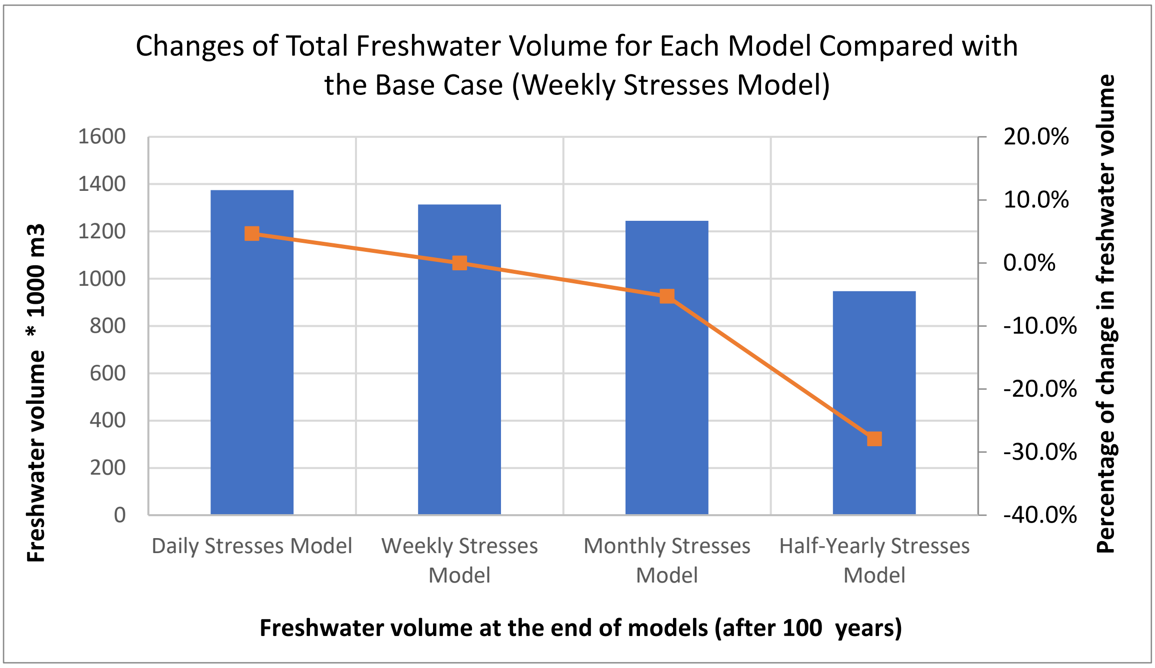

Figure 10: Change in Total Freshwater Volume

It can be noticed from the figures that the relative change of the total freshwater volume of the daily and monthly models compared to the weekly model are not significant (4.5%, -5.5% respectively). However, the freshwater volume of the half-yearly model is less than the weekly model by -28%. As a result, it can be concluded that there is an inverse relationship between the model temporal discretization and the freshwater volume.

4.5.3 Effect on Model Run Time

Usually, the models with groundwater flow and groundwater transport take more time to run than the only groundwater flow models. The total time for the model to run mainly depends on the number of time steps assigned in the model as the equations of the groundwater system will be solved for every time step. Therefore, it is important to know the run time of the different models and which models will have a reliable run time. The following figure shows the run time for the different models.

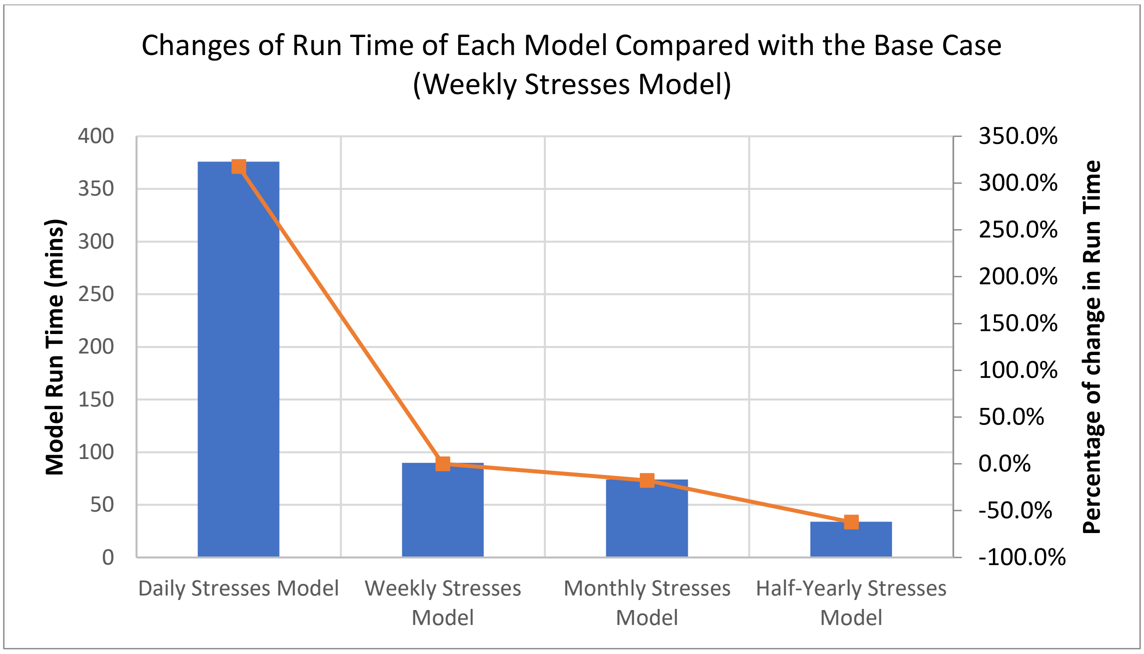

Figure 11: Run-Time for the Different Models

It can be noticed that the daily stresses model has a very long run time (315% more than the weekly stress model). As the daily stress model take around 6 hrs and 15 mins (376 mins) to run compared to only 1 hr and a half (90 mins) for the weekly stresses model. While the monthly and half-yearly models had a shorter time than the weekly stresses model (less than the weekly stresses model by 18%, 62% respectively).

5 Task-2: Implementing Different Extraction Rates

The main idea of task 2 is to test how can different extraction rates affect the groundwater system response particularly the fresh-salt water interface and the total freshwater volume. In addition, the water concentration at the well location is important to know the quality of the extracted water which will be used for agricultural purposes. The maximum chloride concentration for the water used for agriculture is around 1 g/l according to the world health organization (WHO). In this task, The extraction rate defined by (Oude Essink & Pauw, 2018) is named as the normal extraction. The water is extracted at a certain period of the year when the natural recharge is limited. The well is located at the origin point of the model (0,0) with depth = 3.5 from the sea level (reference zero level). The extraction process continues for 14 weeks every year with extraction rate = 30 m^3/week, so the total extraction rate = 420 m^3/year. The following sub-sections show a number of models with different extraction rates and later compared them with the base case model (no extraction). For all the models, the total time is 140 years. The first 100 years is with no extraction then applying the extraction rates at the last 40 years (from 100 to 140). This is done to give the contaminants enough time to be stable in the system to provide more representative simulation of the real case. All the models are weekly stresses (length of each stress period = 7 days).

5.1 Normal Extraction Rate

The normal extraction rate is 30 m^3/week applied for 14 weeks every year, so the total extraction rate = 420 m^3/year. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

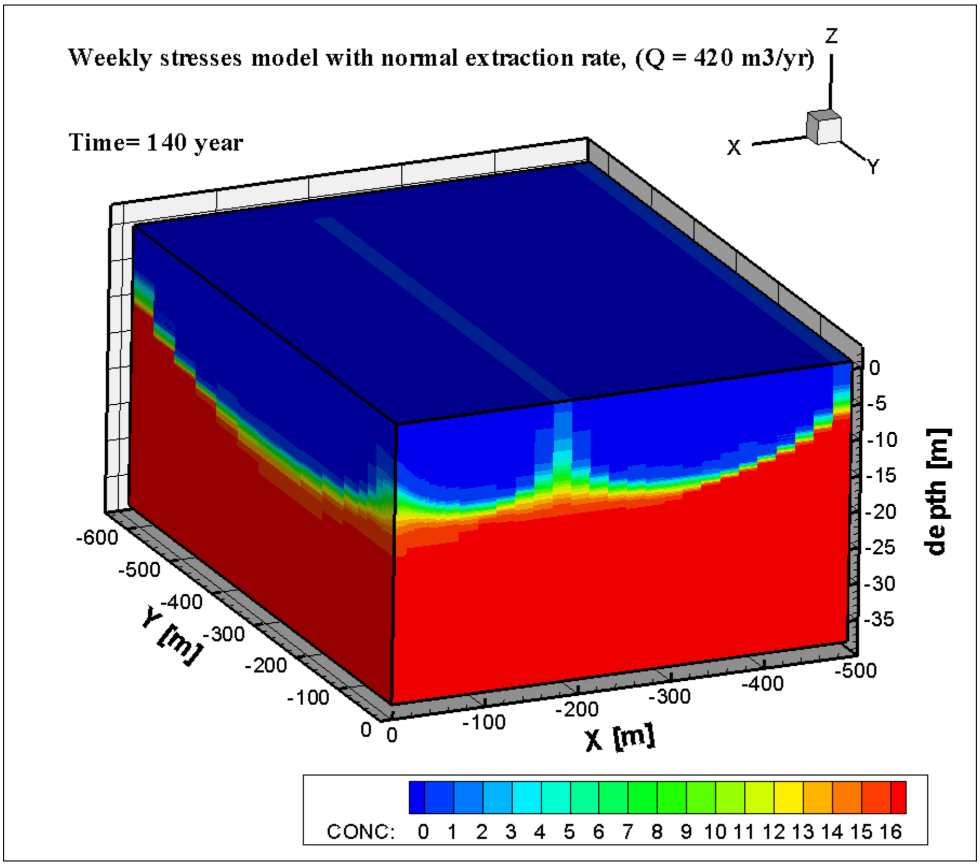

Figure 12: 3D plot of Chloride Concentrations for a Model with Normal Extraction Rate

5.2 Half of the Normal Extraction Rate

The half-normal extraction rate is 15 m^3/week applied for 14 weeks every year, so the total extraction rate = 210 m^3/year. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

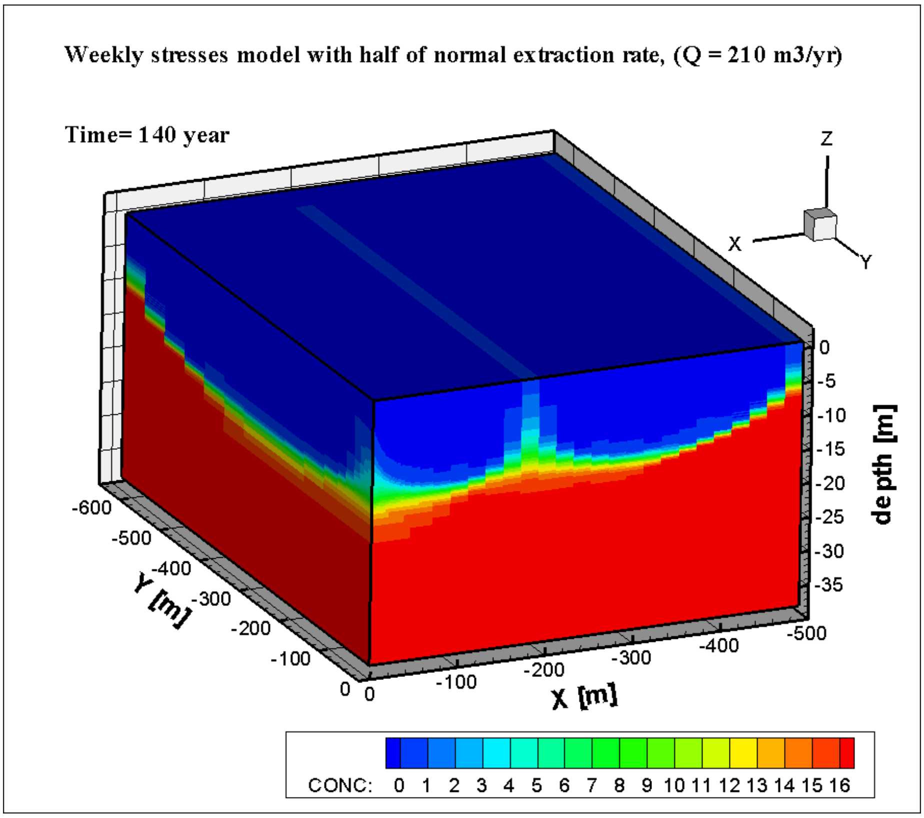

Figure 13: 3D plot of Chloride Concentrations for a Model with Half of Normal Extraction Rate

5.3 Doubled of the Normal Extraction Rate

The doubled normal extraction rate is 60 m^3/week applied for 14 weeks every year, so the total extraction rate = 840 m^3/year. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

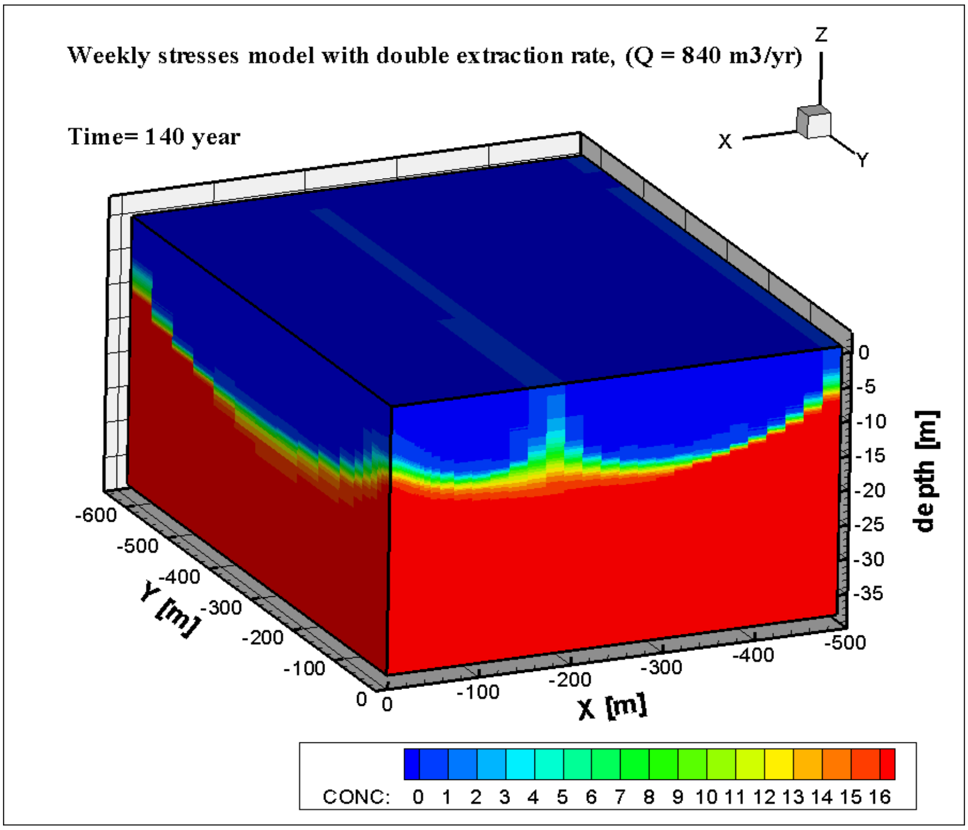

Figure 14: 3D plot of Chloride Concentrations for a Model with Doubled Normal Extraction Rate

5.4 Three Times Normal Extraction Rate

The three-times normal extraction rate is 90 m^3/week applied for 14 weeks every year, so the total extraction rate = 1260 m^3/year. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

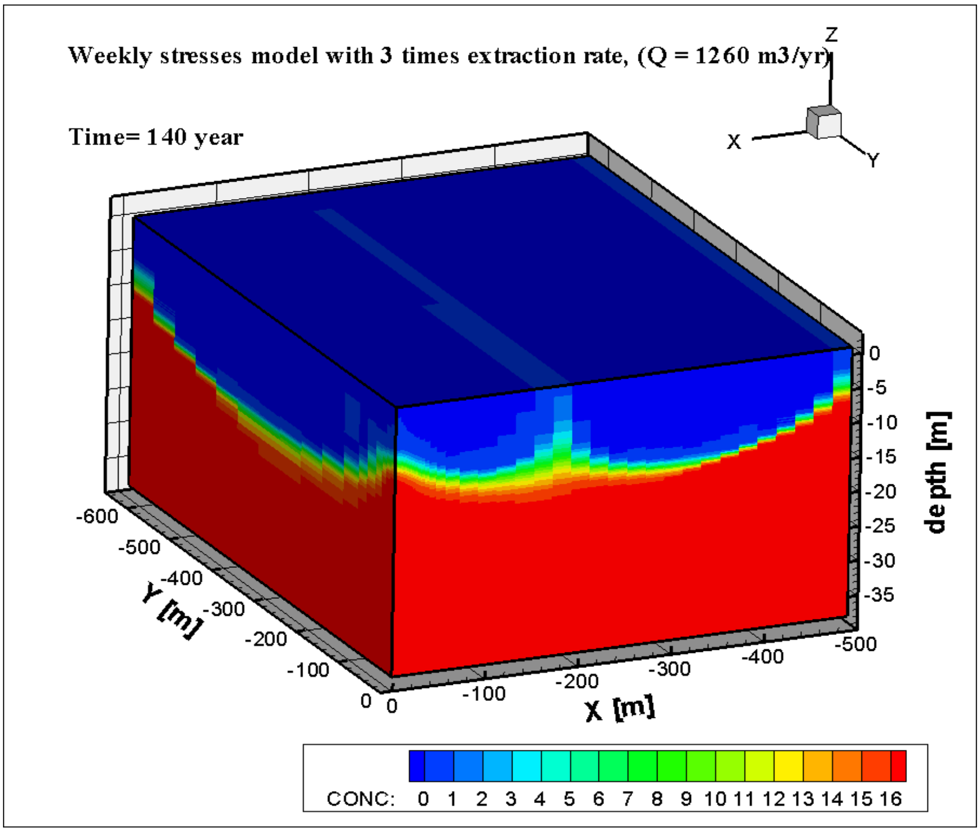

Figure 15: 3D plot of Chloride Concentrations for a Model with 3 Times Normal Extraction Rate

5.5 Effect of Different Extraction Rates on the System Response

5.5.1 Effect on Fresh-Salt water Interface

For results comparison, the fresh-salt water interface was exported from the models at Y = 0 m at the end of the models (after 140 years). The following figures show the fresh-saltwater interface for each model and the difference of the interface position.

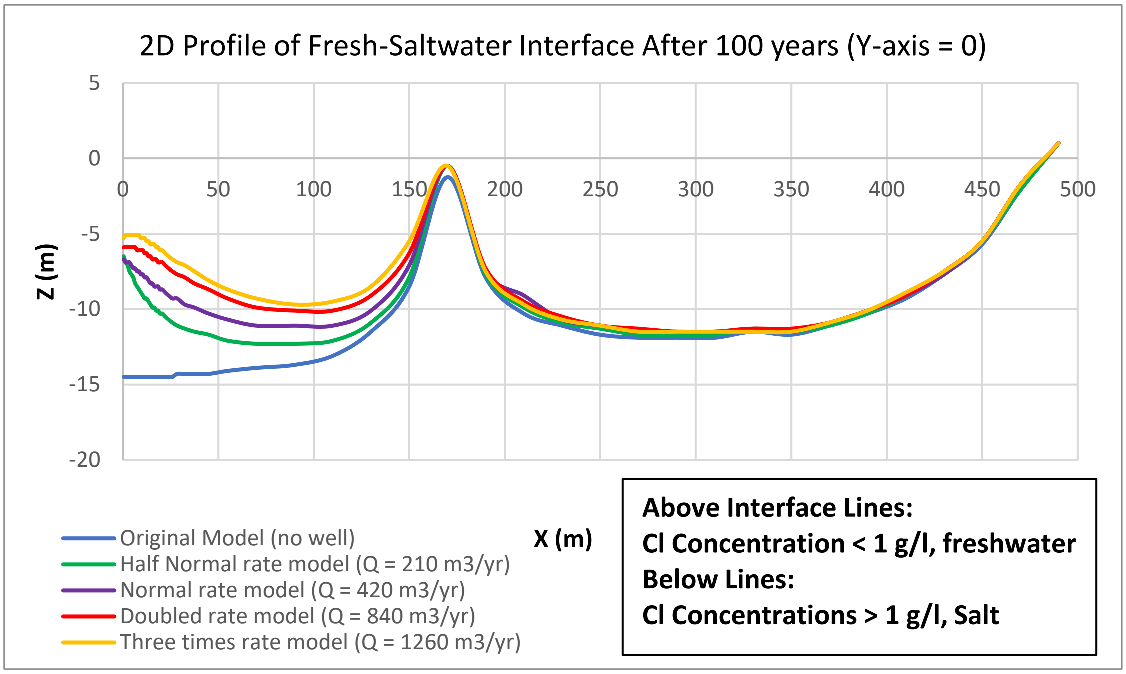

Figure 16: Fresh-Saltwater Interface for Different Models

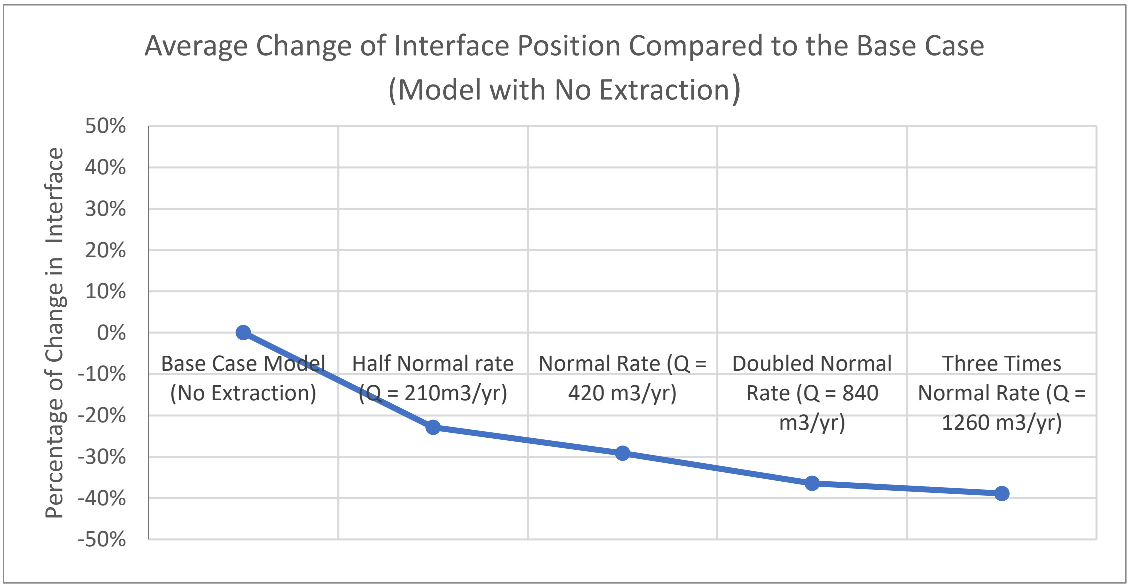

Figure 17: Change of Fresh-Salt water Interface between Different Models

It can be noticed from figure 17 that the relative change of the fresh-salt water interface position for all the extractions models compared to the base case model is significant at the well location (at x=0) then decreased towards the drain (from x=0 to x=170m) and diminished after the drain (from x = 170 to x = 500). The average change of the freshwater interface compared to the base case (no extraction) was (-23%, -29%, -36%, -39%) for the half-normal rate model, normal rate model, doubled normal rate model and three-times normal rate model respectively.

5.5.2 Effect on Freshwater Volume

The total freshwater volume was calculated for each model as shown:

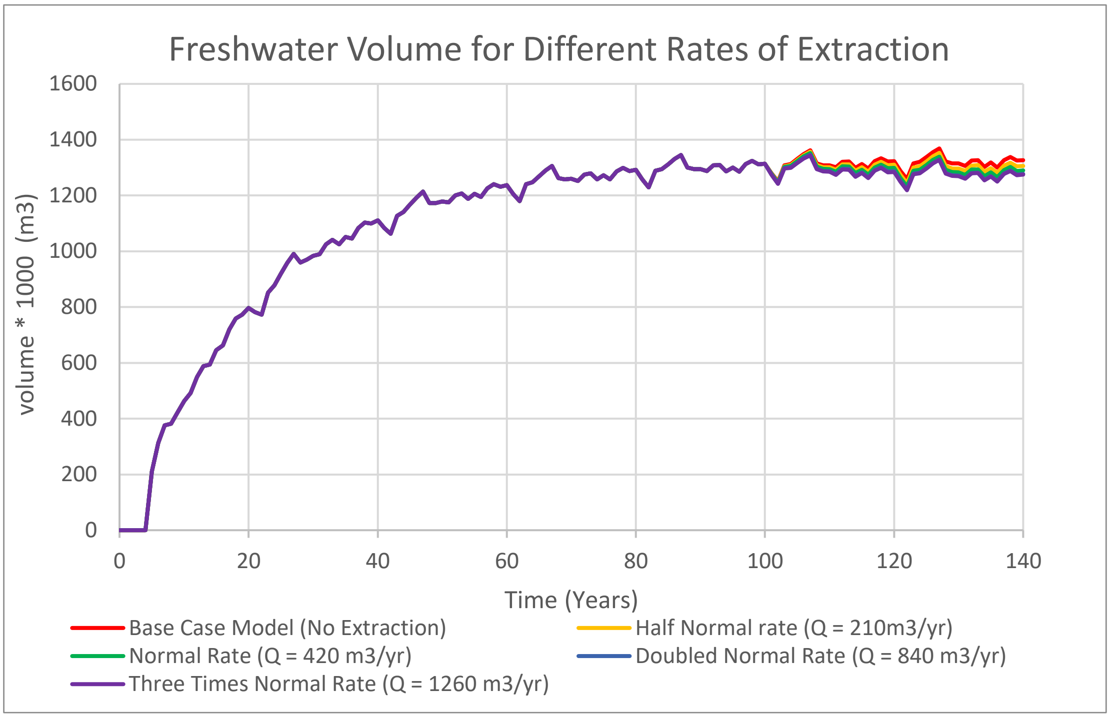

Figure 18: Freshwater Volumes for Different Models

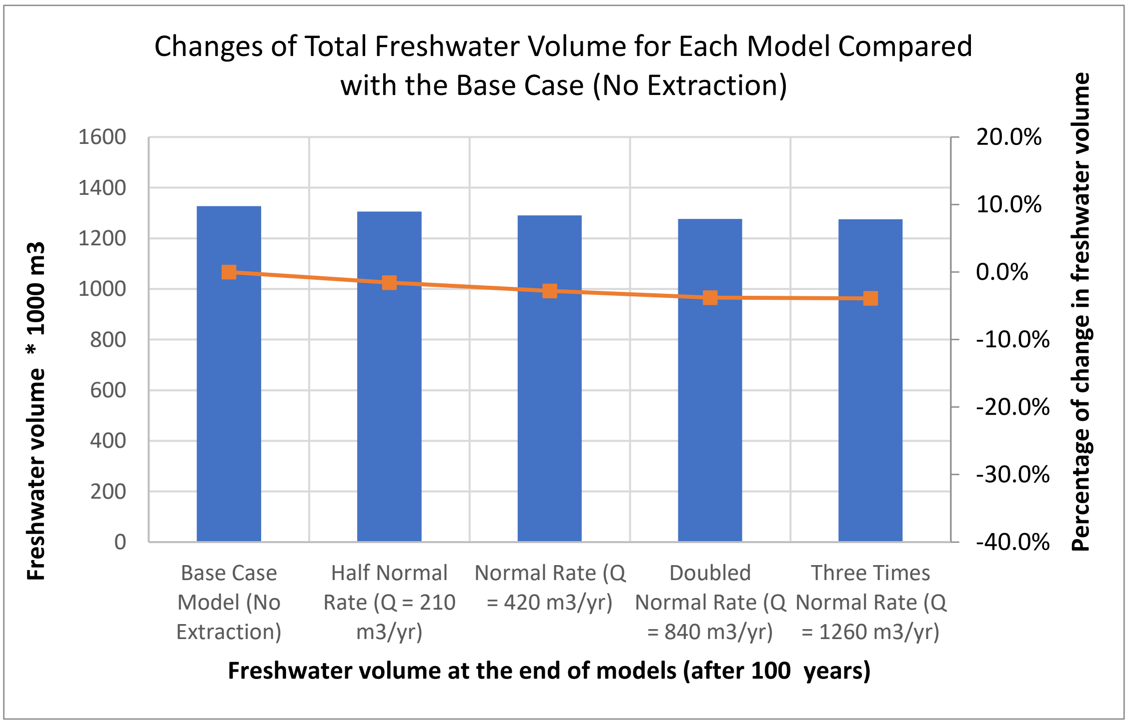

Figure 19: Change in Total Freshwater Volume for Different Models

It can be noticed from the figures that the relative change of the freshwater volume for all the extractions models compared to the base case model (no extraction) is very low. As the changes in the freshwater volume were (-1.6%, -2.8%, -3.8%, -3.9%) for the half-normal rate model, normal rate model, doubled normal rate model and three-times normal rate model respectively.

5.5.3 Effect on Water Concentration at the Well Location

The water concentration at the well point was defined in all the models as an observation point to detect the effect of the extraction on the water concentration. The following figure (left side) shows the water concentration at the well for all the models over the model's total time (140 years). While the right side of the figure shows the water concentration at the well only at the time of extraction (from year: 100 to year: 140) for only two models (half-normal rate model and normal rate model).

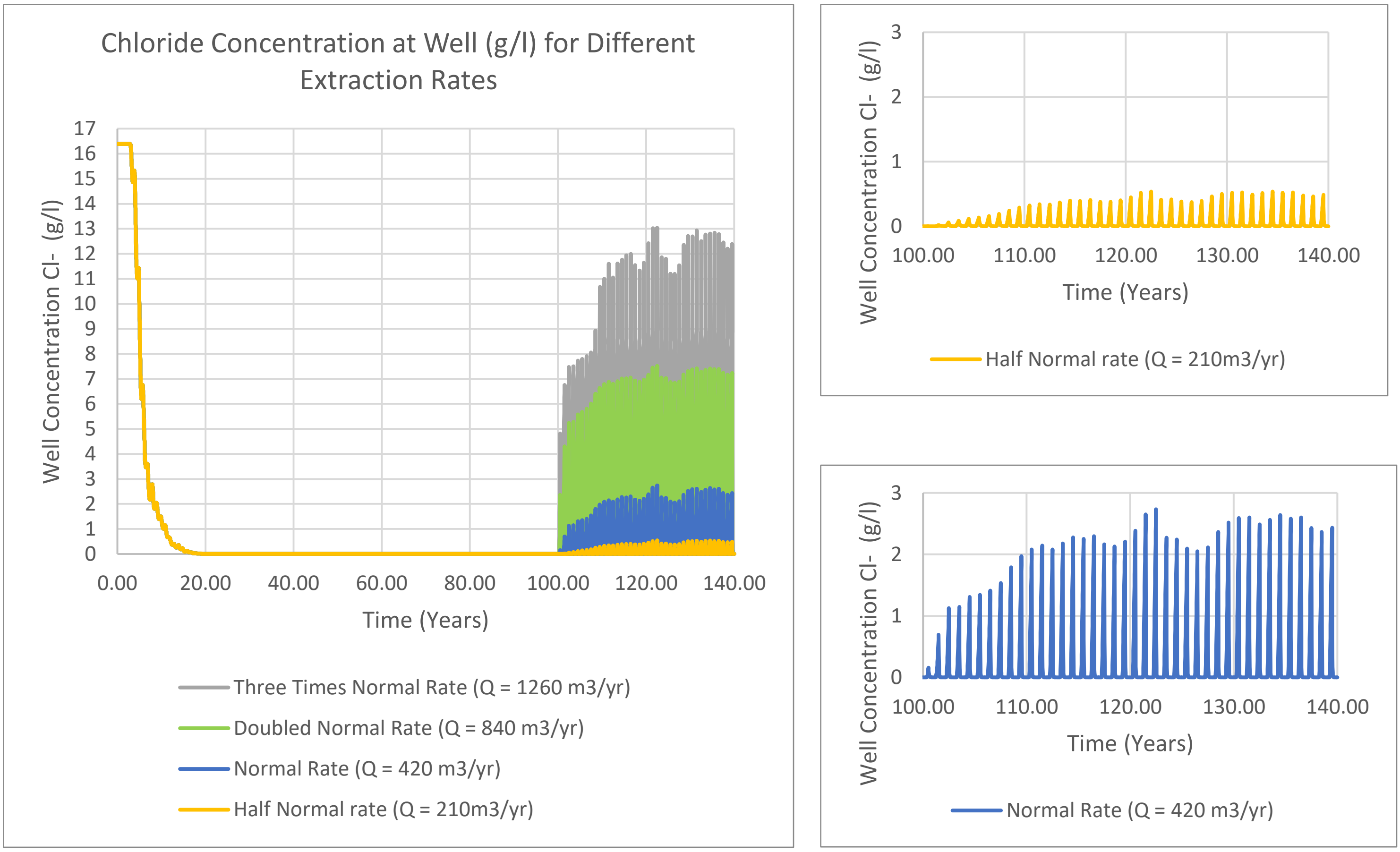

Figure 20: Chloride Concentration for Different Extraction Rates

As it was mentioned, the extraction process in the model starts after 100 years. So, it can be noticed that the concentration at the well will start from the initial value = 16.4 Cl^{-1} g/l then decreases over the first 100 years. Once the extraction process starts, the water concentration at the well will start to increase at the periods of extraction (14 weeks every year) and decrease again at the periods of no extraction. The concentration values are directly proportional to the rate of extraction as it can be noticed from figure 20, that the half-normal rate model has a maximum concentration of around

0.5 Cl^{-1} g/l while the normal rate model has a maximum concentration of around 2 Cl^{-1} g/l. Therefore, the extraction rates (normal, doubled normal and three-times normal) provide water with concentration higher than the maximum concentration allowable (1 Cl^{-1} g/l) for agricultural activities.

5.5.4 Effect on Model Run Time

As the models in this task had the same setting except for the extraction rates, there was no difference between the run times between the different models.

6 Task-3: Changing the Model Total Depth

The main idea of task 3 is to test how the vertical discretization particularly the total depth of the model can affect the groundwater system response particularly the fresh-salt water interface and the total freshwater volume. All the models will have the same settings (weekly stresses), no well extraction, same horizontal discretization but different total depth for each model.

6.1 Base Case with 40 m depth

The model that will be considered as the base case in task 3 is the model of Schoonderwoerd, (n.d.) with total depth = 40m. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

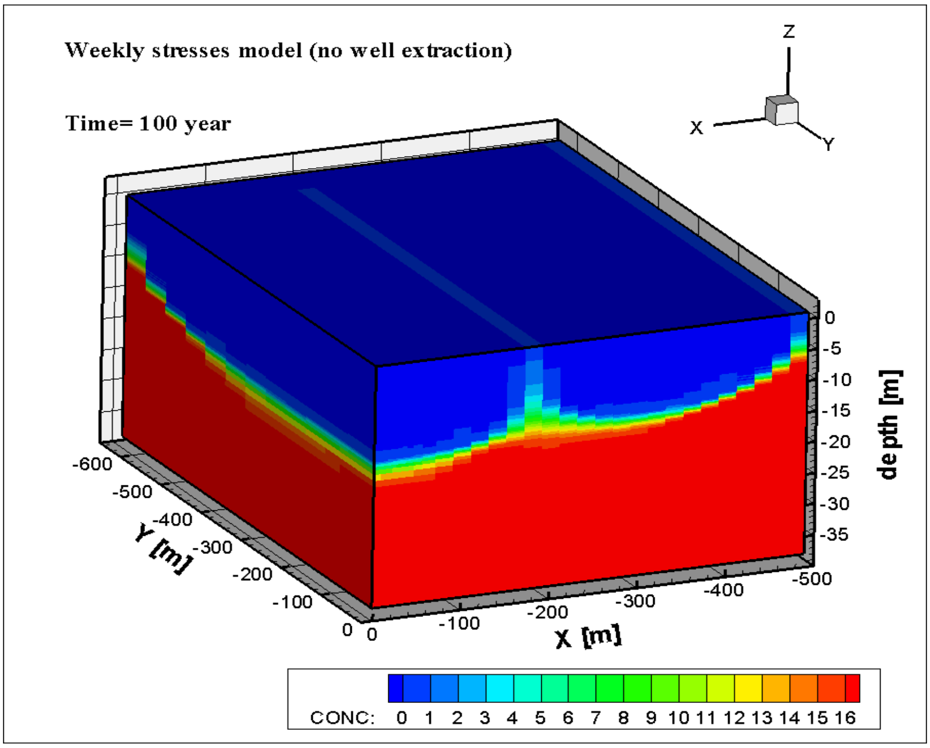

Figure 21: 3D plot of Chloride Concentrations for a Model with 40 m depth

6.2 Model with 20 m depth

The total depth was limited to 20 m in this model. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

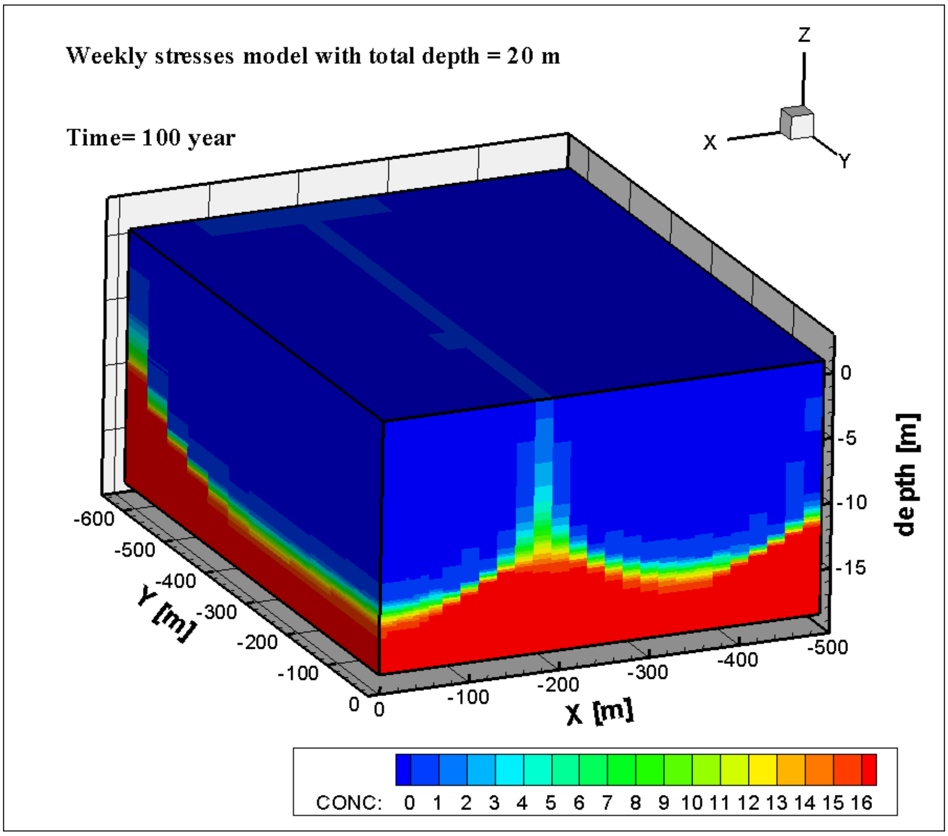

Figure 22: 3D plot of Chloride Concentrations for a Model with 20 m depth

6.3 Model with 15 m depth

The total depth was limited to 15 m in this model. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

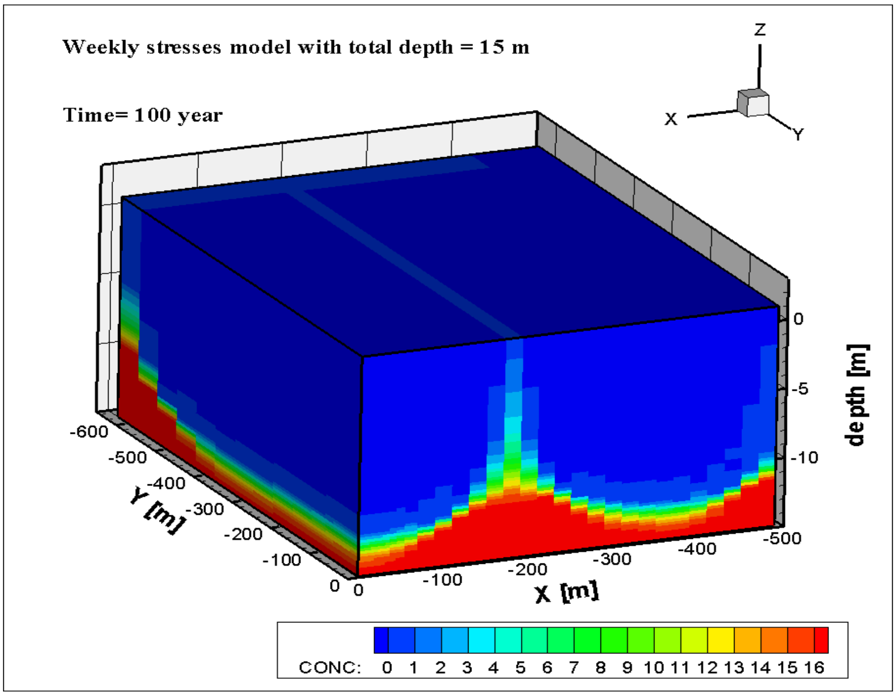

Figure 23: 3D plot of Chloride Concentrations for a Model with 15 m depth

6.4 Model with 12 m depth

The total depth was limited to 12 m in this model. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

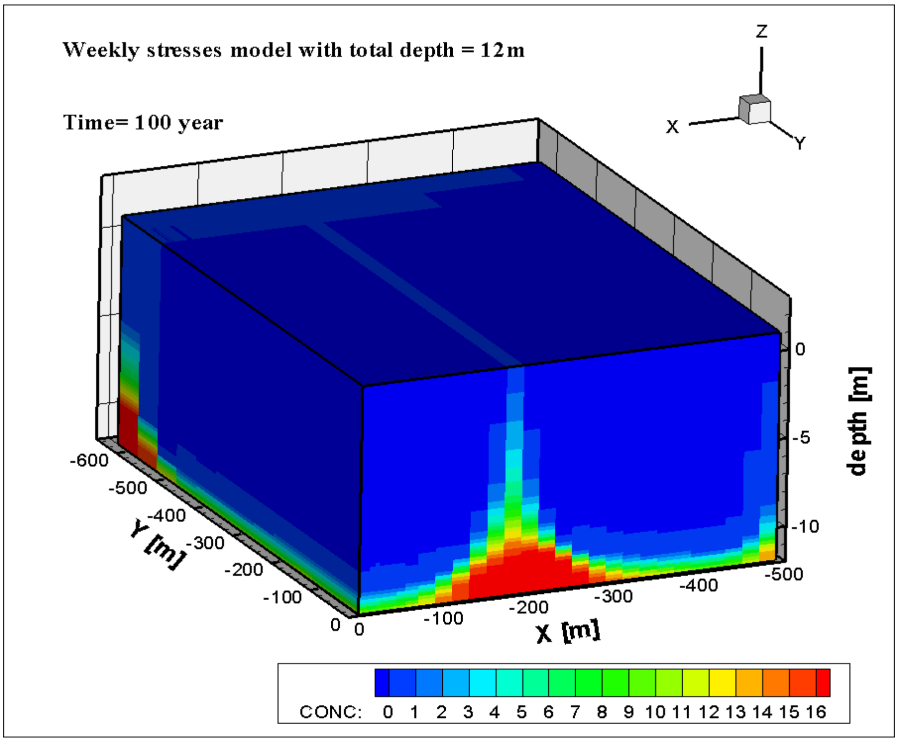

Figure 24: 3D plot of Chloride Concentrations for a Model with 12 m depth

6.5 Effect of Different Model Depth on the System Response

6.5.1 Effect on Fresh-Salt water Interface

For results comparison, the fresh-salt water interface was exported from the models at Y = 0 m at the end of the model (after 100 years). The following figures show the fresh-saltwater interface for each model and the difference of the interface position.

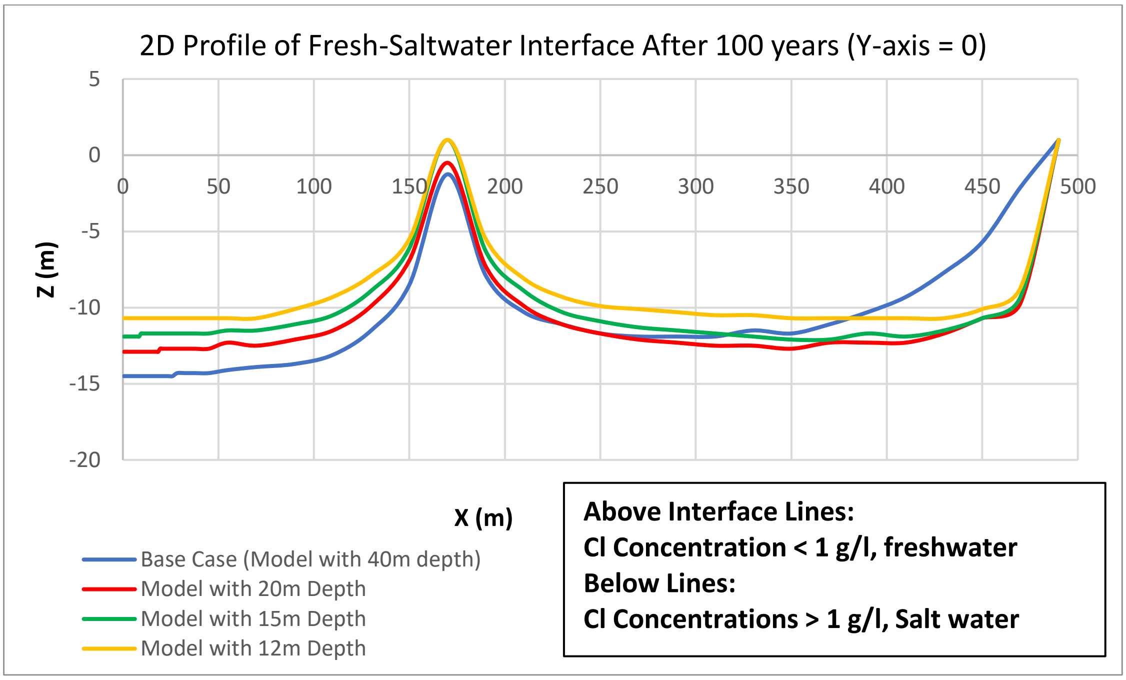

Figure 25: Fresh-Saltwater Interface for Different Models

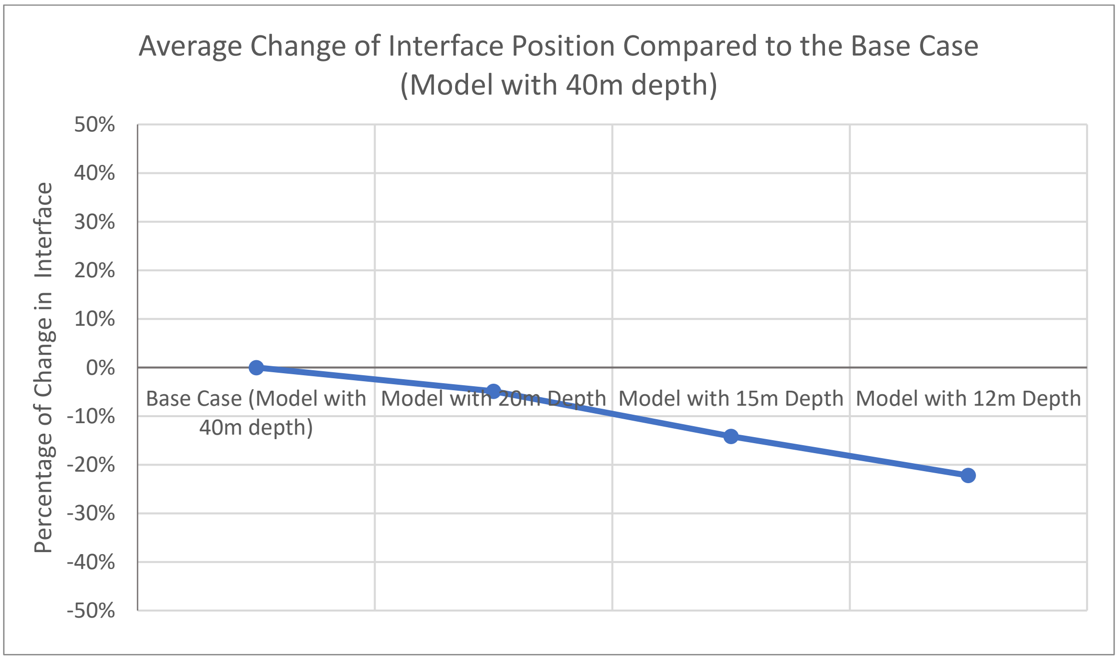

Figure 26: Change of Fresh-Salt water Interface

It can be noticed that the relative change of the fresh-saltwater interface position for the 20m depth model, 15m depth model and 12m depth model compared to the base case (40m depth model) is -5%, -14% and -22% respectively. Therefore, it can be concluded that there is an inverse relationship between the fresh-salt water interface position and the total model depth. Moreover, the pattern of the interface is also changing. For example, at Figure 25, at x=50m, the interface of the base case model is lower than all the other models while at x= 350, the interface of the base case is upper than the models with 20m depth and 15m depth but lower than the model with 12m depth.

6.5.2 Effect on Freshwater Volume

The total freshwater volume was calculated for each model as shown:

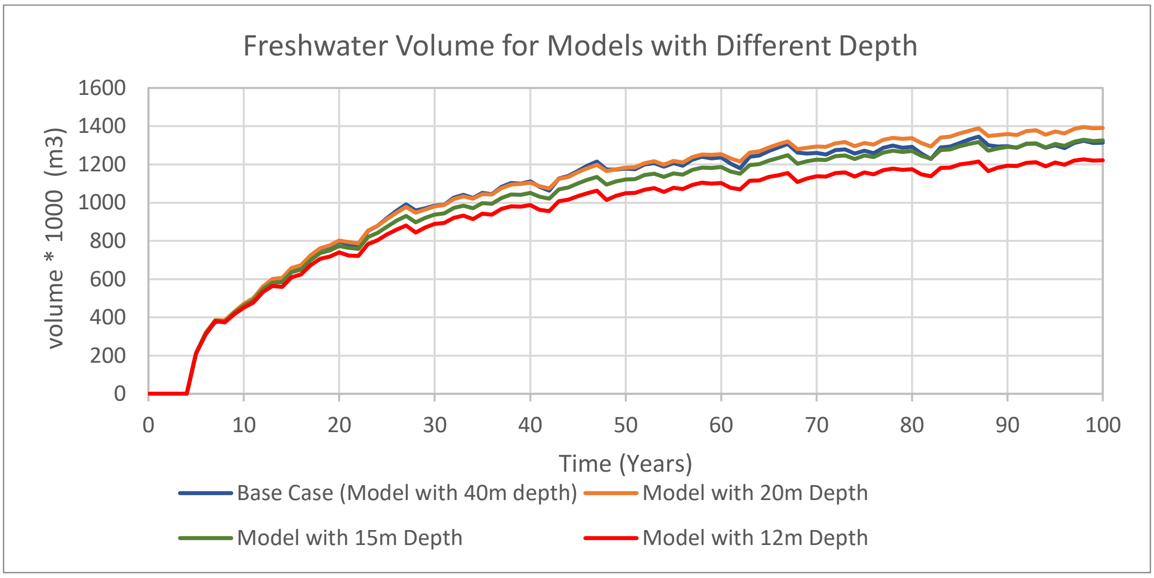

Figure 27: Freshwater Volumes for Different Models

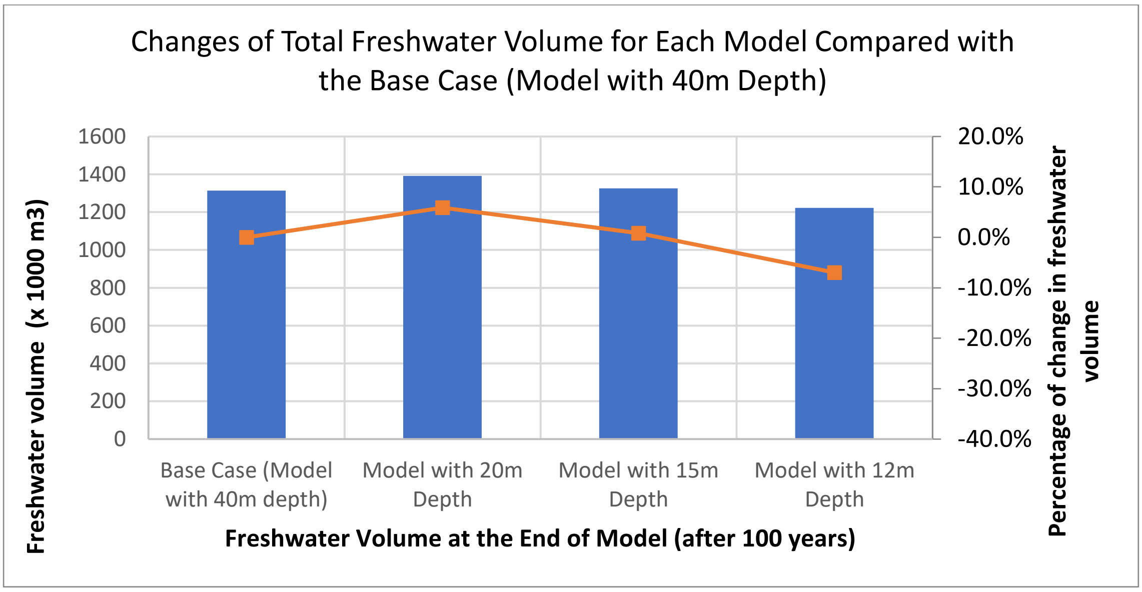

Figure 28: Change in Total Freshwater Volume

It can be noticed that the relative change of the total freshwater volume of the 20m depth model, 15m depth model and 12m depth model compared to the base case (40m depth) are not significant (6%, 1%, -7% respectively).

6.5.3 Effect on Model Run Time

The following figure shows how reducing the total depth of the model affect the run time.

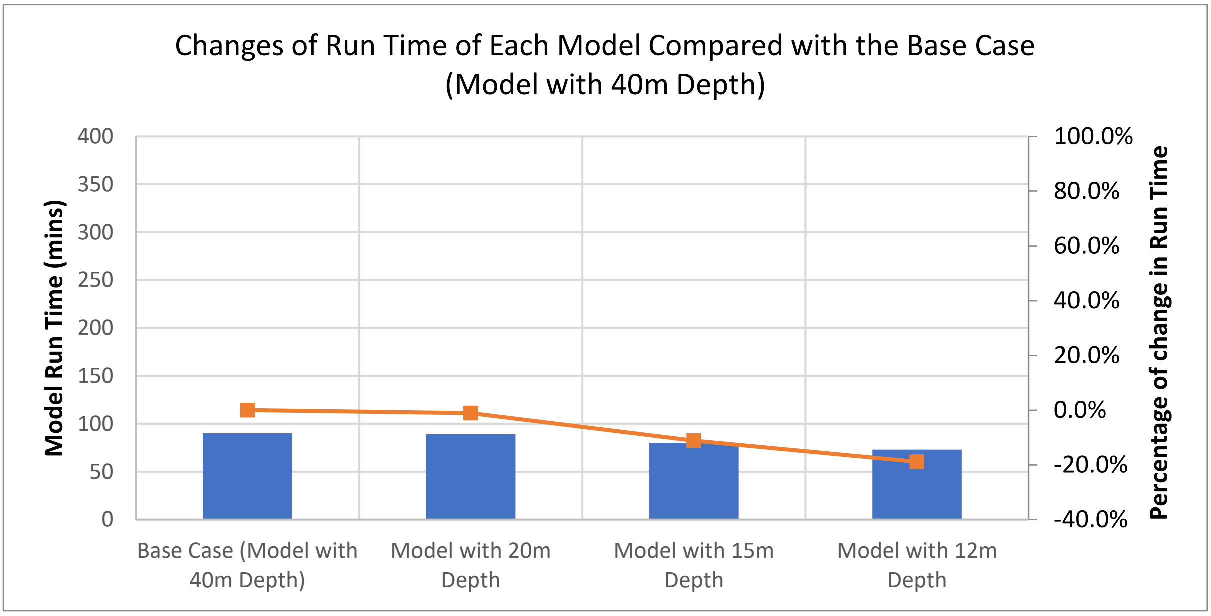

Figure 29: Run-Time for the Different Models

It can be noticed that the relative change of the models with 20m depth, 15m depth and 12m depth compared to the base case model (40m depth) are -1%, -11%, -19% respectively. However, the times for all these models are within one hour and a half (90 mins). Therefore, it can be concluded that the effect of changing the model depth on the run time is not significant.

7 Task-4: Lumping the Thickness of Model Layers

The main idea of task 4 is to test how the vertical discretization particularly the thickness of the model layers can affect the groundwater system response particularly the fresh-salt water interface and the total freshwater volume. All the models will have the same settings (weekly stresses), no extraction, same horizontal discretization but different vertical discretization (thickness of layers) for each model. As it was mentioned, the location of the well is at the origin (0,0) point with depth = 3.5 from the sea level. Therefore, the changes of the thickness of the layers will be below the first 4m of the models in order to keep the area of the extraction with the same fine resolution.

7.1 Base Case with 84 layers

The model that will be considered as the base case in task 4 is the model with 84 vertical layers which was defined by Schoonderwoerd, (n.d.). This model has fine resolution for the first 15m (0.2m for each layer). Then for the last 25m (from 15 to 40m), the thickness of the layers begins to be larger (0.5, 1 or 2m). The following figure shows a 3D plot of the model grid.

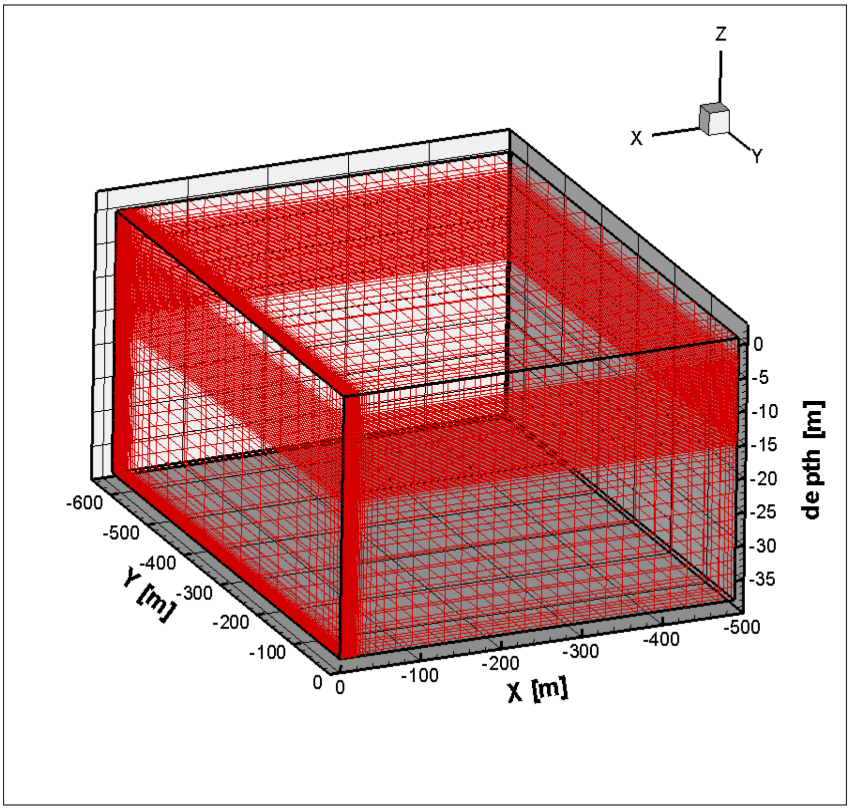

Figure 30: 3D Plot of Base Case Model Grid

The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

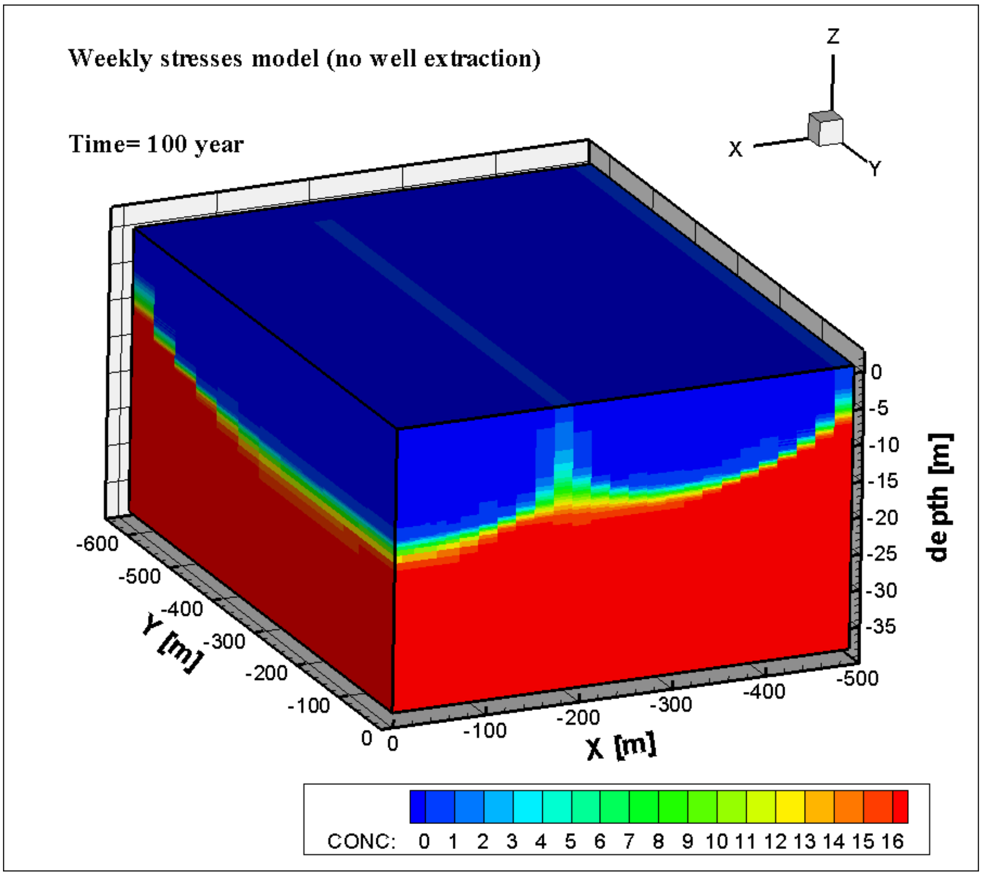

Figure 31: 3D plot of Chloride Concentrations for the base case model

7.2 Lumping the Thickness One Time (77 layers)

The thickness of the layers of the first 4m was fixed as the base case model. The thickness of the layers after the first 4m was lumped one time according to the following equation.

$$new\ layer\ thickness = \ thickness\ of\ corresponding\ layer\ of\ base\ case\ model * 2$$

The total number of the layers become 77. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

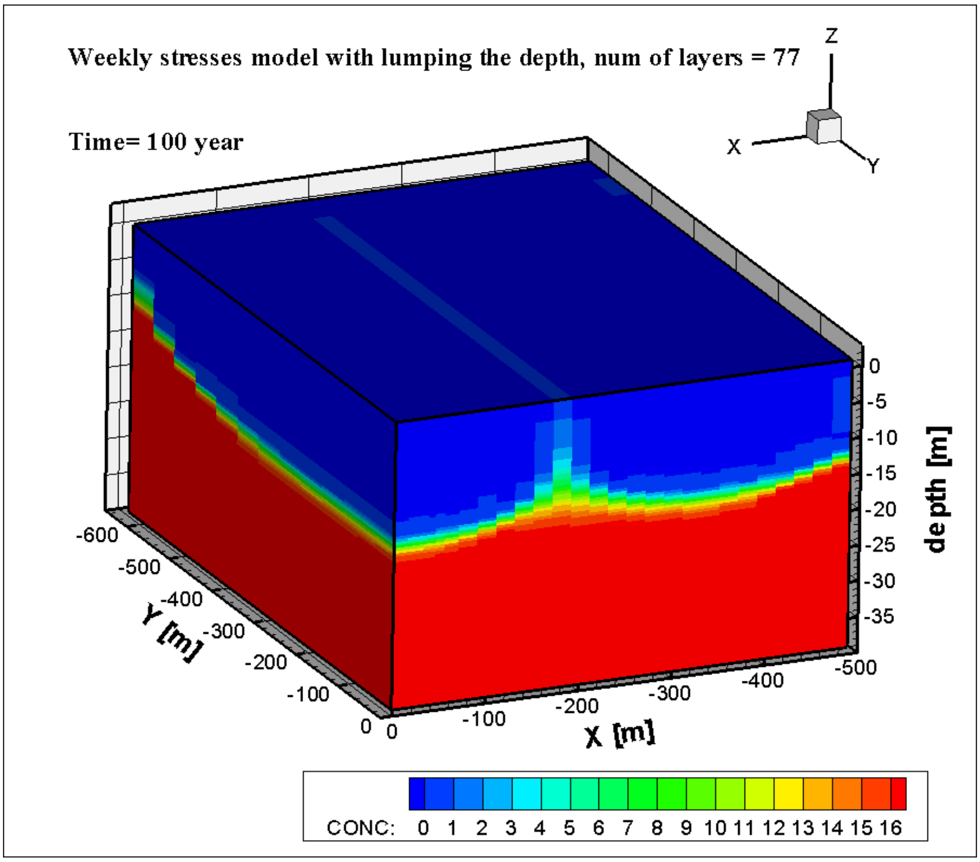

Figure 32: 3D plot of Chloride Concentrations for the model with one-time depth lumping

7.3 Lumping the Thickness Two Time (71 layers)

The thickness of the layers of the first 4m was fixed as the base case model. The thickness of the layers after the first 4m was lumped two times according to the following equation.

$$\mathit{new\ layer\ thickness} = \mathit{thickness\ of\ corresponding\ layer\ of\ base\ case\ model} * 3$$

The total number of the layers become 71. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

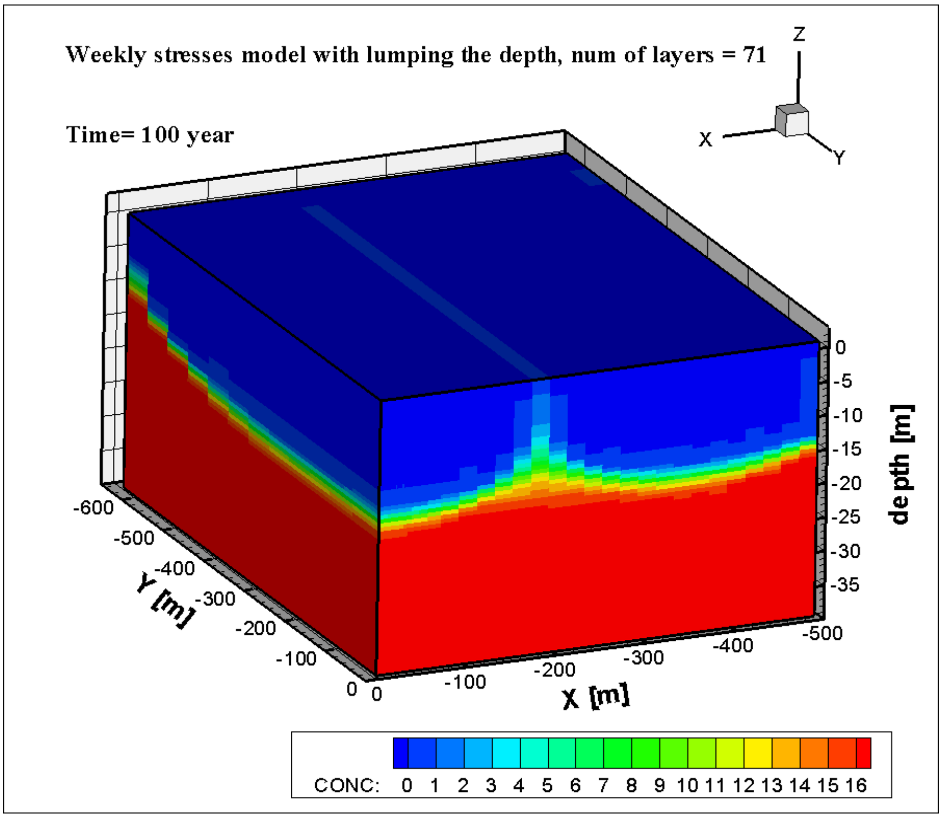

Figure 33: 3D plot of Chloride Concentrations for the model with Two-times depth lumping

7.4 Lumping the Thickness Three Times (58 layers)

The thickness of the layers of the first 4m was fixed as the base case model. The thickness of the layers after the first 4m was lumped three-times according to the following equation.

$$new\ layer\ thickness = \ thickness\ of\ corresponding\ layer\ of\ base\ case\ model * 4$$

The total number of the layers become 58. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

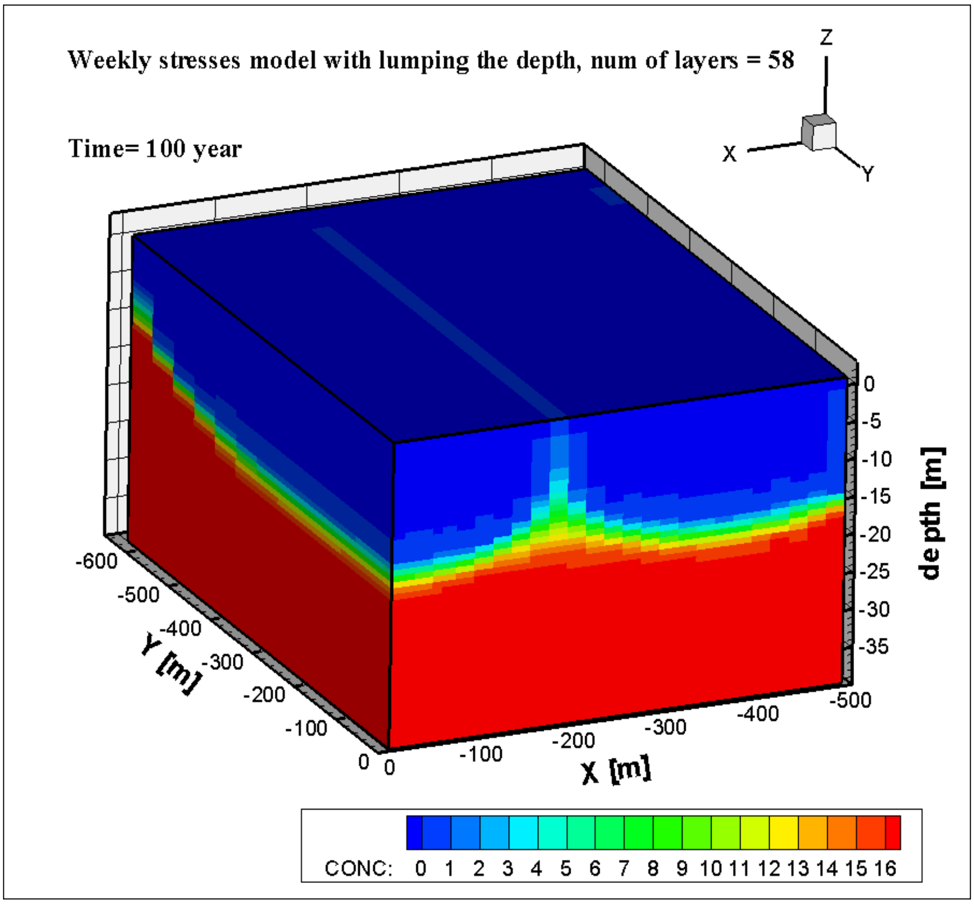

Figure 34: 3D plot of Chloride Concentrations for the model with Three-times depth lumping

7.5 Effect of Different Layers Thickness on the System Response

7.5.1 Effect on Fresh-Saltwater Interface

For results comparison, the fresh-salt water interface was exported from the models at Y = 0 m at the end of the model (after 100 years). The following figures show the fresh-saltwater interface for each model and the difference of the interface position.

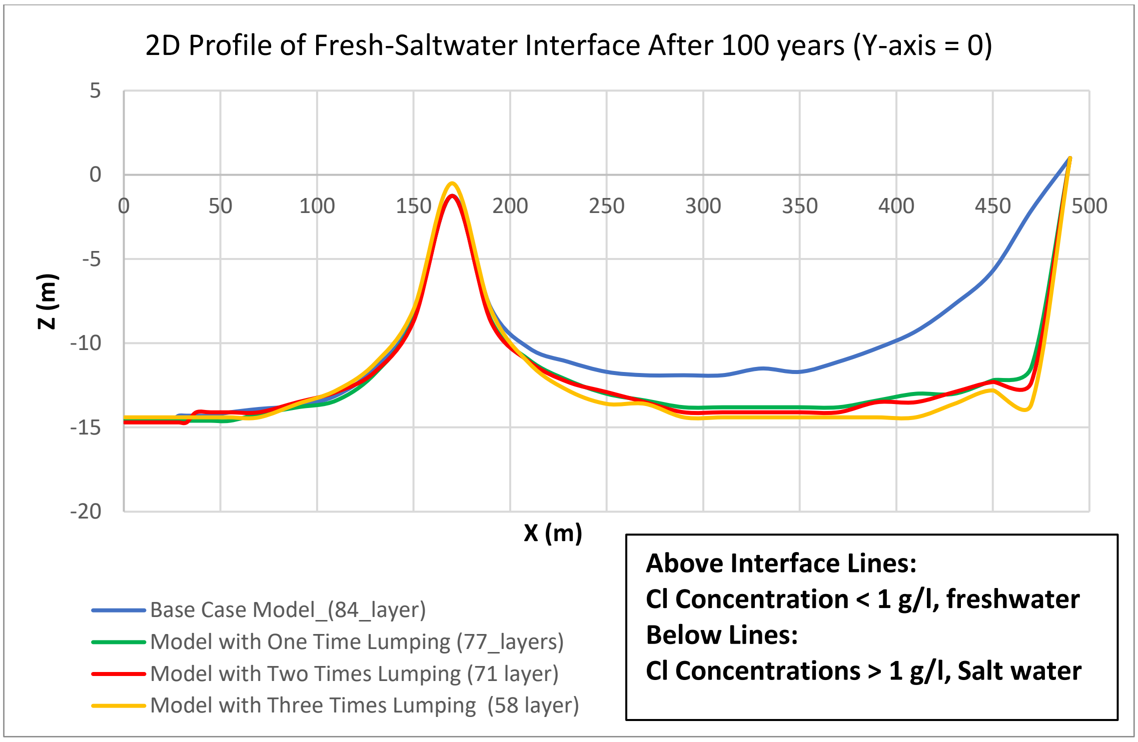

Figure 35: Fresh-Saltwater Interface for Different Models

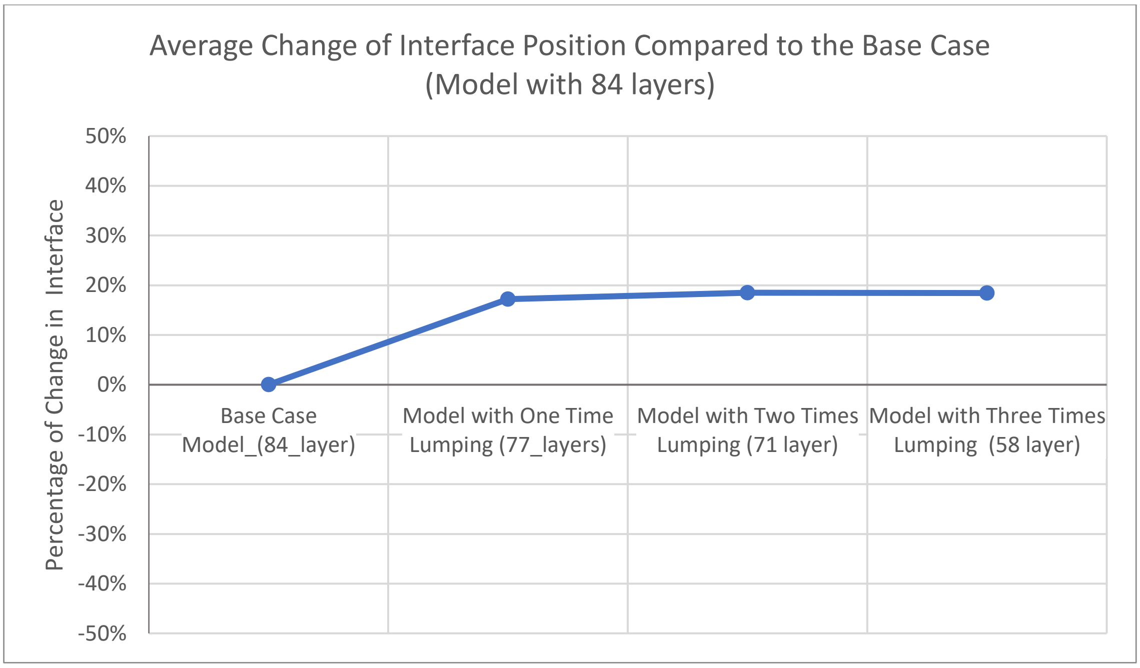

Figure 36: Change of Fresh-Salt water Interface

It can be noticed that the relative change of the fresh-saltwater interface position for the 77 layers model, 71 layers model and 58 layers model compared to the base case (84 layers model) is 17.2%, 18.4% and 18.5% respectively. Therefore, it can be concluded that there is a direct relationship between the fresh-salt water interface position and the thickness of the layers.

7.5.2 Effect on Freshwater Volume

The total freshwater volume was calculated for each model as shown:

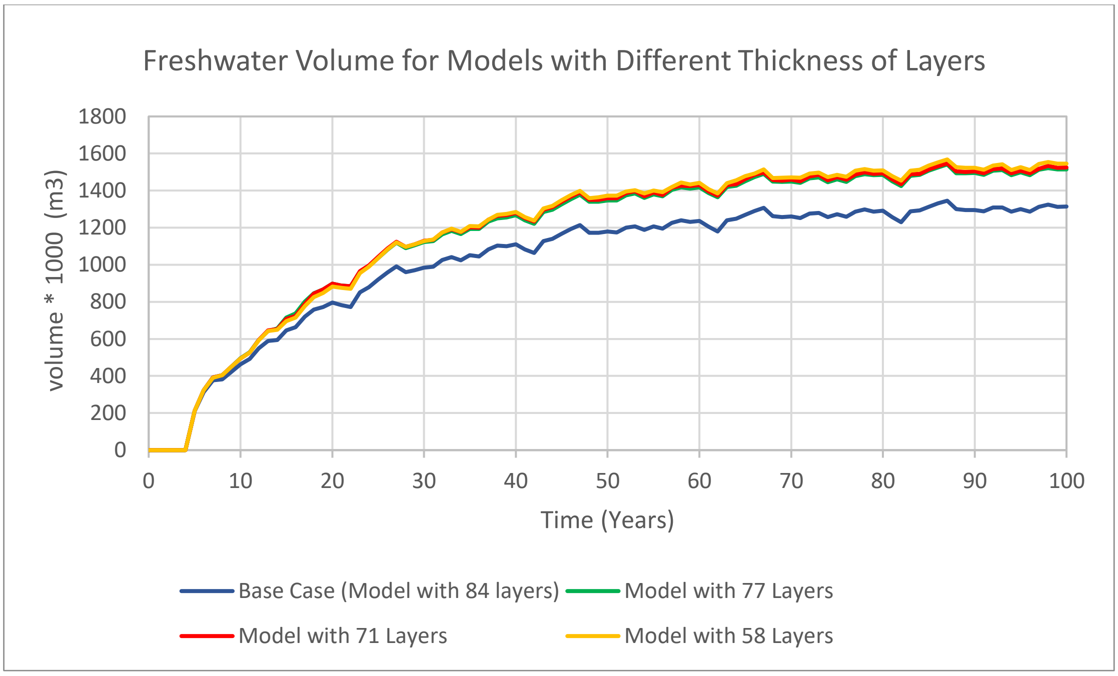

Figure 37: Freshwater Volumes for Different Models

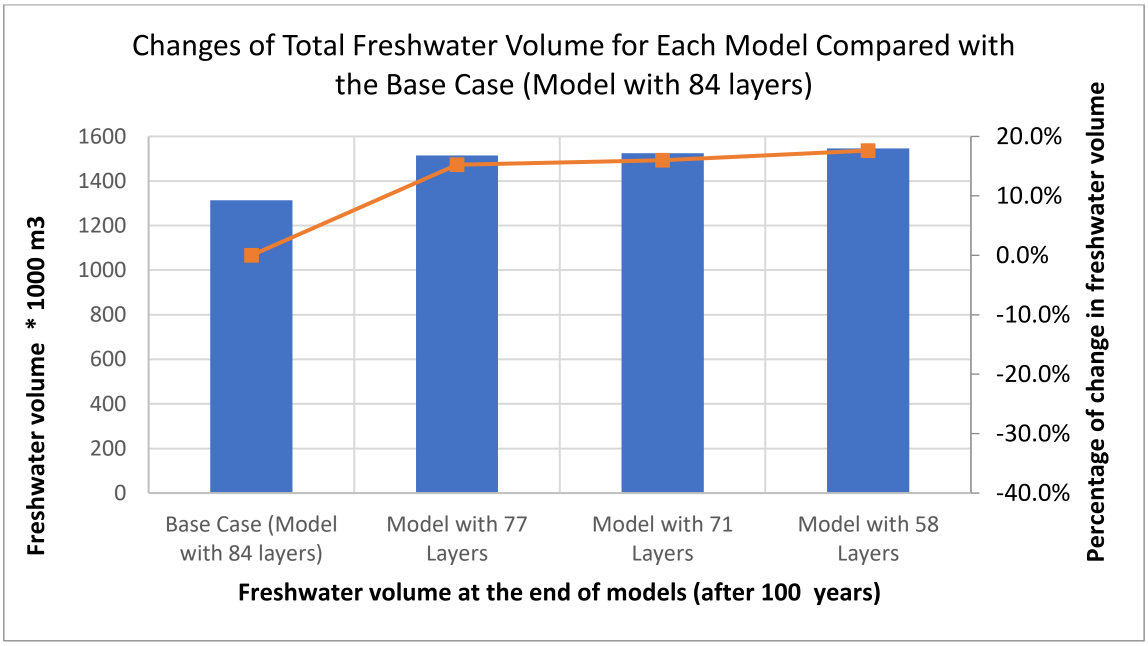

Figure 38: Change in Total Freshwater Volume

It can be noticed that the relative change of the total freshwater volume for the 77 layers model, 71 layers model and 58 layers model compared to the base case (84 layers model) is 15.3%, 16% and

17.6% respectively. Therefore, it can be concluded that there is a direct relationship between the total freshwater volume and the thickness of the layers.

7.5.3 Effect on Model Run Time

The following figure shows how lumping the thickness of the model layers affects the run time.

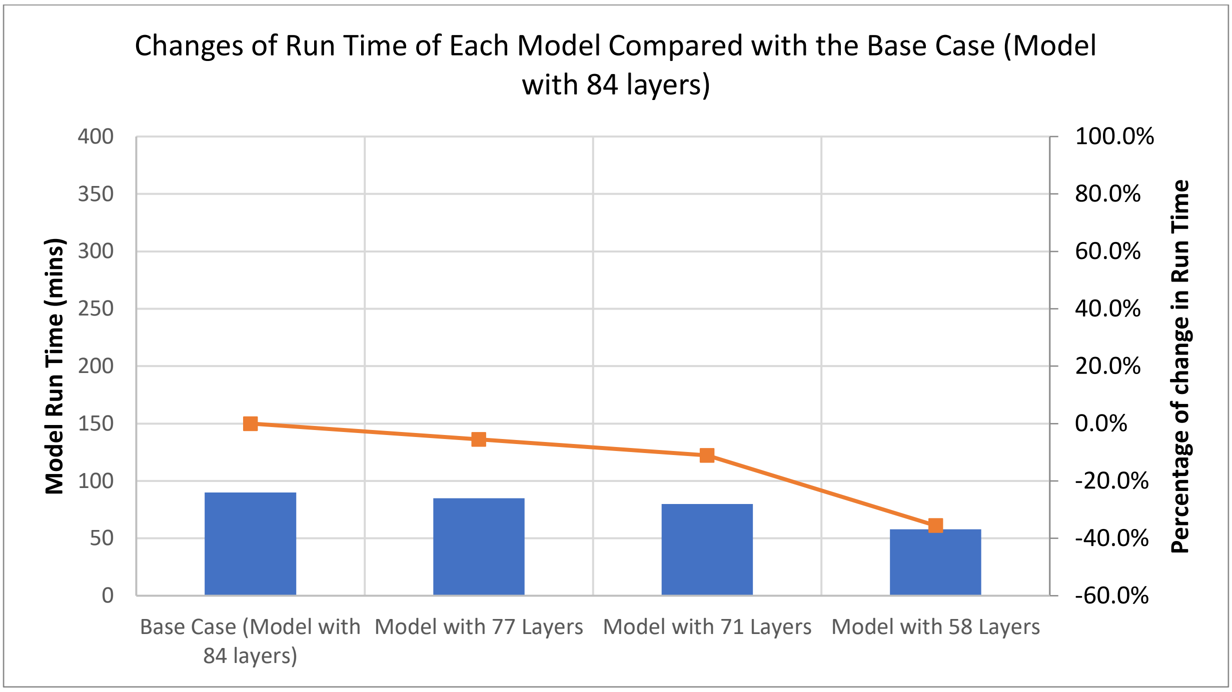

Figure 39: Run-Time for the Different Models

It can be noticed that the relative change of the models with 77 layers, 71 layers and 58 layers compared to the base case model (84 layers) are -5.5%, -11%, -35% respectively. Therefore, it can be concluded that the effect of changing the thickness of the model layers on the run time is significant.

8 Task-5: Different Solvers for the Transport Model

The main idea of task 5 is to test how different numerical solvers can affect the groundwater system response particularly the fresh-salt water interface and the total freshwater volume. In the meantime, MODFLOW 6 doesn’t support yet all the well-known solvers used for the contaminant transport models compared with MT3DMS. The current available numerical solvers in MODFLOW 6 are the Third-Order TVD solver and the Finite-Difference solver with two options of weighting (upstream weighting and central weighting). Due to the limitations of the input and output documentation of the transport model, the default settings of these solvers will be used. All the models will have the same settings (weekly stresses), no extraction, same spatial discretization but with different solver.

8.1 Base Case Model (TVD solver)

The numerical methods to solve the contaminant transport (advection-dispersion-reaction equation) can be classified as Eulerian, Lagrangian and mixed Eulerian-Lagrangian (Zheng & Wang, 1999). The TVD method is a higher-order finite difference method which belongs to the Eulerian category. Using the TVD solver will allow diminishing the concentration difference between two adjacent nodes over the time step of the transport model. The main advantage of TVD method is that it is much more accurate in solving the advection dominated problems (Zheng & Wang, 1999). In all the previous tasks, the used solver was the TVD solver, therefore the model with TVD solver will be considered as the base case. The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

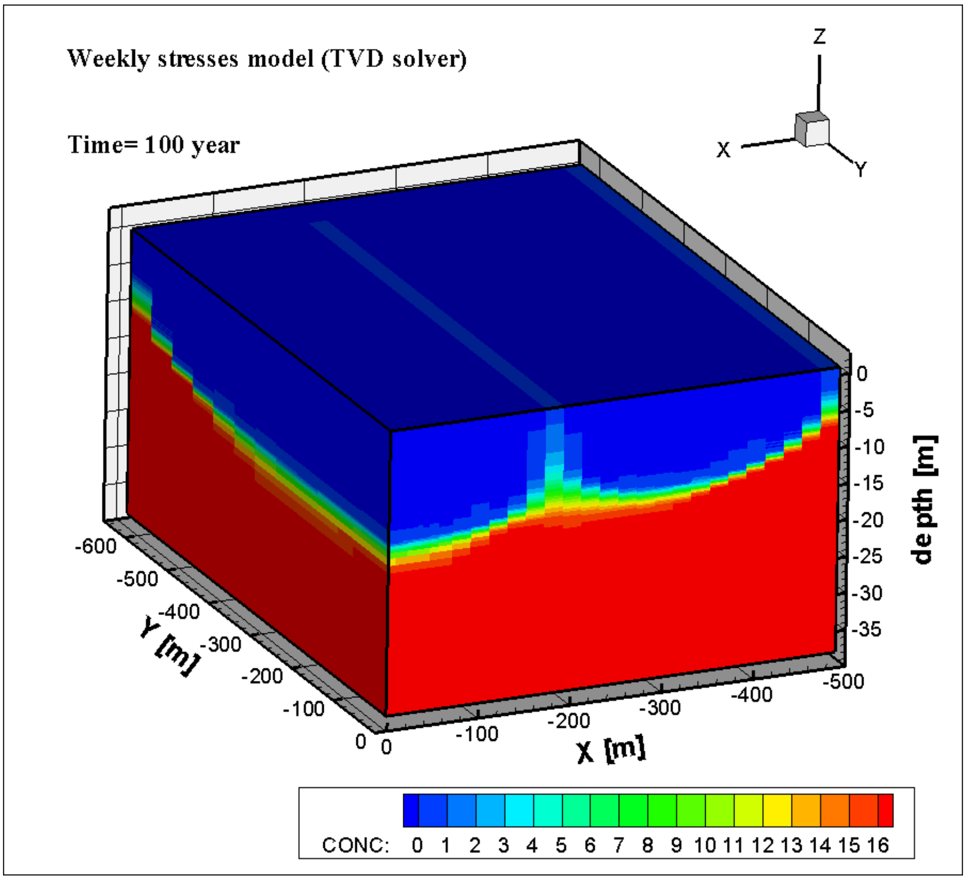

Figure 40: 3D plot of Chloride Concentrations for the Model with TVD Solver

8.2 Finite difference Solver with Upstream Weighting

The finite difference solver belongs to the Eulerian category which is a mass conservative approach. It also solves the transport equation with a fixed grid and better handle the dispersion dominated problems (Zheng & Wang, 1999). The grid consists of a group of cells which each cell has three dimensions (x, y, z). Each cell will be connected with the neighbouring cells through a number of interfaces which each interface should be normal to x, y or z directions. Determination the interface concentration is what distinguishes one solution technique from another. There are two different schemas used in the finite difference method (upstream schema and central schema). For the upstream weighting schema, the interface concentration between two neighbouring nodes in a particular direction is set to the concentration at the upstream node along the same direction. However, the solution of the advection term is only accurate to the first order which can lead to significant numerical dispersion in case of advection dominated problems (Zheng & Wang, 1999). The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

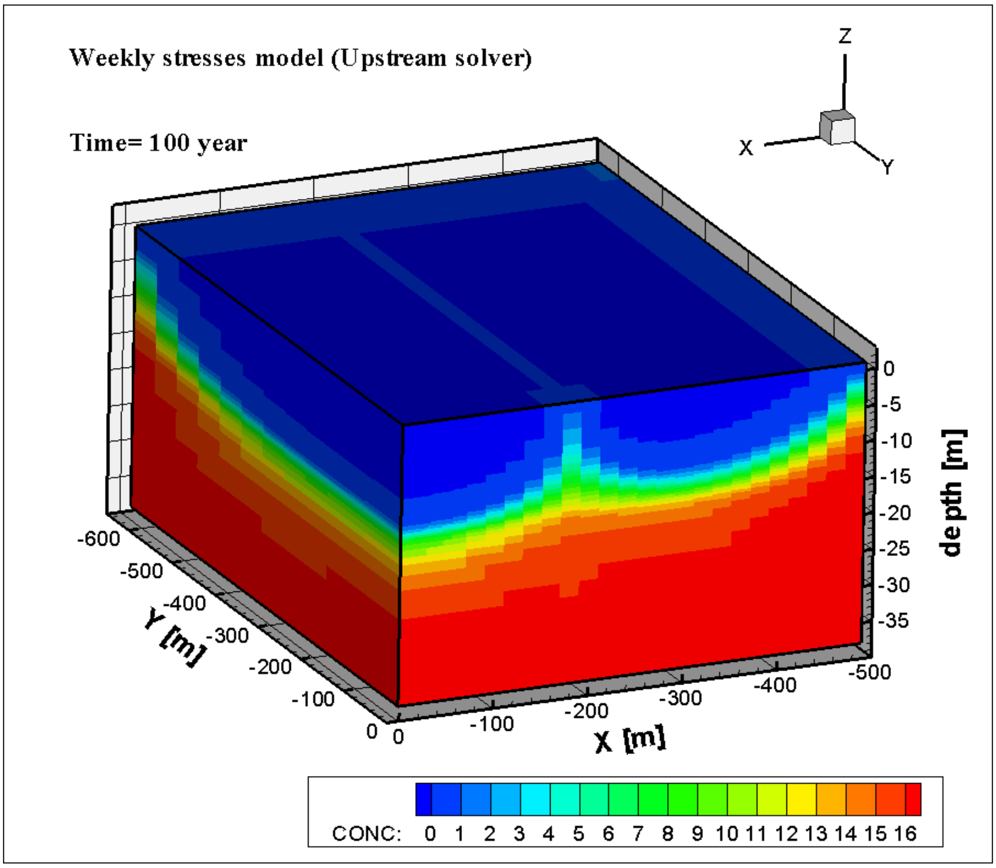

Figure 41: 3D plot of Chloride Concentrations for the Model with Upstream Weighting Schema

8.3 Finite difference Solver with Central Weighting

For the central weighting schema, the interface concentration is set equal to the weighted average of the concentration on the two sides of the interface. Therefore, the solution of the advection term is accurate to the second order which doesn’t lead to any numerical dispersion. However, it can lead to excessive artificial oscillation which leads to truncation errors in case of advection dominated problems (Zheng & Wang, 1999). The following figure shows a 3D plot of the Chloride concentration (CONC) distribution after 100 years. Values of concentrations are in Cl^{-1} g/l.

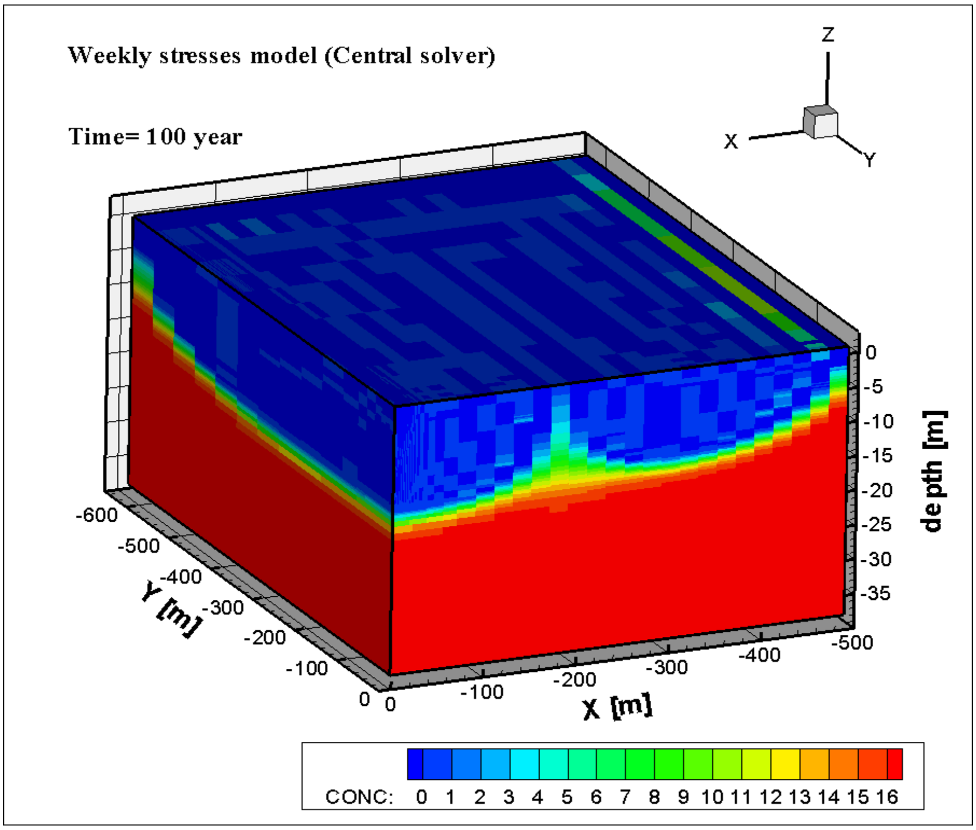

Figure 42: 3D plot of Chloride Concentrations for the Model with Central Weighting Schema

8.4 Effect of Different Numerical Solvers on the System Response

8.4.1 Effect on Fresh-Salt water Interface

For results comparison, the fresh-salt water interface was exported from the models at Y = 0 m at the end of the model (after 100 years). The following figures show the fresh-saltwater interface for each model and the difference of the interface position.

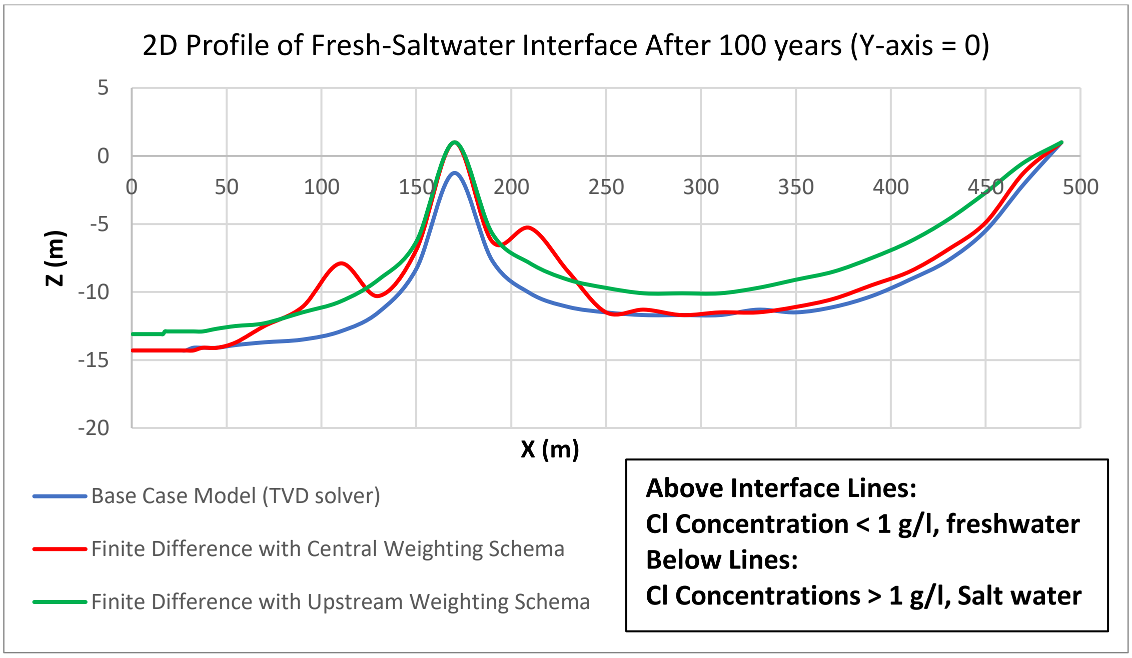

Figure 43: Fresh-Saltwater Interface for Different Models

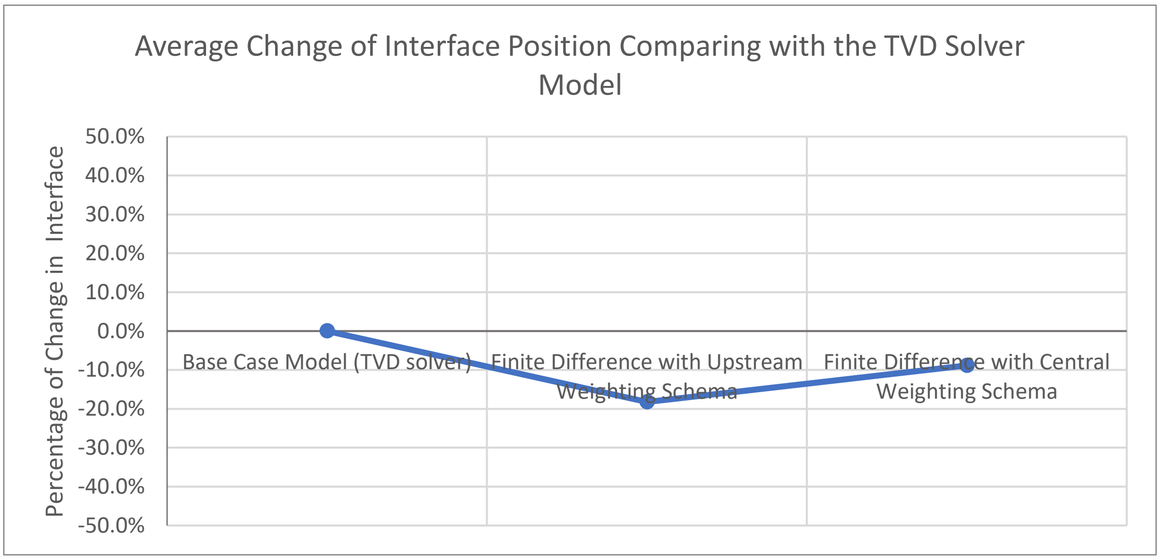

Figure 44: Change of Fresh-Salt water Interface

It can be noticed that the relative change of the fresh-saltwater interface position for the models with finite difference solver with (upstream weighting schema and with central weighting schema) compared to the base case (TVD solver model) is significant (-18.2% and -8.8% respectively).

8.4.2 Effect on Freshwater Volume

The total freshwater volume was calculated for each model as shown:

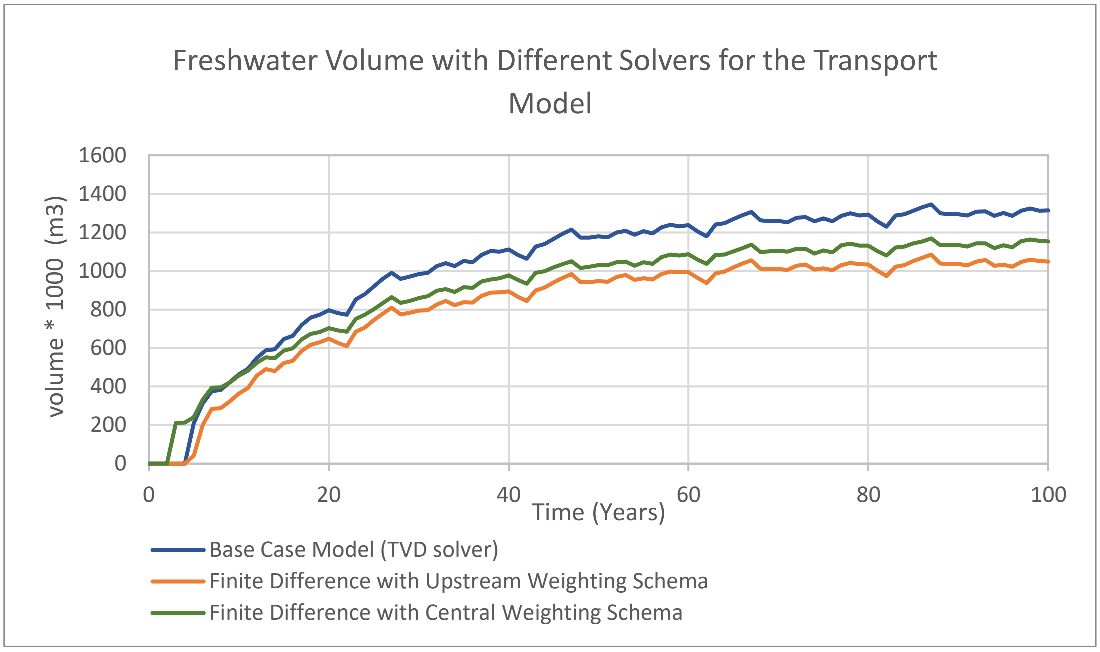

Figure 45: Freshwater Volumes for Different Models

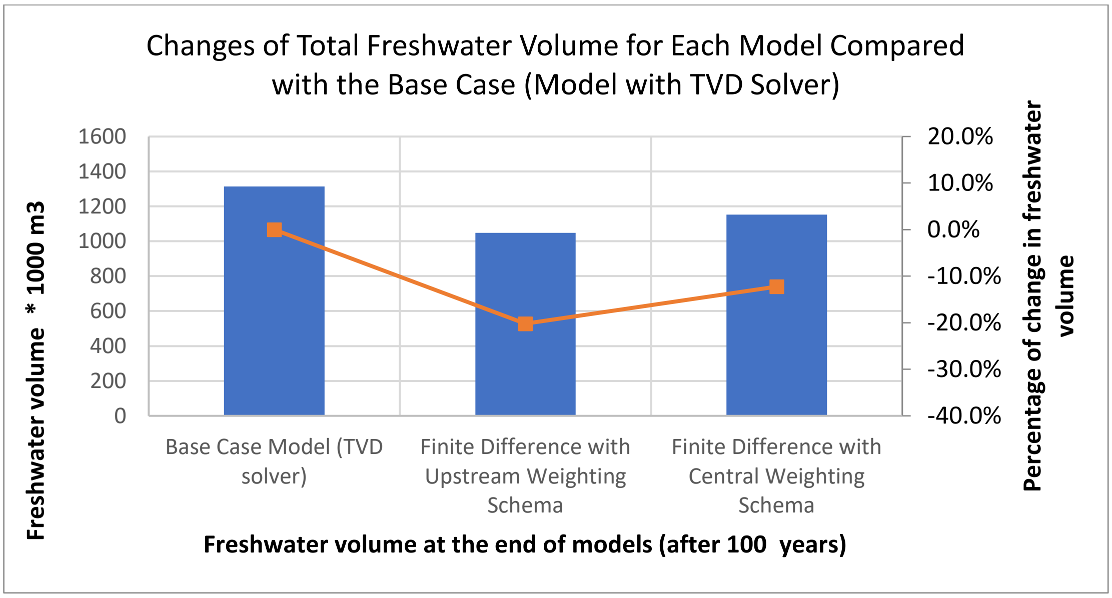

Figure 46: Change in Total Freshwater Volume

It can be noticed that different solvers gave different total freshwater volume. The relative change of the total freshwater volume of the finite difference solver models with upstream schema and central schema compared to the base case (TVD solver model) are significant (-20.2% and -12.2% respectively).

8.4.3 Effect on Model Run Time

As the models in this task had the same setting except for the solver, there was almost no difference between the run times between the different models.

9 Discussion

Task 1 shows the effect of the temporal discretization of the model stresses on the groundwater system response. It was noticed that the daily, weekly and monthly stresses models provide very close behavior for the fresh-salt water interface and the total freshwater volume (changes only in a range of ∓5%). However, the run time needed for the daily stresses model was too long (315% longer) compared with the weekly stresses model. The half-yearly stresses model gave different system behavior (underestimation of the fresh-saltwater interface by 46% and less freshwater volume (28%) compared with the weekly stress model. Therefore, it can be concluded that lumping the stresses weekly or monthly is accepted while the half-yearly lumping is not recommended.

Task 2 shows the effect of different extraction rates on the groundwater system response. It was noticed that the different extraction rates have no significant effect on the total freshwater volume (change in range of ∓5%), as all the tested extraction rates were not high. However, different extractions rates had a high effect on the concentration at the well location. As it was noticed that the model with the half-normal rate of extraction is the only one that provided extracted water with a concentration lower than the maximum concentration allowable for agriculture purposes (1 Cl^{-1} g/l) according to the WHO. Hence, it can be concluded that all other extraction rates (normal, doubled normal and three times normal) are not acceptable.

Task 3 and 4 show the effect of the vertical discretization of the model on the ground system response by changing the total depth of the model (Task 3) and the thickness of the model layers (Task 4). It was noticed that the total depth of the model doesn't have a significant effect on the total freshwater volume (changes only in a range of ∓7%). However, it is not recommended to create a model with a total depth close to the interface of the fresh saltwater. In this study, the fresh-salt water interface is almost at the level of (-10 to -12 m below sea level), so creating any model with a total depth less than 12 m is not recommended. Moreover, it was noticed that lumping the thickness of the layers has a significant effect on the total freshwater volume. As the lumped models (model with 77 layers, 71 layers and 58 layers) gave more freshwater volume than the base case model (84 layers) by 15.3%, 16% and 17.6% respectively. Therefore, it can be concluded that changing the depth of the model is acceptable as the depth is not close to the predicated fresh-salt water interface while creating a model with coarser thickness for the layers is not recommended.

Task 4 test the effect of using different numerical solvers for the transport model on the groundwater system response. It was noticed that different solvers result in different freshwater volume (changes in a range of ∓20%). Therefore, it is recommended to choose carefully the most appropriate solver depending on the conditions of the study area and if relative information is provided whether the problem is an advection dominated problem or a dispersion dominated problem.

10 Conclusion and Recommendations

Due to the limitations of the input and output documentation of MODFLOW version that include the transport models, the default parameters of the numerical solvers were used. Therefore, it is recommended to study the effect of changing these parameters on the system response for each solver. This can be done when the Official version of MODFLOW with the transport model will be published and enough documentation for the input and output is provided.

In conclusion, this research shows the reasonable conditions that can be applied to give more accurate results for the case of a variable density groundwater system. Moreover, it adds more details to the studies that are done before for the same study area (Zeeland province). Creating a model with very coarse temporal discretization or coarse vertical discretization is not recommended. Also, the numerical solver is still an important issue. Therefore, it is recommended to consider the results of this research for further studies in the same area or in a different area with similar conditions.

11 References

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