EFFECT OF FRESHWATER RECHARGE ON SALTWATER INTRUSION THROUGH AQUIFER

A DISSERTATION

Submitted in partial fulfilment of the

Requirements for the award of the degree

Of

MASTER OF TECHNOLOGY

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By

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CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled **'Effect of freshwater recharge on saltwater intrusion through aquifer'** towards the partial fulfilment of the requirement for the award of the degree of **Master of Technology** in **Hydrology** submitted in the Department of hydrology, Indian Institute of Technology Roorkee, Roorkee (India) is an authentic record of my own work carried out under the guidance of **Dr. Brijesh Kumar Yadav** (Associate Professor), Department of hydrology, Indian Institute of Technology Roorkee.

The matter presented in this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

Place: Roorkee **(SAURABH SHARMA)**

Date: **En. No. – 14537011**

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief.

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Date: **SAURABH SHARMA**

ABSTRACT

The management of salt water intrusion in the coastal aquifer is the major environmental problem faced by water resource planners worldwide. Saltwater intrusion is the process of movement of saline water into the fresh water aquifer, which contaminate the drinking water resources. This contamination process is occurring because of high demand of water during summer months when people extract more groundwater from aquifer. Once saltwater intrusion has begun, the continued irrigation of crops using water with high salt content produces a progressively higher salt residue in soil which accelerates the desertification of soils. In order to control the process of salt water intrusion, various laboratory experiments were performed to study the pattern of saltwater transport in freshwater aquifer. All experiments were conducted in a sand box. The sand box was divided into three distinct chambers: a central flow chamber containing the porous medium and two constant-head chambers containing salt water and freshwater. There were several ports present on the back side of the sand box. These ports were arranged at a 14 cm apart from each other but first port was at 7 cm from left side of sand box and second port was at 7cm ahead from first port and remaining ports were 14cm apart from each other. Each port was connected with syringe from which the sample of saltwater was collected. In first experiment the sand box was allowed to transmit freshwater from left to right at a fixed gradient condition. Subsequently saltwater was introduced in the sand box to see the progression of saline water concentration in the aquifer system. The saltwater concentration was measured with the help of conductivity meter. After that a series of three experiments was performed with three different freshwater recharging fluxes (900mm/day, 2000mm/day and 3300mm/day) by keeping the similar hydrological conditions. The breakthrough curves were obtained at different locations by sampling the soil water from various ports. After 6 hours, It was observed that under no recharge of freshwater a salt concentration was observed upto 40% of the boundary condition (35000ppm) at port 2, while it was further delayed in ports located to down gradient locations. On the other hand, under recharging cases of 900mm/day, 2000mm/day and 3300mm/day the saltwater concentration in port 2 increased only upto 37%, 33.6% and 28.6% of initial concentrations, respectively. This shows the positive role of surface water recharge on ingress of saline water in fresh aquifer zones. Before simulating our experiments datasets first we took literature datasets and simulate these datasets in SEAWAT simulator of

visual MODFLOW for model testing. After that, simulation experiments were conducted for these cases using SEAWAT simulator in visual MODFLOW integrated with PCG solver. The simulated and observed breakthrough curves were compared under different recharging conditions and compared well by calculating normalized root mean square value for all model domains. The results of this research are direct use in controlling the saline water intrusion by surface water recharging techniques at field level.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

The management of saltwater intrusion in the coastal aquifer is the major environmental management problem faced by water resource planners worldwide. Saltwater intrusion is the process of movement of saline water into the freshwater aquifer, which contaminate the drinking water resources. The most common pollutant of groundwater that affects many aquifers in coastal region is salt. This contamination process is occurring because of high demand of water during summer months. Once saltwater intrusion has begun, the continued irrigation of crops using water with high salt content produces a progressively higher salt residue in soil, that is not eliminated when aquifers are recharged and which helps to accelerate the desertification of soils.

The boundary between salt water and fresh water is not distinct. Extraction of groundwater is the main cause of intrusion of saltwater. Under baseline conditions, the inland extent of salt water is limited by higher pressure applied by the freshwater column, owing to its higher elevation. Due to extraction of Groundwater freshwater table become lower, reducing the pressure applied by the freshwater column and allowing denser saline water to displace freshwater. This situation commonly occurs in coastal aquifers due to excessive amount of pumping of well.

The other category concerns the alteration of natural barriers that separate fresh and saline waters. An example would be the construction of navigation channels or agricultural and drainage channels, which provide conduits for saltwater to move inland and sea level rise. The third mechanism deals with the subsurface disposal of waste saline water, such as into disposal wells, landfills and other waste repositories.

Saltwater intrusion can also be worsened by extreme meteorological events. Contamination by salts strongly deteriorates water quality making fresh water unsuitable for human consumption and for irrigation. Even a small concentration of chlorides in fact deteriorates water quality. For this reason saltwater intrusion induces the interruption of water diversion for agriculture. If when diverted, water has values of salinity greater than 1.5-2 permil, it is dangerous to irrigate (only rice crops can slight tolerate these values of salinity). Other problems can be the interruption of supply for aqueducts, the salinization of groundwater, the dry-up of coastal areas and desertification of soils.

Fig 1.1 Desertification of soil Mediterranean Sea area

These problems could theoretically be solved by desalting. However this is expensive and therefore desalting should be taken as an ultimate solution in cases where the cheaper conventional groundwater resources are insufficient (Dam J. C. van, 1999)

Moreover a by-product of desalting is brine, which is difficult to dispose off. In fact disposal in fresh surface waters will certainly not be tolerated while transport and discharge into saline surface water as estuaries and seas and injection of the brine into deep aquifers, if feasible and acceptable from the hydrogeological point of view, adds also to the costs.

An activity that can cause serious problems is the control (mostly lowering) of the groundwater table by means of artificial control of the surface water in an area or land drainage. This applies in particular in land reclamation projects. In the case of land reclamation in lagoons, tidal inlets or lakes, the lowering of the water table can even be several meters. Such great lowering over sometimes very large areas must have considerable effect on the regional groundwater flow system and can cause an unfavourable redistribution of fresh, brackish and saline groundwater. Artificial lowering of the groundwater table in an area induces seepage or increase of seepage in that area. The seepage water may be or become brackish or saline.

1.2 Chemical characteristics and sources of saltwater

All water consist dissolved chemical materials is called "salts". When the concentration of these dissolved materials becomes high, then this type of water is called "Saline water". This term may be confusing because it can mean different things for different people. As a result, many classification methods have been developed for creating difference between saline water and freshwater.

With reference to the circular 1262 of the USGS water can be defined as "freshwater" which having a total dissolved-solids concentration lower than 1000 mg/l; water with a total dissolved-solids concentration more than 1000 mg/l is saline water (or salt). This upper limit of freshwater is defined according to the suitability of the human being.

Although waters having total dissolved-solids concentrations higher than 1000 mg/l have been used for domestic supply in some parts of the United States where water of less dissolved-solids concentration are not available, water containing total dissolved solids more than 2000 to 3000 mg/l is generally too salty to drink (Freeze R. A., Cherry J. A., 1979).

Brackish water is defined as water which consist a total dissolved-solids concentration in range of 1000 to 35000 mg/l. The upper limit of concentration for brackish water is set at the approximate concentration of saline water (35 g/l). Water having total dissolved-solids concentration more than 35000mg/l is called “brine".

1.3 Objectives

In order to control the problem of saltwater intrusion, the objectives of this study are:

- To study the pattern and progression of saltwater transport in freshwater aquifer.
- To study change in concentration of saltwater in freshwater aquifer under different fluxes of surface water recharges.
- To simulate the saltwater ingress using SEAWAT simulator of Visual MODFLOW.
- To validate the simulated breakthrough curves using the experimental database.

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CHAPTER 2

LITERATURE REVIEW

2.1 Literature review

The theory of variable-density ground-water flow has been studied for many years, beginning with the early work of **Ghyben (1888)** and **Herzberg (1901).** Later, **Hubbert (1940)** presented a equation which is related to the elevation of a sharp interface to freshwater heads measured on the interface and related to the freshwater density and saltwater density. **Henry (1964)** used a semi analytical solution to showed shape, location of interface under constant seawater flux freshwater condition towards ocean boundary.

Cooper et al (1964) concluded that in coastal formations, seawater is not stagnant but it is in constant cyclic motion where a certain amount of intruding salt water is carried back towards the sea by dispersive mixing due to the seasonal rainfall and tidal motion. They concluded that due to dispersion the saltwater wedge is not sharp in shape and that a wide transition zone exists, bound the landward seawater intrusion, as opposed to the sharp interface formed by the Ghyben-Herzberg line. The same report provide a analytical solution to the density coupled flow equations that allow mixing of freshwater and saltwater by considering a large dispersion coefficient, which later became called the Henry problem. Over the years many works were published (ex. Voss and Sousa, 1987), where the Henry problem was taken as a benchmark for numerical simulators. None of them look like to match exactly to each other's results or the Henry solution itself.

Goswami et al (2007) presented laboratory results of steady-state and unsteady state data to be used for benchmarking numerical models. In that work, they provide a set of new benchmark data sets for checking saltwater intrusion models. This new benchmark is a stronger alternative to the original Henry problem since it take saltwater transport under both steady state and unsteady conditions. They present many experimental data sets which include a steady state salt-wedge data set, a data set of steady state flux, and two types of unsteady salt-wedge data sets. This experimental setup described explained a novel approach for simulating the boundary condition of saltwater in a laboratory-scale saltwater intrusion model. The results explained that the mixing of freshwater and saltwater within the saltwater reservoir was minimal, and hence the system was able to imitate the constant-head boundary condition of saltwater. The experimental results also show that the transition zone between the freshwater and saltwater regions is sharp under both steady state and unsteady state transport conditions.

Rejani et al (2007) worked at Balasore in Orissa coastal groundwater basin, India is subject to a serious problem of seawater intrusion. Leaving many shallow wells in the basin resulted in overexploitation. The main objective of this study development of 2-D groundwater flow and transport model of the basin in the end, based on the results of modelling, the main groundwater basin management strategy is suggested for long-term sustainability of important groundwater resources is the development of Balasore. The following conclusions can be making to the field of study based on the modelling results:

Reduction in the pumpage from the second aquifer by 50% in the downstream region and an increase in the pumpage to 150% from the first and second aquifer at potential locations

Karasaki kenzi et al (2013) worked on numerical study of saltwater fresh water interface; in this study author numerically check the dynamics of interface of saltwater and freshwater.

After that they compared experimental result with numerical simulator and obtained a good fit between experimental and numerical result, with both producing sharp saltwater freshwater fronts.

We conclude that the wide transition zone is due to the seasonal fluctuation (low frequency) of freshwater head rather than tidal effects (high frequency) and is an unsteady phenomenon.

In the heterogeneous two layer case, the upper layer consists of glass beads having 1mm diameter and the bottom layer consist glass beads having 0.4 mm diameter. Now the salt water wedge generated in upper layer is very fast as compare to the bottom layer. Hence we concluded that the layer which has glass beads of larger size formed saltwater wedge much faster than layer of small size glass beads.

Matt D webb et al (2011) worked on transient response of saline water in order to rising sea level, In order to manage the available resources of freshwater it is essential to understanding the interactions between freshwater and saltwater intrusion. As a result of sea level rise in global temperature is likely to rise, one implication of which is the potential exacerbation of sea water intrusion into coastal aquifers. About 70% of the world population lives in coastal areas, For this study, controlled investigation has been carried out by concerning the temporal variation in sea water intrusion as a result of level of seas become rise. A series of fixed inland head two-dimensional models of sea water intrusion were developed by SEAWAT in order to evaluate the impact of rising sea levels on the unsteady migration of saline water intrusion in coastal aquifers under a certain range of hydrogeological property conditions. A wide range of responses were observed for typical value of hydrogeological parameter. Systems which have high ratio of hydraulic conductivity to recharge and high effective porosity lagged behind the equilibrium saline water toe positions during sea-level rise, often by many hundreds of meters, and frequently taking many centuries to equilibrate following a cease in sea-level rise. Systems which have less ratio of hydraulic conductivity to recharge and less effective porosity is unable to develop such a high degree of disequilibrium and generally stabilized within decades following a finish(cease) in sea-level rise. This study gives qualitative initial estimates for the expected intrusion rate and estimate degree of disequilibrium formed by sea-level rise for a certain range of hydrogeological parameter values.

The literature review shows that the impact of surface water fluxes on mitigating saline water ingress in freshwater aquifers is not investigated thoroughly. Therefore, laboratory experiments along with simulation were performed in this research.

CHAPTER 3

METHODLOGY

In methodology we discuss various laboratory experiments for investigating the dynamics of saltwater intrusion. These experiments were performed in a sand box; in this sand box we used homogenous sand as a porous media. So first we determine parameters related to sand are as follows:

3.1. Porosity

Soil is a mixture of small particles is known as pads. These soil particles are held together but not necessarily sticking together therefore some empty space remains between these particles. Porosity is simply defined as the amount of empty pores present in the soil. Porosity can be calculated by various methods like water evaporation method, gas expansion method and volumetric method, out of these volumetric method is a simple method to calculate porosity in the laboratory condition.

3.1.1. Volumetric Method:

In this method we took 50ml water and then add 50gms Soil in medium grade. Then we measured the rise in the water level after adding some amount of soil. We also measured Radius of the volumetric flask. The change in the volume after adding soil gives an estimate of the amount of void space present in the soil. Porosity is estimated with the help of void space.

Radius of volumetric flask = 1.6cm

Initial water level = 2.8cm

Final water level = 4.2cm

Total Volume = Volume of soil + Volume of void = $\prod r^2 H$

$= 3.14*1.6*1.6*4.2 = 33.76\ cm^3$

Volume of soil = $\prod r^2 h = 3.14*1.6*1.6*2.8 = 22.50\ cm^3$

Void space = Total Volume – Volume of soil = $33.76 - 22.5 = 11.26 cm^3$

Porosity = Void Space/ Total Volume

= 11.26/33.76

= 0.3335 or 33.35%

3.2 Hydraulic Conductivity

The hydraulic conductivity is the property of a soil is a measure of the ability of soil to transmit water at a particular hydraulic gradient. We can define hydraulic conductivity through Darcy law as follows:

Q = KA (dh/dl)

Q = volume flowing per unit time.

K = Hydraulic conductivity of soil sample

A= Area of cross section.

dl= length of sample.

dh= Hydraulic head difference

For measurement of hydraulic conductivity of soil sample we used constant head Permeameter. Readings obtained from the permeameter are as follows:

Constant head = 3.4cm

Sample head= 5.1cm

Sr. no.	Sample time for discharging 30ml water
1	31.38sec
2	31.42sec
3	31.73sec

Total mean time (T) =31.51 s

Now hydraulic conductivity = Qdl/Adh = vdl/tAdh

A = 3.14*3.02*3.02 = 28.63cm^2

Q =V/T =30/31.51 = 0.9521cm^3/sec

Hydraulic head difference = 5.1- 3.4= 1.7cm

Length of sample = 4cm

Then Hydraulic conductivity = Qdl/Adh =0.9521*4/28.63*1.7 = 0.0782cm/sec.

3.3. Laboratory method:

3.3.1. Detail of experimental setup:

Experiment was conducted in a sand box. The dimension of porous media is 150cm (length)_ 11cm (width)_ 55cm (height). A photograph of the sand box used in this experiment shown in figure 3.1.

Fig 3.1 Sand box used for salt water intrusion experiment.

The sand box used in this study is divided in three parts: the central flow chamber contain porous medium and remaining two parts are the wells of diameter 8cm and height 1m, which containing freshwater and saltwater. These two wells were separated from porous media by two fine screen which was fold around the wells as shown in figure 3.1.

The value of porosity and hydraulic conductivity of sand using in these experiments were 0.33 and 0.0782cm/s and molecular diffusion coefficient is 0.0124m^2/day. The freshwater and saltwater densities are 1000kg/m^3 and 1025 kg/m^3. Now we make the solution of salt water of concentration 35000ppm. We measured the concentration of saltwater with the help of conductivity meter.

3.3.2. Data collection method:

First we saturate the whole sand of the sand box. After that sand box was allowding to transmit the freshwater from left to right at a fixed gradient condition. The freshwater at a rate of 70ml/hr were injected in the left hand side constant head chamber(well 1) with the help of peristaltic pump1 in order to maintained head h = 24.5cm. This transmitted fresh water exited the sand box through another peristaltic pump2 in order to maintained outlet level at a head h = 23.5cm and this water were collected in the bucket. After establishing freshwater flow the process of saltwater was initiating by inserting the salt water in right hand side constant head chamber (well 2) with the help of peristaltic pump3 into right well as shown in figure 3.2 as follows

Fig 3.2 Experimental set up for investigating the dynamics of saltwater intrusion

Now salt water which is dense as compare to the freshwater, which settled down in left chamber and freshwater is move upper side and exited the system with the help of peristaltic pump, now the rate of salt water was 250ml/hr fixed with the help of peristaltic pump3. after that dense salt water start to invade porous medium.

(Peristaltic pump RH-P100VS-100-2H is a two channel pump for the use in laboratory where accurate is essential. Pumping action is done by a roller cage driven by stepper motor. The motor are almost independent of temperature. The pump has load and line compensate circuit. The roller is made up of carbon filled nylon for trouble free operation. The electronic circuit provides constant flow rate even there is line voltage or load variation. The peristaltic model used in our study does not require any regular service or maintenance other than replacement of worn out tubing. No lubrication is required as the internal mechanism is lubricated for life. Lightly lubricate the roller whenever it is necessary. External lubrication of tubing is recommended for longer life of the tube. Silicon grease can be used with advantage on all material except silicon rubber.)

After that we took the sample from the ports exist on the backside of the sand box (as shown in figure 3.3) at every two hours interval.

Fig 3.3 Backside of the sand box used for studying saltwater intrusion

Fig 3.3 shows the back view of sand box, there are several sample collection ports which are arrange at a 14 cm apart from each other but first port is at 7 cm from left side of sand box as shown in fig 3.3 and second port is at 7cm ahead from first port and remaining ports are 14cm apart from each other. Each port is connected with syringe in which we collect sample.

Now we collected the sample with the help of syringe and measure the concentration with the help of conductivity meter as shown in figure 3.4. Now this conductivity meter gives the concentration in the ms/cm. We convert the ms/cm into ppm as 1ms/cm = 640ppm. Now we note the concentration at regular interval of 2 hours. This experiment completed in 18 hours.

Fig. 3.4 Conductivity meter used for measurement of saltwater concentration

When first experiment completed then we removed whole freshwater and saltwater from sand box. After that a series of three experiments were performed with three different freshwater recharging fluxes (900mm/day, 2000mm/day and 3300mm/day) by keeping the similar hydrological conditions. we note the salt concentration in all experiments at an interval of 2 hours.

3.3.3 Experimental Result:

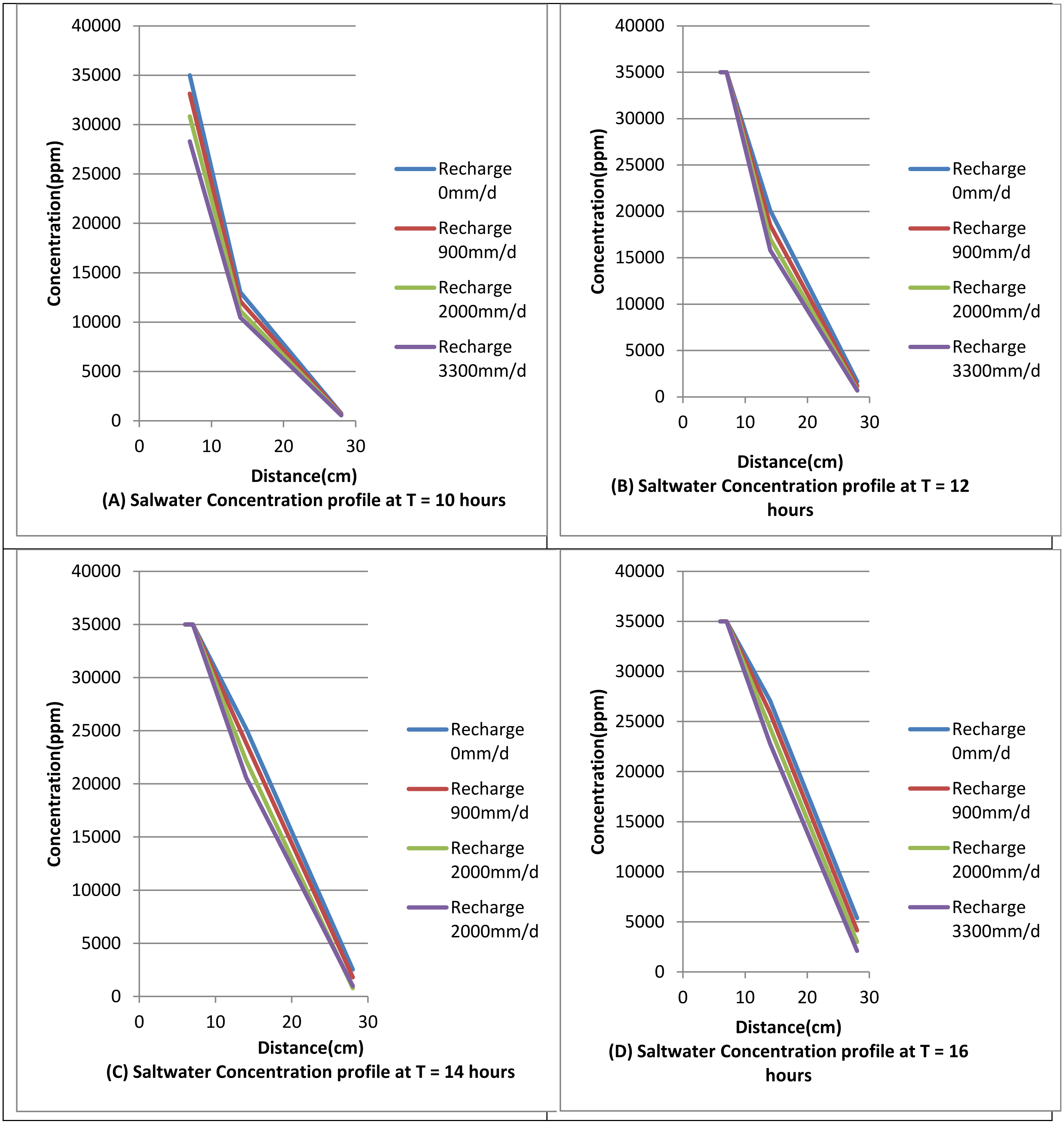


Fig 3.5 Saltwater concentration profile at different time periods

Using table 3.1, 3.2 and 3.3 we draw saltwater concentration profile graph at different time periods is shown in Fig 3.5. In Saltwater concentration profile we can see saltwater concentration at different locations at particular time period. Now we can also conclude that at each location (upto 28cm from right side of sand box) the salt water concentration is increases with increase in time period.

The table of saltwater concentration for port 1(this port is present in the well in which we provide salt water with the help of peristaltic pump 3) is as follows:

Table 3.1 Saltwater concentrations at port 1

Time(hours)	Salt Conc.(ppm)	Salt Conc.(ppm) When recharge is 900mm/d	Salt Conc.(ppm) When recharge is 2000mm/d	Salt Conc.(ppm) When recharge is 3300mm/d
0	384	384	384	384
2	2470	2056	1480	888
4	5568	4814	3716	2631
6	8892	7638	6115	4782
7	16808	15500	13600	11220
8	23800	22000	19796	17840
10	35000	33120	30840	28300
12	35000	35000	35000	35000

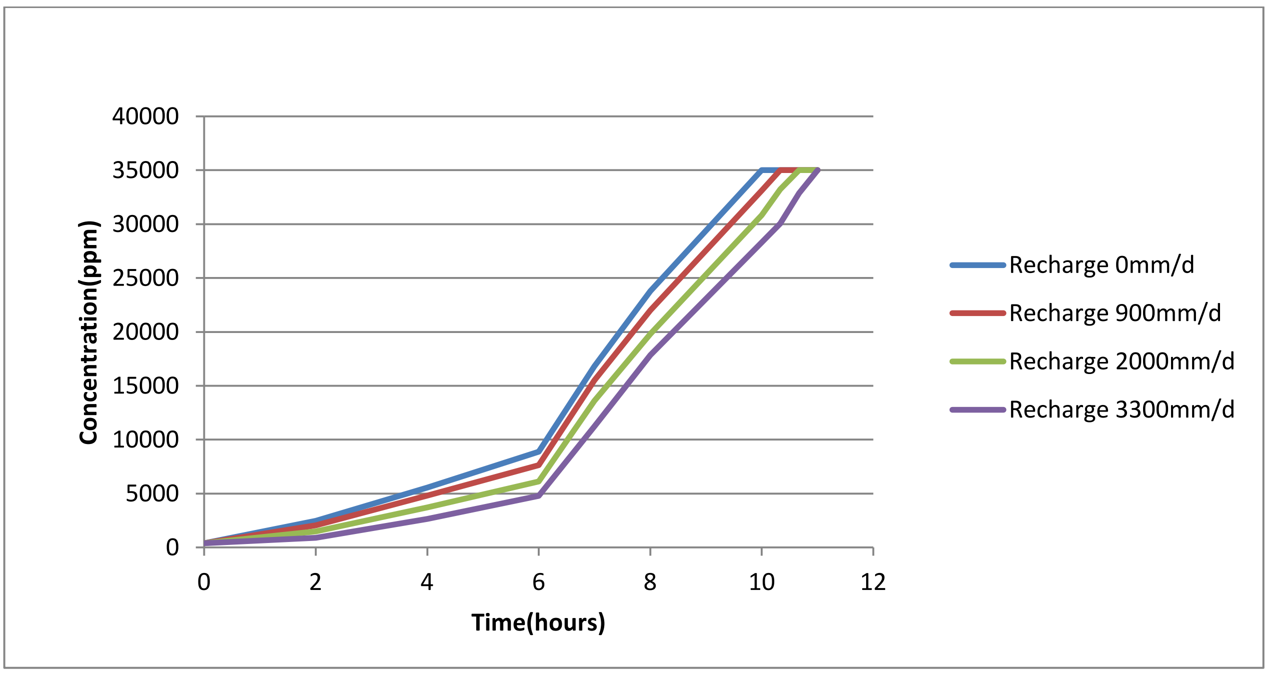


Fig 3.6 Breakthrough curve for port 1

For port 1, the salt concentration reached to 35000ppm in 10 hours.

The table of saltwater concentration for port 2 is as follows:

Table 3.2 Saltwater concentrations at port 2

Time(hours)	Salt conc.(ppm) When there is no recharge	Salt conc.(ppm) When recharge is 900mm/d	Salt conc.(ppm) When recharge is 2000mm/d	Salt conc.(ppm) When recharge is 3300mm/d
0	384	384	384	384
2	384	384	384	384
4	384	384	384	384
6	1843	1408	1216	1126
8	5376	4672	3968	3400
10	13030	12113	11164	10475
12	20082	18514	17048	15824
14	25172	23834	22190	20584
16	27112	25885	24382	22808
18	28588	27245	25965	24453

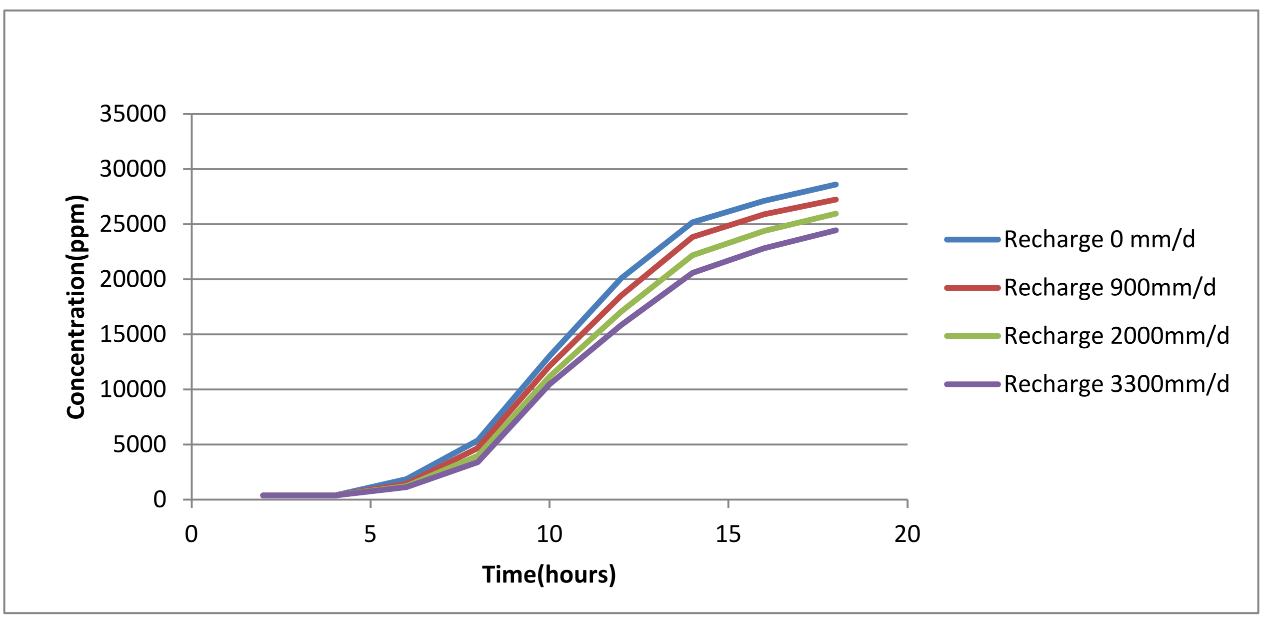


Fig 3.7 Breakthrough curve for port 2

Port 3 which is 14 cm ahead from the port 2. The table of saltwater concentration for port 3 is as follows:

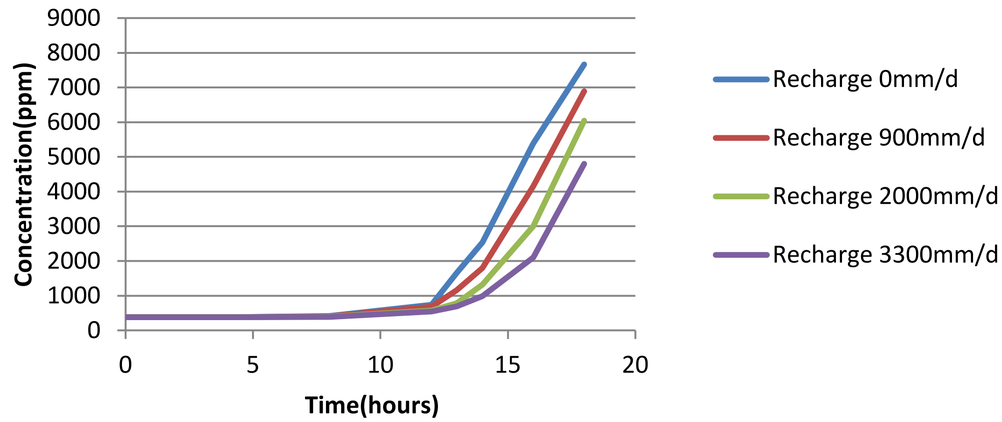
Table 3.3 Saltwater concentrations at port 3

Time(hours)	Salt conc.(ppm) When there is no recharge	Salt conc.(ppm) When recharge is 900mm/d	Salt conc.(ppm) When recharge is 2000mm/d	Salt conc.(ppm) When recharge is 3300mm/d
0	384	384	384	384
4	384	384	384	384
8	413	406	398	390
10	738	688	576	547
12	1656	1167	787	689
14	2532	1800	1322	989
16	5387	4160	3000	2100
18	7665	6889	6048	4800

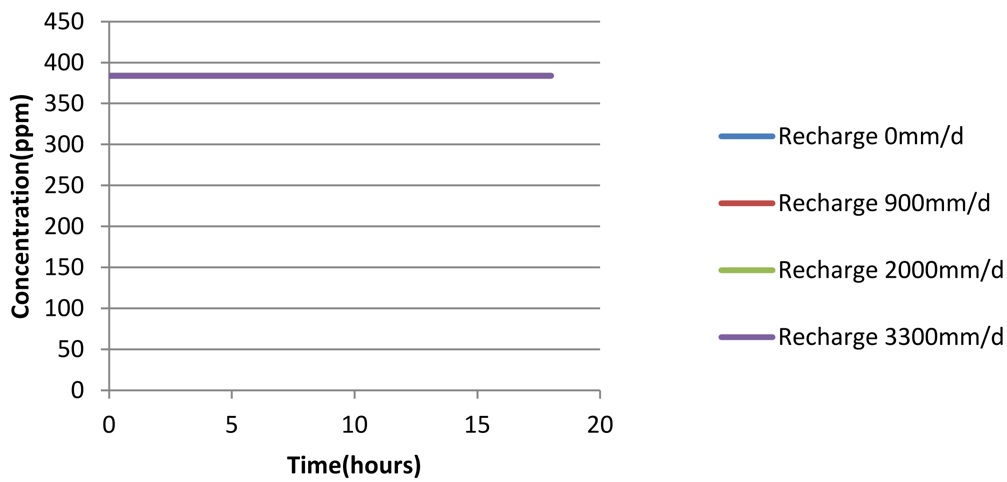
The port 4 which is 14cm ahead from port 3, there is no change in concentration during all cases the concentration is constant (384 ppm) in all cases:

Table 3.4 Saltwater concentrations at port 4

Time(hours)	Salt conc.(ppm) When there is no recharge	Salt conc.(ppm) When recharge is 900mm/d	Salt conc.(ppm) When recharge is 2000mm/d	Salt conc.(ppm) When recharge is 3300mm/d
0	384	384	384	384
6	384	384	384	384
12	384	384	384	384
18	384	384	384	384



(A) Breakthrough curve for port 3



(B) Breakthrough curve for port 4

Fig 3.8 Breakthrough curve for port 3 and 4

Now in first case when there was no recharge of freshwater, the salt concentration in port 1 reached to 35000ppm in 10 hours. but in next cases when there were 900mm/day, 2000mm/day and 3300mm/day recharge of freshwater, the salt concentration in port 1 reached to 35000ppm in 10.33 hours, 10.67 hours and 11.25 hours respectively. the saltwater concentration reading after 10 hours for port 2(when there were no recharge, 900mm/day, 2000mm/day and 3300mm/day recharge of freshwater) is as follows:

Table 3.5 Saltwater concentrations after 10 hours at port 2

Time(hours)	Salt water conc. for port 2 when there is no recharge	Time(hours)	Salt water conc. for port 2 when there is 900mm/day recharge
10	13030	10.33	13180
12	20082	12	18514
14	25172	14	23834
16	27112	16	25885
18	28588	18	27245
Time(hours)	Salt water conc. for port 2 when there is 2000mm/day recharge	Time(hours)	Salt water conc. for port 2 when there is 3300mm/day recharge
10.67	13125	11.25	13818
12	17048	12	15824
14	22190	14	20584
16	24382	16	22808
18	25965	18	24453

Now in simulation boundary condition was defined in the model domain for saltwater concentration (at time t = 0, saltwater concentration c = 35000ppm) after that model give the result of saltwater concentration after 2, 4, 6, 8 hours. but in first experiment the saltwater concentration reached upto 35000ppm in 10 hours and at the same time saltwater concentration at port 2 is 13030ppm, so in order to observed the change in saltwater concentration after 2, 4, 6 and 8 hours in port 2, when the initial concentration of saltwater was 35000ppm in port1, we subtracted the saltwater concentration at t=12,14,16,18 hours from saltwater concentration at t=10 hours is as follow:

Table 3.6 Change in saltwater concentrations after 10 hours at port 2

Time(T-10)hours	Salt concentration for port 2 (C_T-C_{10}) when there is no recharge	Time(T-10.33)hours	Salt concentration for port 2 (C_T-$C_{10.33}$) when there is 900mm/day recharge
0	0	0	0
2	7052	1.67	5334
4	12142	3.67	10654
6	14082	5.67	12705
8	15558	7.67	14065
Time(T-10.67)hours	Salt concentration for port 2 (C_T-$C_{10.67}$) when there is 2000mm/day recharge	Time(T-11.25)hours	Salt concentration for port 2 (C_T-$C_{11.25}$) when there is 3300mm/day recharge
0	0	0	0
1.33	3923	0.75	2006
3.33	9065	2.75	6766
5.33	11257	4.75	8990
7.33	12840	6.75	10635

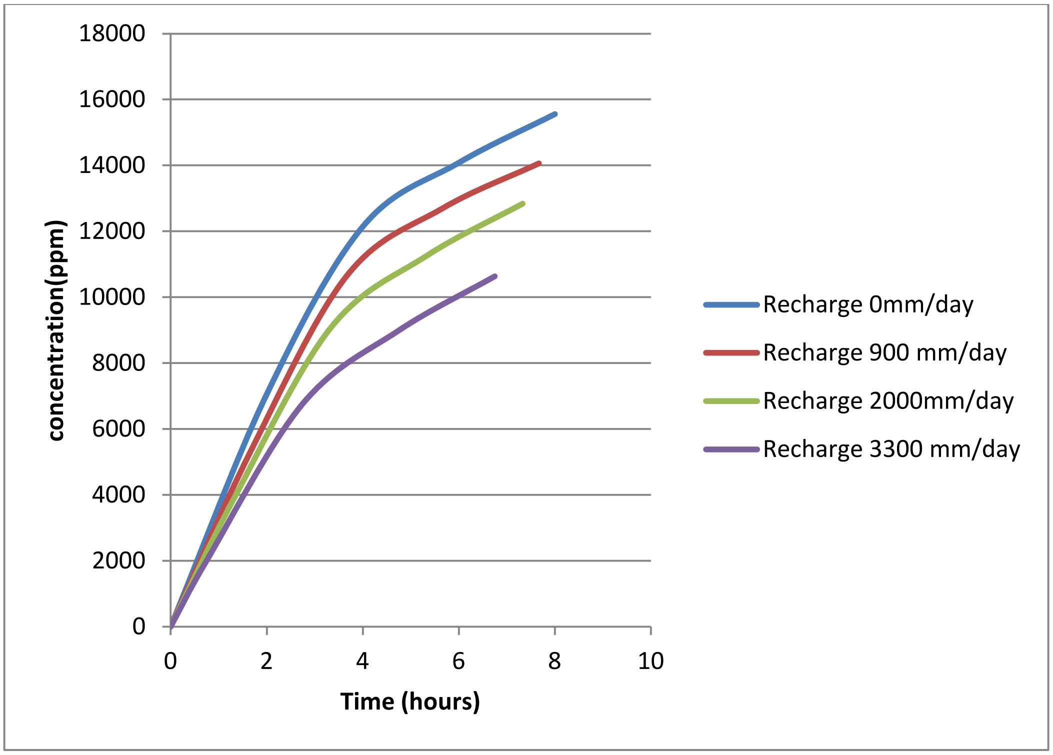


Fig 3.9 Modified breakthrough curve for port 2 under different recharge of freshwater.

Fig 3.9 shows modified breakthrough curve for port 2 under different recharge of freshwater. We used the data of this curve for calibration of our experiment with the help of Visual MODFLOW.

Now when we give 900mm/day recharge of freshwater then water table of porous media is increase up to 32cm. Similarly when we give 2000mm/day and 3300mm/day recharge of fresh water then water table of porous media increase upto 42cm and 53cm.

CHAPTER 4

EXPERIMENTAL DATASETS SIMULATION

4.1 VISUAL MODFLOW

We used visual modflow Software for the simulation of diffusion of saltwater concentration for certain time period. It is easy to operate the Visual MODFLOW software.

In Visual MODFLOW:

- It is easy to assign the boundary conditions like constant concentration, recharge etc and properties like conductivity, initial concentration etc for the model.
- It is easy to assign the location of pumping well and concentration well.
- We can easily visualize model results in 2D or 3D.
- We can easily define different model of same parameter by selecting setup option.
- We can easily define solver and its properties in simulation scenario.
- We can easily translate and run the model after selecting numerical engine.

4.2 Model Input Data

This chapter described: Allotting data in a new Visual Modflow model, and editing data in an existing Visual Modflow model.

Modflow stores all the data for the path line, flow and contaminant transport model parts in a set of files having Data structures and formats which are quite different than the model input data files required by Modpath, Seawat, Modflow-Surfact, and Mass Transfer3D. There are several reasons for these differences, but the main reasons are:

Modflow does not demand any consistent units for length and time. Instead, Modflow allows mixed units for different model parameters (for example: length in metres, Recharge rate in mm/yr)

Modflow does not demand any boundary conditions to be explained in terms of stress periods. Instead, Modflow allows each boundary condition to be explained using real time values and raw field data.

These differences are two of the important elements that make Modflow so practical and user-friendly. However, these differences also demand Modflow to store data in a different format, and then translate these data files into the required format prior to running the models. Now first we done simulation based on literature datasets whose information is given as follows:

4.3 Simulation based on literature datasets:

The basic setup consists length 600 m and 150 m high section with impermeable (no-flow) boundaries (see Figure 4.1). A fixed concentration boundary was defined for the left hand boundary (source zone) along the model. The concentrations allocated to this boundary correspond to salt water and fresh water, respectively. To other boundaries, i.e., the top and bottom boundaries, a no-flux concentration boundary condition was assigned.

The pressure (and head) distribution is initially hydrostatic and the entire domain is filled with fresh water. Solutes can enter or leave the model domain only via diffusion transport through the source zone and, once sufficient solute has accumulated in the boundary layer, flow within the domain is solely generated by density gradients. The parameter values for our problem are listed in fig 4.1(post and prommer 2007) but in this literature the value of salt concentration is 285700mg/l which is very high so we take salt concentration value is 28570mg/l and value of density of saltwater is 1025kg/m^3.

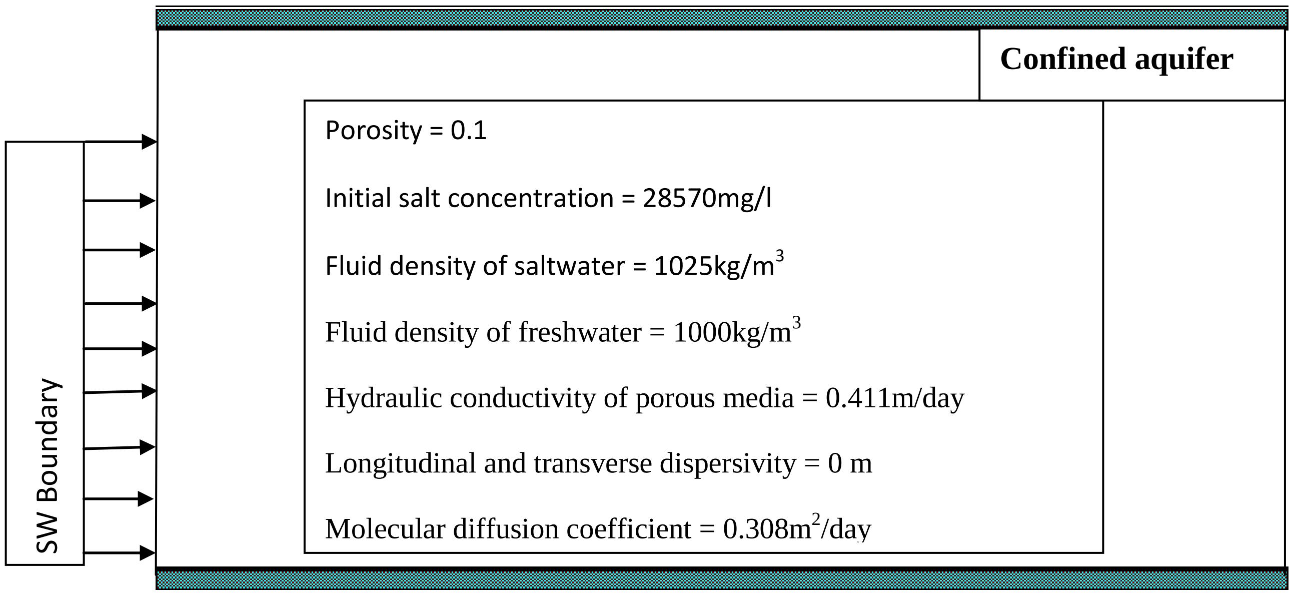


Fig 4.1 Parameters used for the domain

Now we create a model domain on the basis of literature datasets, first we define parameter value and use saturated (variable density) flow type in flow simulation. After that we create a uniform spaced having 44 columns and 27 layers finite difference grid

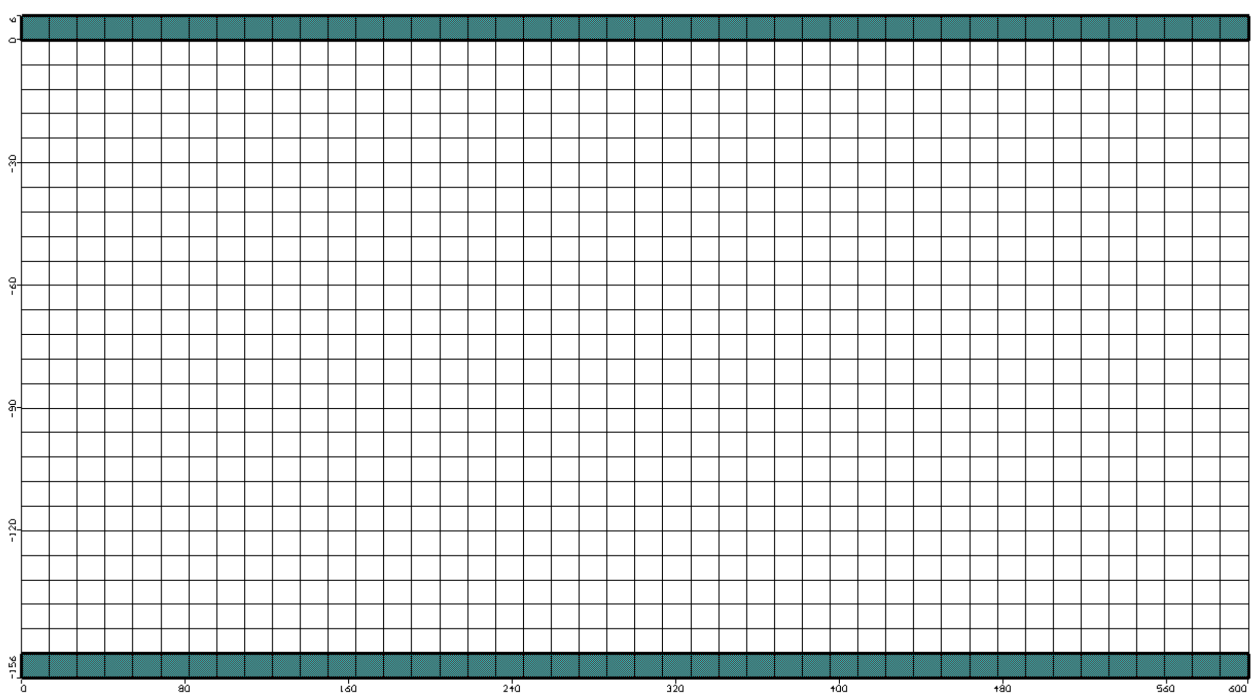


Fig 4.2 Grid formation for the model domain

In above model domain the hydraulic conductivity for no flux boundaries (upper and lower boundary) is 1E-5. And the hydraulic conductivity for medium between no flux boundaries is 0.411m/day. In model, we give initially salt concentration from left side of model domain which is 28570mg/l and for remaining portion of model salt concentration is zero.

4.4 PCG (Preconditioned Conjugate-Gradient) Solver

PCG uses the preconditioned conjugate-gradient method to solve the simultaneous equations produced by the model domain. Linear and non-linear flow conditions may be simulated. PCG includes two preconditioning options: modified incomplete Cholesky preconditioning, which is efficient on scalar computers and polynomial preconditioning, which requires less computer storage and with computer specific modifications, is most efficient on vector computers. Convergence of the solver is determined using both the head-change and residual criteria. Non-linear problems are solved using the Picard iterations. The parameter used for pcg solver is shown in table 4.1

Table 4.1 PCG solver parameter

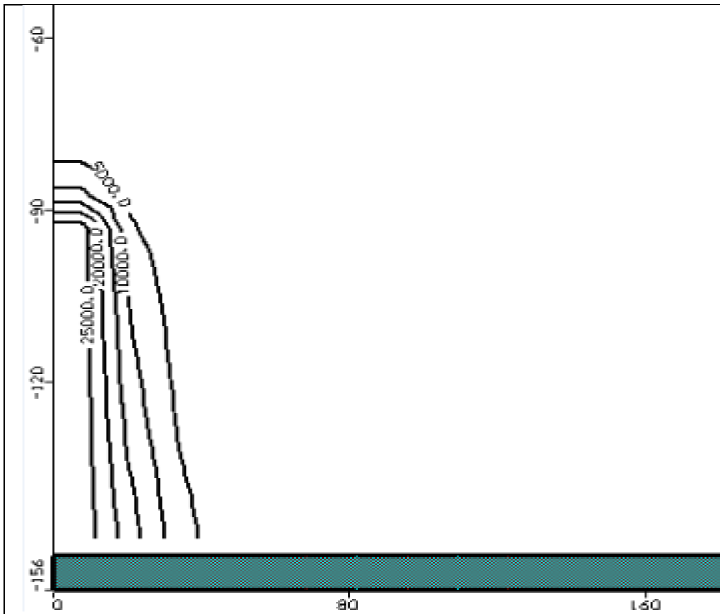
Outer iteration	20
Inner iteration	10
Head Change Criterion for Convergence	1E-7
Residual Criterion for Convergence	1

4.5 Simulation Results

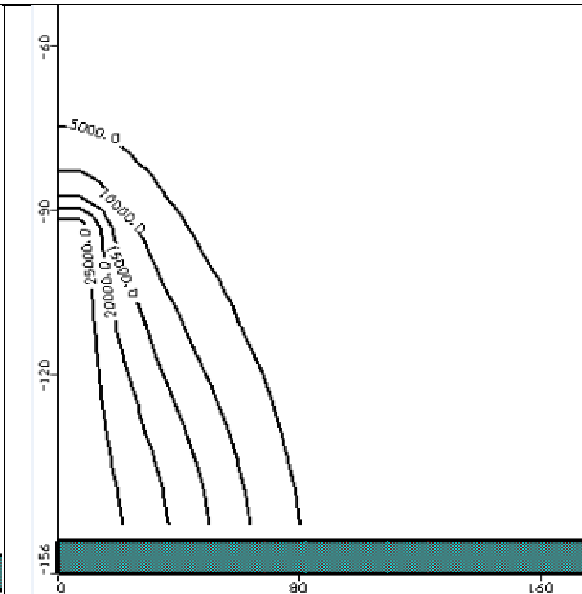
Sea water intrusion is one of a typical example of water contamination in coastal regions. In the present study, simulation approach for seawater intrusion in confined aquifer has been studied and the results obtained after simulation has been discussed in the following paragraphs.

4.5.1 Areal and temporal movement of salt water

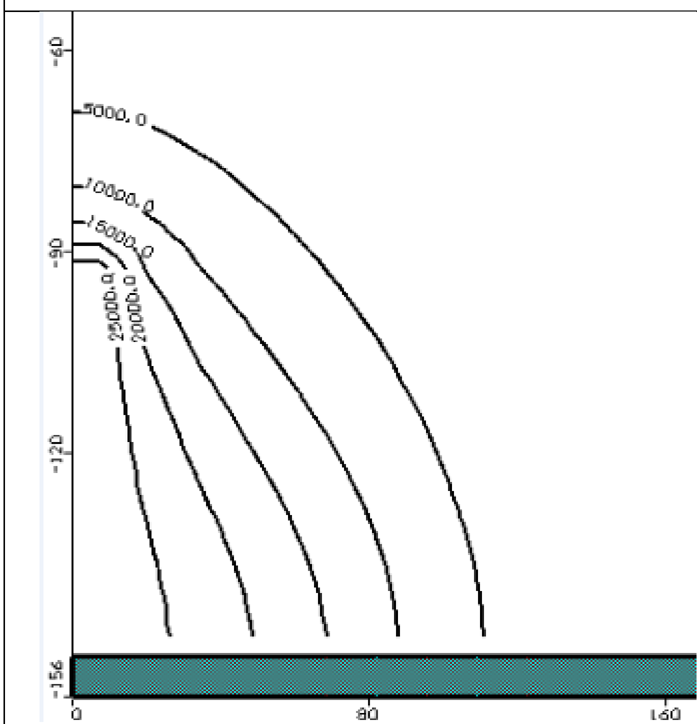
It For the study area domain hydraulic properties, mentioned in the Fig 4.1, the spatial and temporal movement of Salt water interface in confined aquifer has been shown in Fig 4.3. Fig. 4.3(A) depicts the movement of salt water after one years. it can be observed that the maximum spatial spread of the saltwater during one year is 40m. The lowest concentration observed during this duration is 5000 mg/litres. That means, about 17.5% of initial concentration has reached 40m in one year.



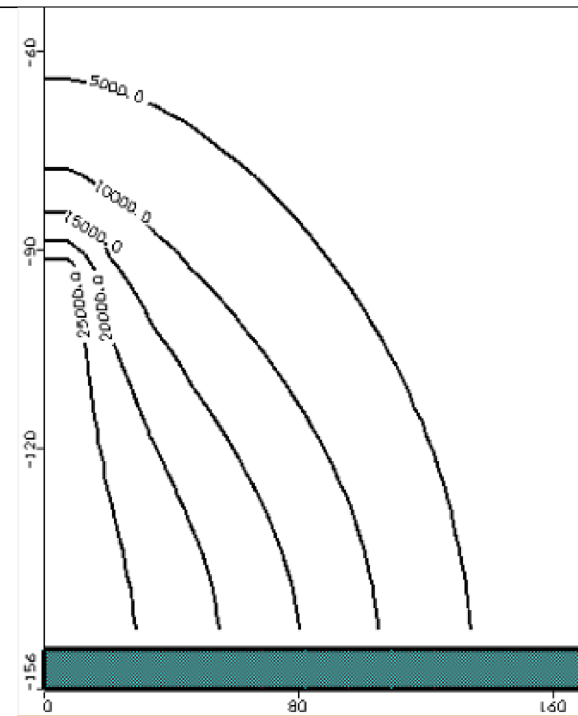
(A) Contours of Salt Conc. after 1 years



(B) Contours of Salt conc. after 5 years



(C) Contours of Salt conc. after 10 years



(D) Contours of Salt conc. after 15 years

Fig. 4.3 Contours of salt water interface obtained at different time interval

Similarly, Fig. 4.3(B), 4.3(C) and 4.3(D) depicts the maximum spatial and temporal spread of the saltwater during fifth, tenth and fifteenth year respectively.

The areal spread of salt water for 17.5% (5000 mg/litre) of the initial concentration has been shown in Fig 4.4. It can be observed that during the first five years, the movement of salt water is very rapid. After 5 to 10 years, the movement is slower than the previous one.

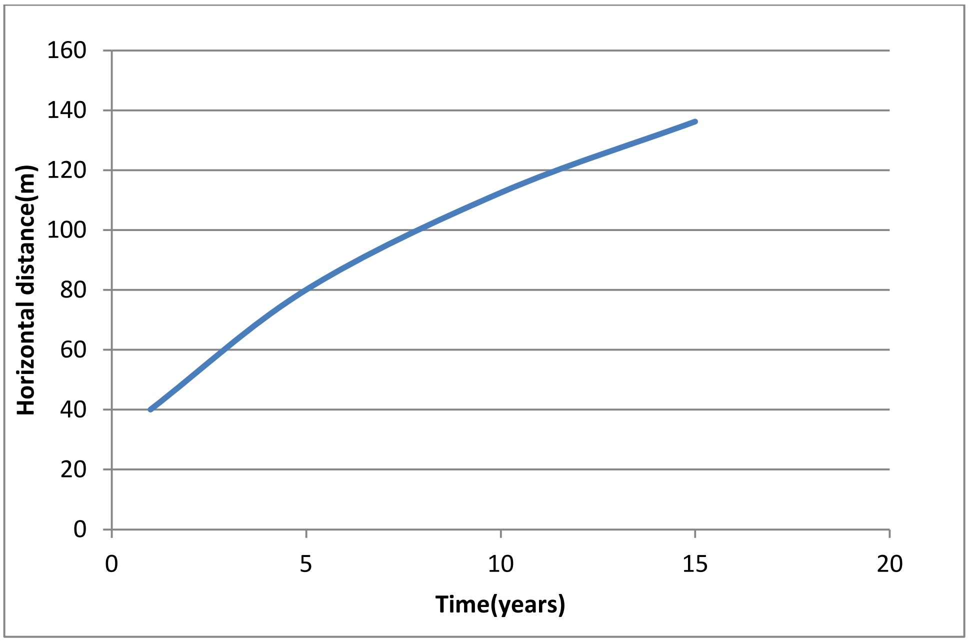


Fig. 4.4 17.5% isochlor curve at different position and time

4.5.2 Sensitivity analysis

Hydraulic conductivity is one of the main parameters which can affect the salt water interface. For conducting sensitivity analysis, the areal and temporal movement of salt water had been studied by varying hydraulic conductivity up to 20% of the initial hydraulic conductivity. Thus, the study had been performed for hydraulic conductivity of 0.8K and 1.2K (where K is the initial hydraulic conductivity of the study domain).

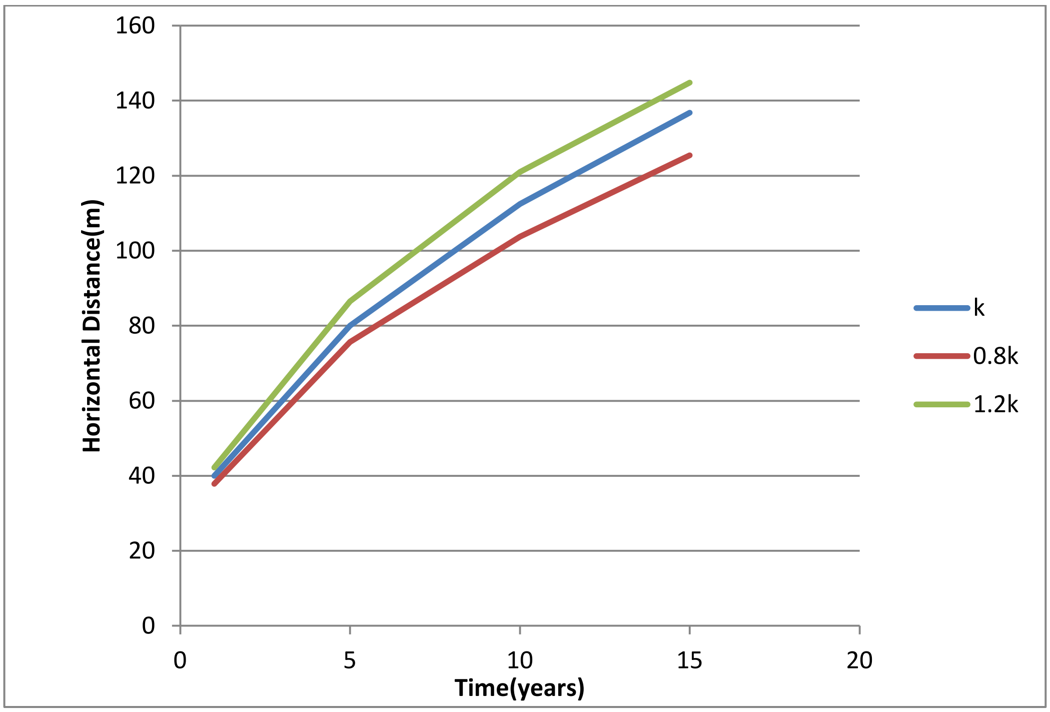


Fig. 4.5 17.5% isochlor curve for varying hydraulic conductivity

Fig. 4.5 depicts the 17.5% isochlor curve for hydraulic conductivity at 0.8K, K and 1.2K. From this Figure 4.5, it can be observed that the areal and temporal salt water intrusion is very sensitive as far as hydraulic conductivity is concern.

4.6 Simulation based on experiment

We used visual modflow software to simulate our experiment result; the main aim of simulation is to check whether our experimental result is consistent with the prediction made by our simulation result. Now during simulation first we defined our project name and as we used salt and freshwater which means our flow is type of saturated (variable density), after choosing saturated (variable density) flow type, the software automatically choose the numeric engine (USGS SEAWAT from SWS) and simulation type is groundwater flow. The units of various parameter used in our simulation is shown in figure 4.6.

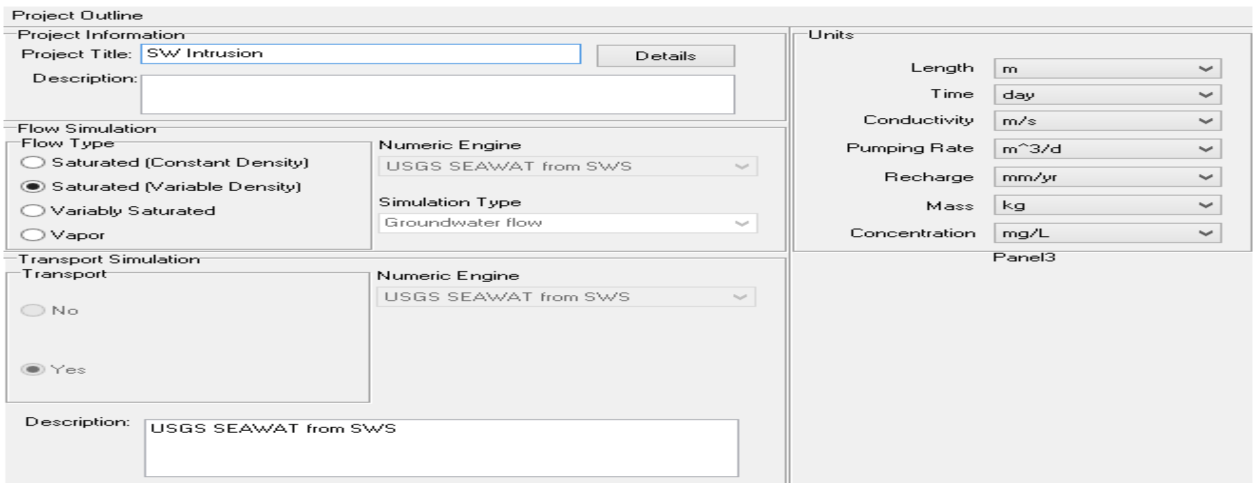


Fig 4.6 Details of model domain.

After that we define the value of parameters like conductivity, porosity, diffusion coefficient etc and we create a model domain. The detail of model domain is shown in fig. 4.7 is as follows:

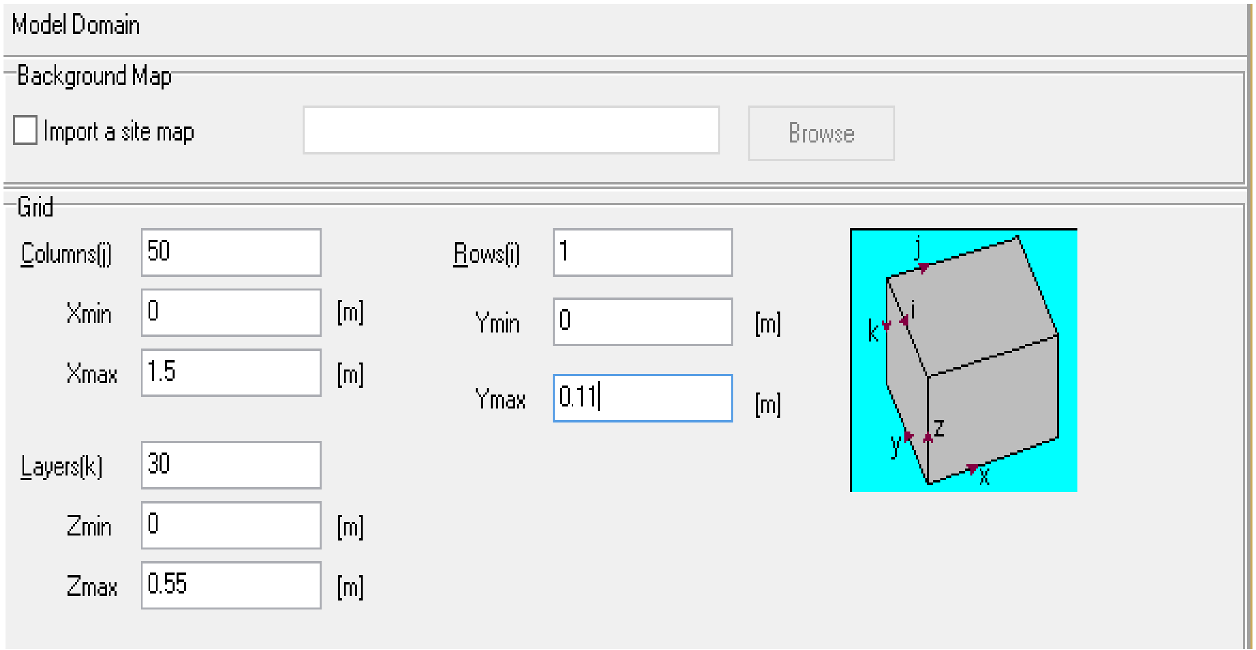


Fig 4.7 Dimensions of model domain

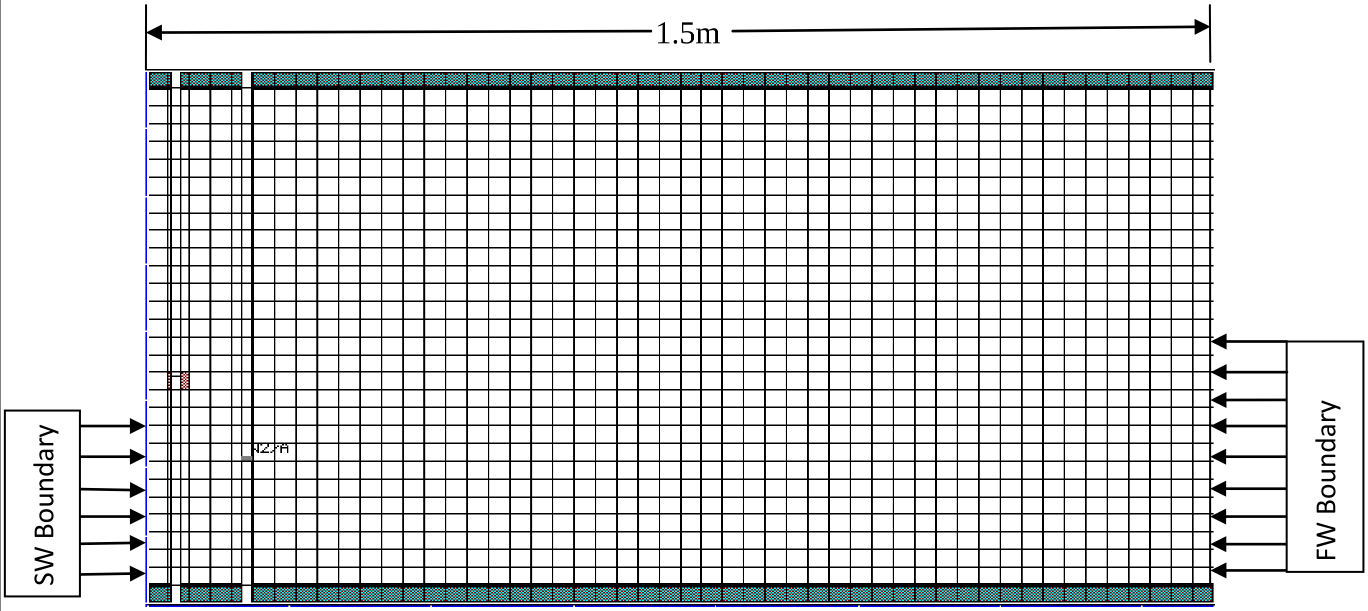


Fig 4.8 Model domain without recharge boundary

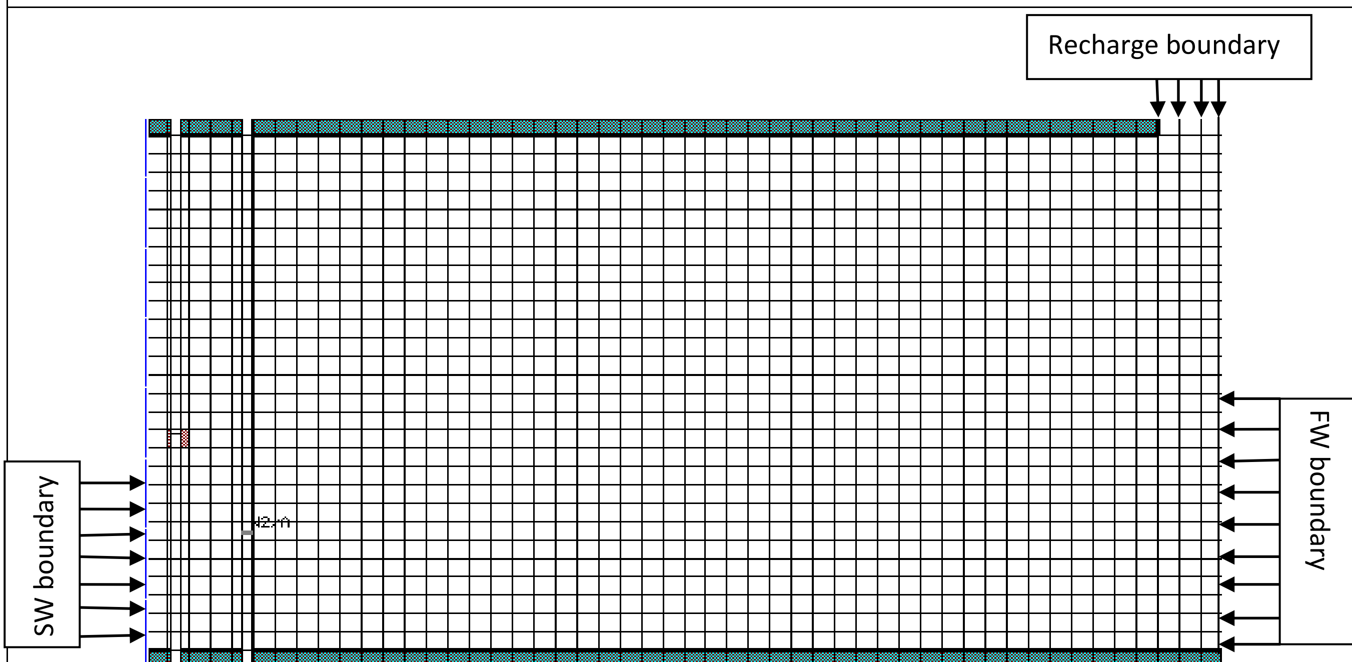


Fig 4.9 Model domain with recharge boundary

A saltwater and freshwater boundary condition was assigned in model domain shown in fig 4.8 in that model domain there is no recharge boundary condition but in fig 4.9 which contain recharge boundary condition through which we give freshwater recharge of 900mm/day, 2000mm/day and 3300mm/day.

Our model domain consist length 1.5m, height 0.55m and width 0.11m no flux boundary condition is defined for the top and bottom layer of model domain. A freshwater boundary condition was defined at the right hand side of model domain up to 0.245 m from bottom layer and a pumping well is defined at the left hand side of domain having well screen placed at 0.235 m from bottom layer(pumping rate of well is 0.00768m^3/day(320ml/hour). A salt water boundary condition was defined at the left hand side of model domain as shown in fig 4.8. The initial concentration of salt in salt water was 35000ppm. Now we defined a concentration well in the model domain shown in fig 4.8, which was placed at a 14cm from the left hand side of model domain. The well screen of concentration observing well is 13.5cm from the bottom layer of model domain. The data for pumping well and concentration well as shown in figure 4.10 and 4.11.

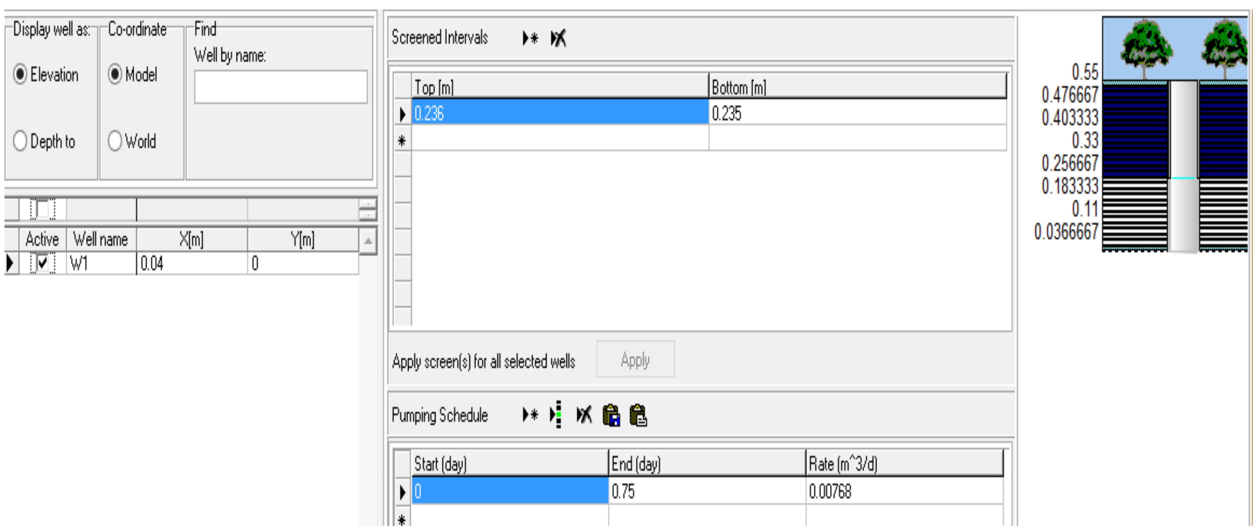


Fig 4.10 Pumping well schedule

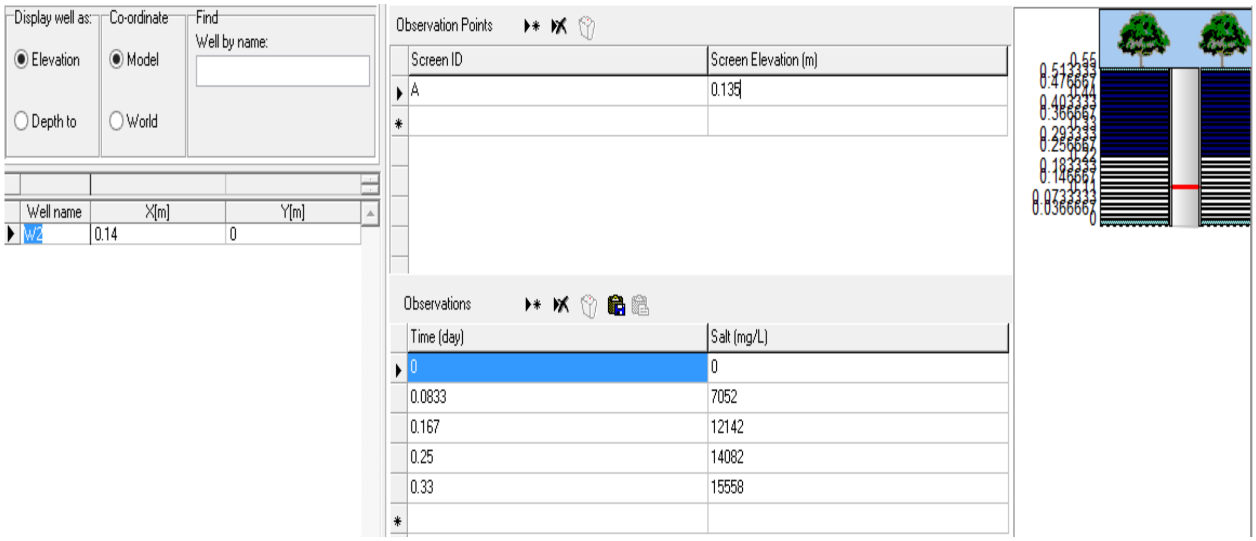


Fig 4.11 Concentration well (port 2) details for model 1

The data given in fig.4.11 is the experimental data which is used for simulating. The PCG solver is used for simulation the detail of PCG solver is given in figure 4.12 as follows:

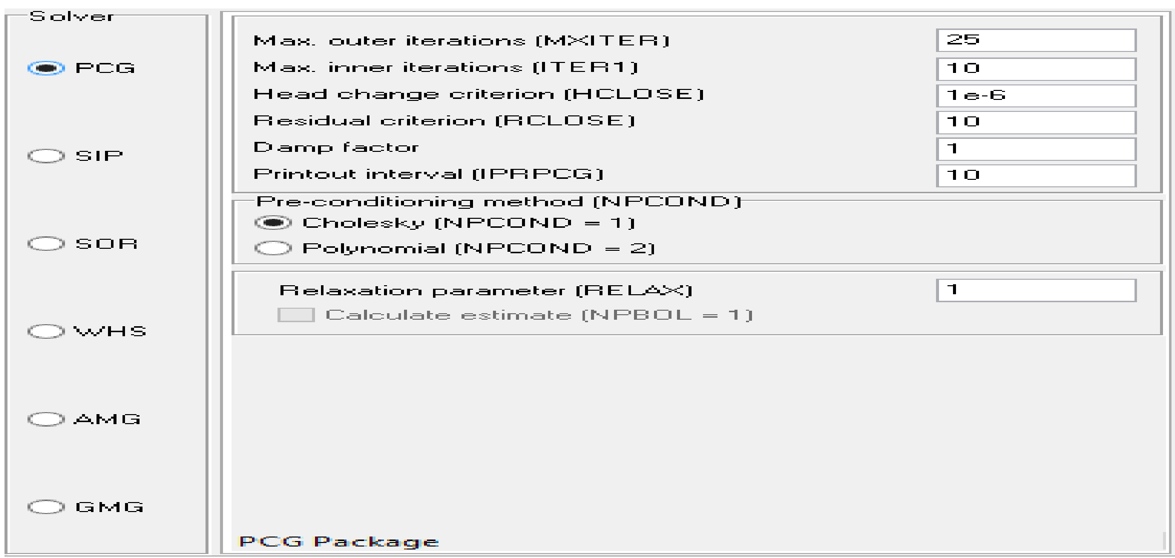
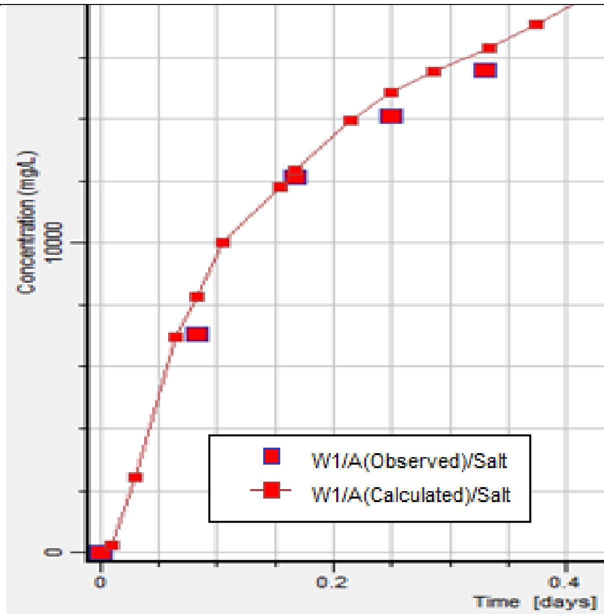


Fig 4.12 PCG solver details

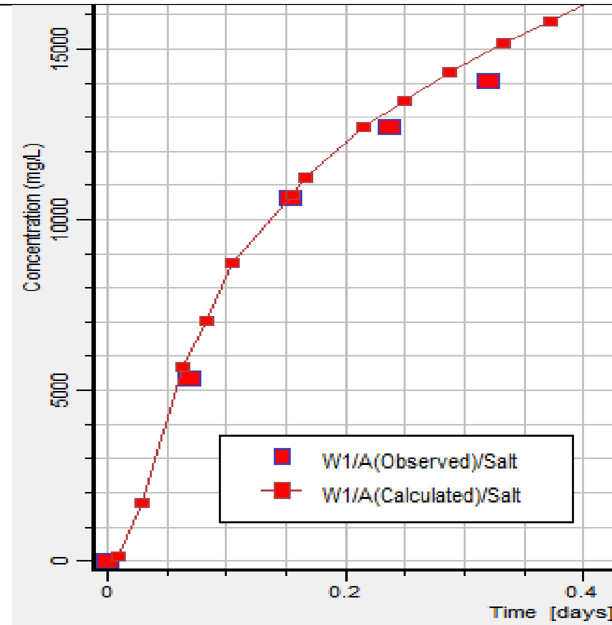
After that we also created three other model domains having different recharge value. In these model domains we also followed same steps as used during creation of first model domain. After that we run our models with the help of SEAWAT engine.

4.7 Simulation Results:

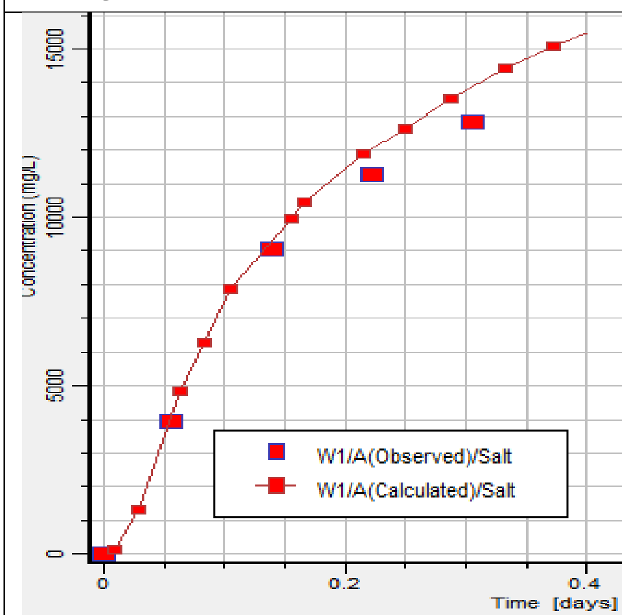
We obtained break through curve for concentration observing well and we also compared this simulation result from experimental result as shown in fig. 4.13



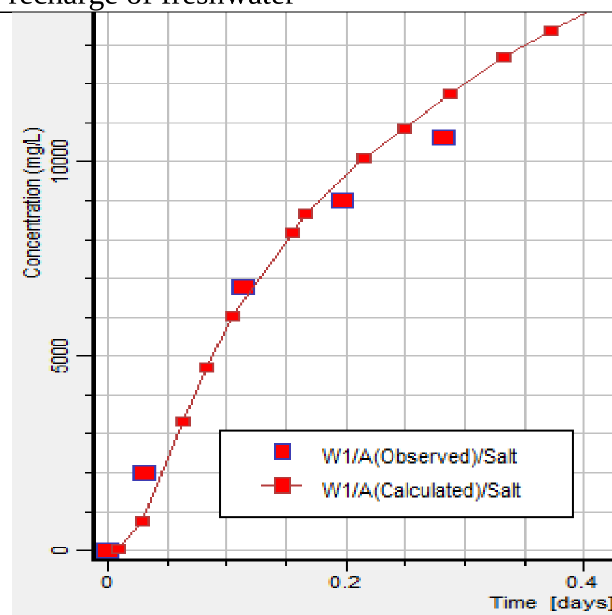
(A) Break through curve when there is no recharge of freshwater



(B) Breakthrough curve when there is 900mm/d recharge of freshwater



(C) Breakthrough curve when there is 2000mm/d recharge of freshwater



(D) Breakthrough curve when there is 3300mm/d recharge of freshwater

Fig. 4.13 Comparison of Breakthrough curves for observed and calculated results

Now we calculate Calibration residual (calibration residual is the difference between calculated results and observed result)

Calibration residual (R_i) = X_{cal} - X_{ob}

Now for case 1 (when there is no recharge of freshwater) calibration residual calculated as follow:

R_1 = 0 – 0 = 0

R_2 = 8092 – 7052 = 1040

R_3 = 12353 – 12142 = 211

R_4 = 14847 – 14082 = 765

R_5 = 16264 – 15558 = 706

Root Mean Square Error

$$\text{RMS} = \sqrt{\frac{R_1^2+R_2^2+R_3^2+R_4^2+R_5^2}{5}}$$

After putting the value of R1, R2, R_3, R_4 and R_5 we get

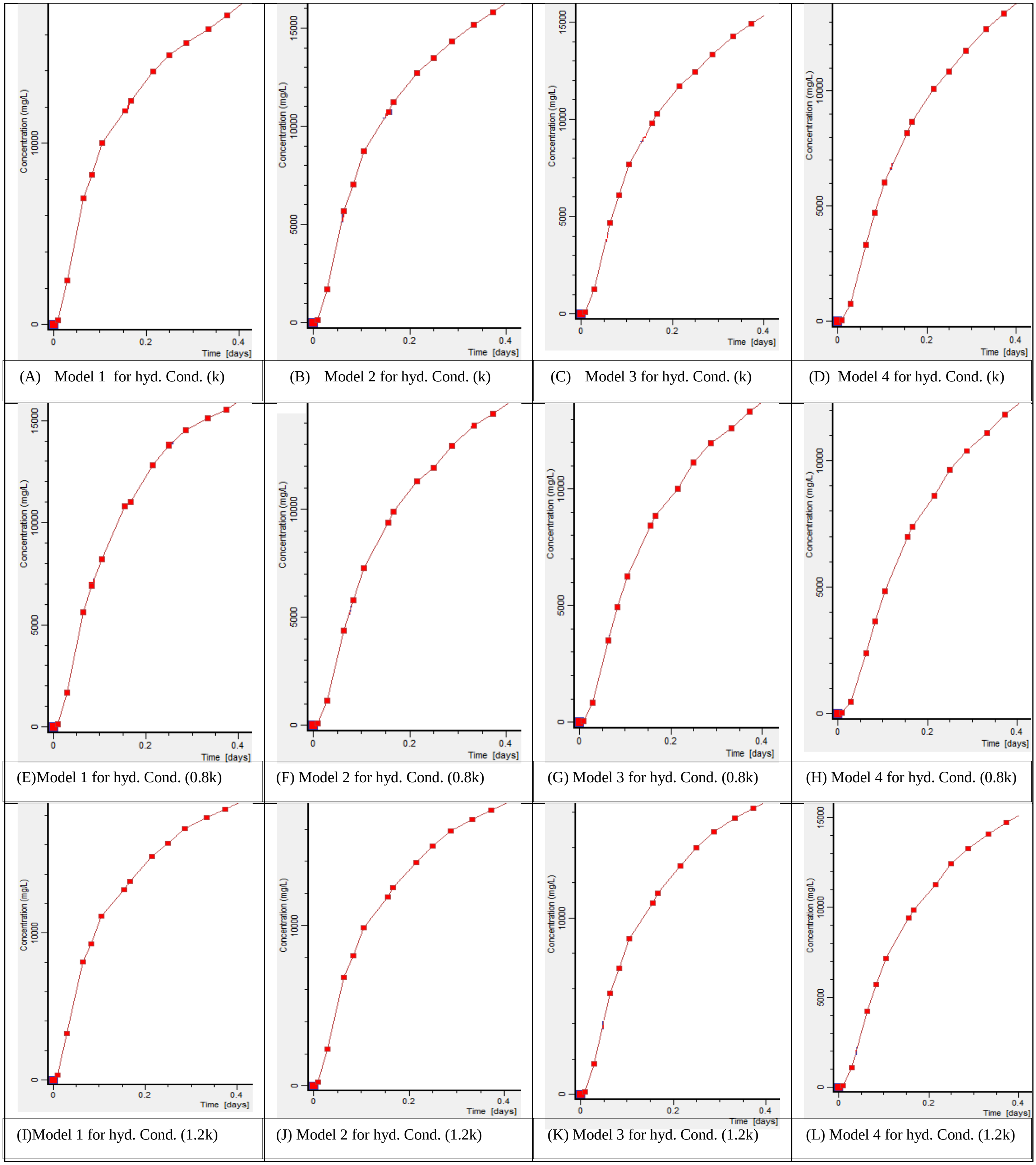
RMS =664.79 ppm

$$\text{Normalized RMS} = \frac{RMS}{X_{ob(max)} - X_{ob(min)}}$$

$$= \frac{664.79}{15558-0} = 0.0427 \text{ or } 4.27\%$$

Similarly in case 2(when there freshwater recharge is 900mm/day), in case 3(when there freshwater recharge is 2000mm/day), in case 4(when there freshwater recharge is 3300mm/day) RMS error are 527.9 ppm, 594.6 ppm and 660 ppm, the normalized RMS value are 3.75%, 4.63% and 6.2%. These normalized RMS values shows good fit between observed and calculated values.

4.8 Sensitivity analysis



(A) Model 1 for hyd. Cond. (k)
(B) Model 2 for hyd. Cond. (k)
(C) Model 3 for hyd. Cond. (k)
(D) Model 4 for hyd. Cond. (k)
(E) Model 1 for hyd. Cond. (0.8k)
(F) Model 2 for hyd. Cond. (0.8k)
(G) Model 3 for hyd. Cond. (0.8k)
(H) Model 4 for hyd. Cond. (0.8k)
(I) Model 1 for hyd. Cond. (1.2k)
(J) Model 2 for hyd. Cond. (1.2k)
(K) Model 3 for hyd. Cond. (1.2k)
(L) Model 4 for hyd. Cond. (1.2k)

Fig.4.14 Breakthrough curve under varying hydraulic conductivity

Hydraulic conductivity is one of the main parameters which can affect the salt water interface. For conducting sensitivity analysis, the temporal movement of salt water had been studied by varying hydraulic conductivity up to 20% of the initial hydraulic conductivity. Thus, the study had been performed for hydraulic conductivity of 0.8K and 1.2K (where K is the initial hydraulic conductivity of the study area). Fig. 4.14 depicts the breakthrough curve for hydraulic conductivity at 0.8K, K and 1.2K. From this Figure 4.13, when we reduced the hydraulic conductivity upto 20% the salt water concentration becomes decreases and when we increase the hydraulic conductivity upto 20% the saltwater concentration increases at a particular time period. Hence it can be observed that temporal salt water intrusion is very sensitive as far as hydraulic conductivity is concern.

CHAPTER 5

Summary and conclusion

5.1 Summary and Conclusion

In this study various laboratory experiments were performed to study the pattern of saltwater transport in freshwater aquifer to control the problem of saltwater intrusion through freshwater aquifer. . All experiments were conducted in a sand box. Sand box was divided into three distinct chambers: a central flow chamber containing the porous medium and two constant-head chambers containing salt water and freshwater. There are several ports present on the back side of the sand box. These ports are arranged at a 14 cm apart from each other but first port is at 7 cm from left side of sand box and second port is at 7cm ahead from first port and remaining ports are 14cm apart from each other. Each port was connected with syringe in which we collected the sample of saltwater. In first experiment the sand box allowed to transmit freshwater from left to right at a fixed gradient condition after that we inserting saltwater in the sand box and note the effect of saltwater concentration with time at a particular locations. Saltwater concentration was measured with the help of conductivity meter. After completing the experiment we removed whole saltwater and freshwater from sand box and we washed whole sand box with the help of freshwater. After that we performed next three experiments in which we followed same steps as described in first experiment. But we give freshwater recharge (900mm/day, 2000mm/day and 3300mm/day) and then we note saltwater concentration on particular locations. For port 2 (fig 3.7) we concluded that the salt concentration was increased very slowly in the first 8 hours after that saltwater concentration was increased very rapidly in the next 8 hours after that saltwater concentration increased by a very small rate or constant after some time but after giving recharge of freshwater the saltwater concentration become decreases at a particular location. .after 6 hours, It was observed that under no recharge of freshwater a salt concentration was observed upto 40% of the boundary condition (35000ppm) at port 2, while it was further delayed in ports located to down gradient locations. On the other hand, under recharging cases of 900mm/day, 2000mm/day and 3300mm/day the saltwater concentration in port 2 increased only upto 37%, 33.6% and 28.6% of initial concentrations, respectively. This shows the positive role of surface water recharge on ingress of saline water in fresh aquifer zones.

In this study first we took the literature datasets for confined aquifer for model testing and simulate it with the help of SEAWAT simulator in visual MODFLOW for 15 years and from simulation contours of saltwater concentration were obtained after 1year, 5year, 10years and 15years. it can be concluded that after 5 years, about 5000 mg/litres of salt water is observed at 80m after 5 years from the initial source of applied salt water concentration. Thus after 5 years, The areal spread has also increased up to 100% as compared to first years. After 10 years, it can be observed that maximum areal spread of salt water fate has reached upto 112.43 meters and After 15 years, it can be observed that maximum areal spread of salt water fate has reached upto 136.2meters respectively. hence the areal extent of its spread is increasing with time. Now from visual MODFLOW we can easily track the movement of saltwater concentration.

After that we simulated these experimental datasets with the help of SEAWAT simulator in visual MODFLOW. We made 4 model domains under no recharge, 900mm/day, 2000mm/day and 3300mm/day in visual MODFLOW, in these model domains we defined properties and boundary condition according to our experiments and we used PCG solver package for simulation. Visual MODFLOW generated the breakthrough curves under different recharge of freshwater after that we calculated Normalized root mean square value for all 4 model domains. The normalized RMS values are 4.27%, 3.75%, 4.63% and 6.2%. Hence we concluded that SEAWAT model in visual MODFLOW is suitable for simulating the problem related to the saltwater intrusion. Based on the normalized root mean square value we concluded that there was a good fit between observed values and calculated values. The results of this research are direct use in controlling the saline water intrusion by surface water recharging techniques at field level.

5.2 Future recommendations

In the present study we performed laboratory experiments to investigate the dynamics of saltwater intrusion under different recharge of freshwater. The porous media used in this study is homogenous sand. In future we will also take the heterogeneous porous media to investigate the dynamics of saltwater intrusion under different recharge of freshwater.

In future we will also study this work in three dimensions instead of two dimensions.

In this study we gave steady state recharge of freshwater to sandbox. In future we will also give unsteady state (transient state) recharge of freshwater to sandbox.

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