# ASSESSMENT OF SALT WATER INTRUSION IN THE SOUTH WESTERN COASTAL AQUIFERS OF KHULNA BY USING VISUAL MODFLOW


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(B.Sc in Civil Engg)


This thesis is submitted to the Department of Civil Engineering, Military Institute of Science and Technology, in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering

April, 2019

# DECLARATION

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

**Nafiz Ul Ahsan**

**09 April, 2019**

## CERTIFICTION OF APPROVAL

We hereby recommend that the M.Sc Engg. Research work presented by Nafiz Ul Ahsan entitled **Assessment of Salt Water Intrusion in the South Western Coastal Aquifers of Khulna by Using Visual Modflow** be accepted as fulfilling this part of the requirement for the degree of Master of Science in Civil Engineering.

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# ABSTRACT

The objective of the study is to investigate the salinity intrusion status of groundwater using visual MODFLOW in the study area (Khulna) and salinity transport scenario in the coastal aquifers. The model domain covers an area of approximately 350 km² in 40m X 40m grid size and defined by three hydro-stratigraphic layers. To set up model fluid transfer boundary of Northern and Southern sides' ground water levels from observed wells and surface water level of various ponds were used. For Eastern and Western boundaries water level of the river Shibsa and Rupsha were used respectively. The observed groundwater levels from the wells were used as a boundary condition for deeper aquifer. Model base represents impermeable boundary and model top represents recharge boundary. Beside this the concentration of different rivers was used as mass transfer boundary condition for upper shallow aquifer. Other than upper shallow aquifer no concentration boundary was used. Recharge due to infiltration of rainfall in the catchment area was estimated to the range between 8% to 12% of rain fall. The value of Kx and Ky is assigned $2.5x10^{-4}$ cm/s to the entire aquifer. In this case the Kx and Ky are the same indicating that the assigned property values are horizontally and vertically isotropic. In these three layer models, layer 1 represents the upper aquifer and layer 3 represents the lower aquifer. Layer 2 represents the aquitard separating the upper and lower aquifers. In the model for contamination transport (salinity) MT3DMS engine was used and also upstream finite difference solution method with the implicit GCG solver. It provides a stable solution to the contaminant transport model in a relatively short period of time. The distribution of salinity was simulated for a period of twenty years in terms of chloride concentration. Through the representation of the salinity model in MODFLOW the salinity concentration in the sub-surface layers appears to increase by about 3.75 times in a span of 20 years due to the occurrence of surface water-groundwater interaction. Present salinity concentration has a value of nearly 800-2200 mg/L while in another two years in 2020 the concentration is expected to reach a maximum of approximately 3200 mg/L. The salinity model developed in MODFLOW was checked for stability using Courant number and it was found that with the increase in time step Courant number also increases which marks the stability of the model. The model was further validated using field data collected in 2013 for the study area and the model data for 2013 in the same location. The salinity data from the field and the model has striking similarities.

**ACKNOWLEDGEMENTS**

First of all I express my highest praise to the omnipresent, omnipotent and omniscient Allah who has enabled me to complete this thesis work.

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A very special gratitude goes to Higher Education Quality Enhancement Project (HEQEP) at MIST for the technical and financial support and also to the Ministry of Science and Technology for funding the work by awarding R&D grant scheme 2016-17.

I am also deeply indebted to Anjuman Anju, Md Arman Habib, the data collection team, HEQEP team and EWCE Dept of MIST for their great cooperation in general.

And finally, last but by no means least, I pay my heartiest thanks to everyone in the Climate Change lab.

Nafiz Ul Ahsan

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## ABBREVIATIONS AND NOTATIONS

| | |
|---|---|
| BIWTA | Bangladesh Inland Water Transport Authority |
| BUET | Bangladesh University of Engineering and Technology |
| BWDB | Bangladesh Water Development Board |
| CCTF | Climate Change Trust Fund |
| DPHE | Department of Public Health Engineering |
| GPS | Global Positioning System |
| GW | Ground Water |
| IPCC | Inter-Governmental Panel on Climate Change |
| IRM | Irrigation Management Division, IWM |
| IWM | Institute of Water Modelling (erstwhile SWMC) |
| JICA | Japan International Co-operation Agency |
| *m* | *Meter* |
| *Mm* | *Millimeter* |
| MoEF | Ministry of Environment and Forest |
| PWD | Public Works Datum |
| Q | Discharge |
| SW | Surface Water |
| WL | Water Level |
| UNDP | United Nations Development Programme |
| WARPO | Water Resources Planning Organization |
| MIST | Military Institute of Science and Technology |
| HEQEP | Higher Education Quality Enhancement Project |
| MoST | Ministry of Science and Technology |
| DoE | Department of Environment |
| WHO | World Health Organization |

# Chapter 1

# INTRODUCTION

## 1.1 BACKGROUND

The south western cities of Bangladesh have been experiencing salinity intrusion due to climate change and withdrawal of upstream fresh water by neighbors. On the other hand, over-abstraction of groundwater may eventually lead to the decrease of fresh water availability to human and ecosystem damage. Saltwater intrusion into freshwater aquifers in Khulna region is also influenced by many other factors such as tidal fluctuations, sea level changes as well as seasonal changes in evaporation and recharge rates. Sea level rise contributing to saline intrusion or inundation of coastal freshwater resources is probably the most direct impact, particularly for shallow sandy aquifers along low-lying coasts. The natural groundwater equilibrium is also susceptible to changes in recharge and discharge associated with it.

In Bangladesh groundwater is the major source of water throughout the year because of its availability and general good quality. Few years ago groundwater was taken as granted for safe use, but the recent circumstances indicate that ground water is seriously vulnerable to depletion and saline water intrusion in the coastal regions. For this it is important to understand the development of groundwater investigations and the development of comprehensive numerical models for analytical solutions or numerical methods of groundwater modeling. As it is a tool that can aid in studying groundwater problems and can help increase our understanding of groundwater systems. Numerical models have been extensively used for groundwater analysis, ground water quality and quantity stabilization and for groundwater management practices. (Lakshmi priya C et al., 2015)

## 1.2 OBJECTIVES OF THE STUDY

- To develop and assess a numerical model to understand the saline water transport phenomena in the studied area of Khulna using visual MODFOLW FLEX 2015.1
- To assess the extent of saltwater intrusion towards inland water and aquifers in the study area.

## 1.3 SCOPE AND IMPORTANCE OF THE STUDY

The implications of saltwater intrusion in the coastal region have not been investigated in great detail. In the coastal area of Bangladesh, drinking water is mainly derived from deep wells and irrigation is limited to surface and in some extent ground water bodies. Fresh water is also available at shallow depth sourced from seasonal precipitation but turns to brackish condition during dry period. There is high vulnerability to salinization due to pumping-induced mixing of pre-existing fresh and saline groundwater. Fresh groundwater is also vulnerable to vertical infiltration of saltwater due to periodic storm surge flooding. The amount of water stored in the soil is fundamentally important to agriculture and has influence on the rate of actual evaporation, groundwater recharge and generation of runoff. Rising sea level causes the tidal saltwater wedge to intrude further upstream in rivers, with resulting changes in salinity affecting coastal groundwater aquifers. In the coastal areas where availability of fresh and safe water is a big problem due to saline water intrusion in upper aquifers, assessment and monitoring of probable impact on fresh water resource is utmost important.

The coastal areas of Bangladesh have already been facing salinity problem which is expected to be exacerbated by sea level rise. Salt affected areas in the coastal region have increased by 26.7% from the year 1973 to 2009 in Bangladesh. (SRDI, 2010). In dry season, when the flows of upstream water reduce drastically, the saline water goes up to 240 km inside the country and reaches to Magura district. Presently around 31 upazillas of Jessore, Satkhira, Khulna, Narail, Bagerhat and Gopalganj districts are facing severe salinity problem (Zahid et al., 2013).

A direct consequence of sea level rise would be intrusion of salinity with tide through the rivers and estuaries. It would be more acute in the dry season, especially when freshwater flows from rivers would diminish. So the study will help to understand saline water transport phenomena in the studied area and saltwater intrusion towards inland water and aquifers. The above objectives of the study have been achieved through the development of groundwater models to understand the behavior of salinity intrusion in a section of the coastal belt. These models allowed for simulation of both groundwater flow and the migration of saltwater in the subsurface. The models helped in understanding and assessment of the salinity intrusion process for present conditions and then evaluate changes due to increased groundwater uses and sea level rise, providing estimates of salinity intrusion impacts to water supply for a variety of uses.

## 1.4 THESIS STRUCTURE

The structure of the project report is briefly described below:

Chapter 1 describes the background, objectives and importance of the study

Chapter 2 describes the literature review of relevant studies

Chapter 3 describes the theory and methodology of the study including data collection and analysis process

Chapter 4 describes the detail of model conceptualization and development

Chapter 5 describes the results and discussions of the study

Chapter 6 describes the conclusions and recommendations

# Chapter 2

# LITERATURE REVIEW

## 2.1 INTRODUCTION

Groundwater in Bangladesh is widely available and in general, the groundwater resources of the country are plentiful. The country is blessed with prolific unconsolidated to semi-consolidated fluvio-deltaic sedimentary aquifers (Ravenscroft 2003; Burgess et al. 2010). Across the extensive floodplains of rural Bangladesh, hand-pumped tube-wells (HTWs) are used for domestic water supply and motorised pumps abstract groundwater for dry-season irrigation. Groundwater meets almost the entire national water-demand for domestic and industrial water supply and for irrigation, mostly from the shallow depth (20 to 70 m) below ground surface. The implications of saltwater intrusion in the coastal aquifers of Bangladesh have not been investigated in great detail. In the coastal area of Bangladesh, drinking water is mainly derived from deep wells and irrigation is limited to surface water bodies. Fresh water is also available at shallow depth sourced from seasonal precipitation but turns to brackish condition during dry period. Rising sea levels would cause the tidal saltwater wedge to intrude further upstream in rivers, with resulting changes in salinity affecting coastal groundwater aquifers. In the coastal areas where availability of fresh and safe water is a big problem due to saline water intrusion in upper aquifers, assessment and monitoring of probable impact of sea-level rise on fresh water resource is utmost important.

## 2.2 RIVER AND DRAINAGE BASIN HYDROLOGICAL SYSTEM

The Bengal delta occupies a unique position among the larger deltas of the world for its varied and complex drainage and river system. Tidal rivers characterized the coastal drainage system is criss-crossed by innumerable large and small channels of which some are decaying; some are active, while some others are being drained only by the tidal flow. The southwestern portion of the Ganges delta, which includes the world's largest mangrove forest, the Sundarbans, is completely a maze of tidal creeks and channels. The river system's channels however carry a substantial amount of water through its various distributaries which join these tidal channels and estuarine creeks. Almost the whole delta is dotted with numerous lakes, marshes and low-lying swamps. (Zahid et al., 2013).

Another significant feature of the delta-rivers is their continual shifting of courses. Most of the major streams of the delta including its premier channel, the Ganges-Padma, have been ceaselessly changing their courses or migrating laterally and occupying new sites. Even the minor channels of the delta show the same tendency. The general flow-trend or direction of these deltaic rivers is north-south. Most of the rivers of the western part of the delta such as the Ichamati and Kuttiganga follow a rather south-easterly direction while some of the eastern rivers show a marked south-westerly tendency (the Arial Khan, Bishkhali, etc). These flow-tendencies of the deltaic rivers have a linkage to the regional geo-tectonic situation. The main channel of the Ganges-Padma has long been maintaining a southeasterly direction.

The Ganges delta shows a mixed drainage pattern. The stem-stream of the delta, the Ganges-Padma, is a braided channel with a meandering course. Most of the other major distributaries also follow a sinuous course. A number of major streams, however, follow straight courses which can presumably be identified as tectonically controlled channels, viz, those of the southeastern creeks. At places the pattern of the streams is parallel, while at other places the pattern is trellis or rectangular.

The Bhagirathi-Hugli, Gorai-Madhumati and Arial Khan are three second-Order Rivers of the system. The Jalangi, Bhairab, Mathabhanga, Kobadak, Bhadra, Ichamati, Kumar, Nabaganga are some other important streams of the delta. Among the tidal or coastal creeks, the Matla, Hariabhanga, Saptamukhi, Malancha, Pasur, Haringhata, Rabanabad channel, Tentulia and Hatiya channels are worth mentioning. The Sundarbans, which occupies the southwestern deltaic coast, is also famous for its complex network of tidal creeks. (Zahid et al., 2013).

The recorded highest flow of the Ganges was 760,000 cumec in 1981, and the maximum velocity ranging from 4-5 m/sec, with depth varying from 20 to 21m. The average discharge of the river is about 11,500 cumec, with an annual silt load of 492 ton/km$^2$. (Zahid et al., 2013).

## 2.3 AQUIFERS AND WELLS

In Bangladesh semi-consolidated to unconsolidated fluvio-deltaic sediments of Miocene to the present have many aquifers. But except the Dupi Tila Sandstone Formation of the Plio-Pleistocene age, others are too deep to consider for ground water extraction except in the Hilly Region of the country.

The floodplains of the major rivers and the active/inactive delta plain of the GBM Delta Complex occupy 82% of the country. In these regions major aquifer systems belongs to the Late Pleistocene to Holocene sediments. From the present available subsurface geological information it appears that most of the good aquifers of the country occur between 30 to 130 m depth. These sediments are cyclic deposits of mostly medium to fine sand, silt and clay. The individual layers cannot be traced for long distances both horizontally or vertically. All the sand or silt layers can be considered as aquifers of limited extent. In such cases, instead of individual layers a zone with identifiable characteristics are generally taken for classification of sediments as well as aquifers. However, after the discovery of arsenic contamination in shallow groundwater (up to about 50 m deep) of Bangladesh, shallow or upper aquifers are no longer safe for groundwater abstraction in many regions. (Zahid et al., 2013).

In all the groundwater studies undertaken in Bangladesh, the aquifer systems have not been divided stratigraphically. Conceptual models of hydro-geological conditions, based on simple lithology and depth rather than stratigraphic units, have been used to assess the engineering and hydraulic properties of aquifers and deep tube well designs to depths of 150 m. The reason being that very little work has been done on the sedimentation history of Late Pleistocene-Holocene in Bangladesh.

BWDB-UNDP (1982) study classified the aquifers into three zones. These are the 1) Upper Shallower or the Composite Aquifer, 2) Main Aquifer, and 3) Deep Aquifer. Greater part of the country except Dhaka and the coastal area generally divided into these three zones from a study of the lithologic section up to a depth of 137 m from the existing bore hole logs: Upper clay and silt; Silty to fine sand; and Medium to coarse grained sand and gravel. This study also divided the country into 15 hydrogeological zones on the basis of the geological factors, aquifer characteristics and development constrains. These 15 zones have different potentialities for the development of groundwater. The extensive geological analysis presented in Technical Report 4, MPO

(1987) classified the main aquifer into 36 units (Figure 2.3). A more flexible two-tier classification was presented by EPC/MMP. (Aggarwal et al. 2000) on the basis of isotopic studies classified the water at different depths in four types and made a three-tier division of the aquifers. BGS-DPHE (1999) and BGS-DPHE (2001), with slight adjustments of the BWDB-UNDP (1982) study also made a three-tier classification of the aquifers zones. Comparative picture showing these divisions are presented in the Table 2-1 below.

Table 2-1: Aquifer Type of Holocene-Pleistocene Sediments (Down to ~ 350 m)

| **BWDB-UNDP, 1982** | **BGS-DPHE, 2001** | **Aggarwal et.al, 2001; Zahid et al., 2009** |
|---|---|---|
| Upper aquifer (composite aquifers)<br>Main aquifer<br>Deep aquifer | i) Upper Shallow<br>ii) Lower Shallow<br>iii) Deep Aquifer | i) 1st aquifer (Type 1 and 2)<br>ii) 2nd aquifer (Type 3)<br>iii) 3rd aquifer (Type 4) |

The upper (shallower) or the composite aquifer: Below the upper clay and silt unit of depth ranging from less than a meters to several hundred meters, very fine to fine sand, in places inter bedded or mixed with medium sand of very thin layers are commonly encountered. Discontinuous thin clay layers often separate these sand layers. The thickness of this zone ranges from a few meters in the northwest to a maximum of 60 m in the south. Over most of the country it represents the uppermost water bearing zone. In the coastal region water in this aquifer zone is saline with occasional fresh water pockets.

The main aquifer: This is the main water-bearing zone and occurs at depths ranging from less than 5 m in the northwest to more than 75 m in the south and most of the country. It is both semi-confined and leaky or consists of stratified interconnected, unconfined water bearing zones. This aquifer is comprised of medium and coarse grained sediments, in places inter bedded with gravel. These sediments occur to depths of about 140 m below ground surface. Presently, groundwater is drawn predominantly from this aquifer zone.

Two groundwater observation well nests have been installed at Khulna sadar and Rupsha upazilas under Khulna district by BWDB. Four bore holes were drilled at Khulna BWDB Campus, Khulna Sadar down to the maximum depth of 325 m. Two aquifers have been identified at this location till investigated depth of 325 m and separated by 10 to 50 m thick clay and silty clay aquitard (Figure 2.1). An upper clay auitard occurs at the surface that overlays the upper or 1st aquifer and thickness is about 40 m. The 1st aquifer is encountered at depth 35 to 100 m and dominated by gray very fine sand.

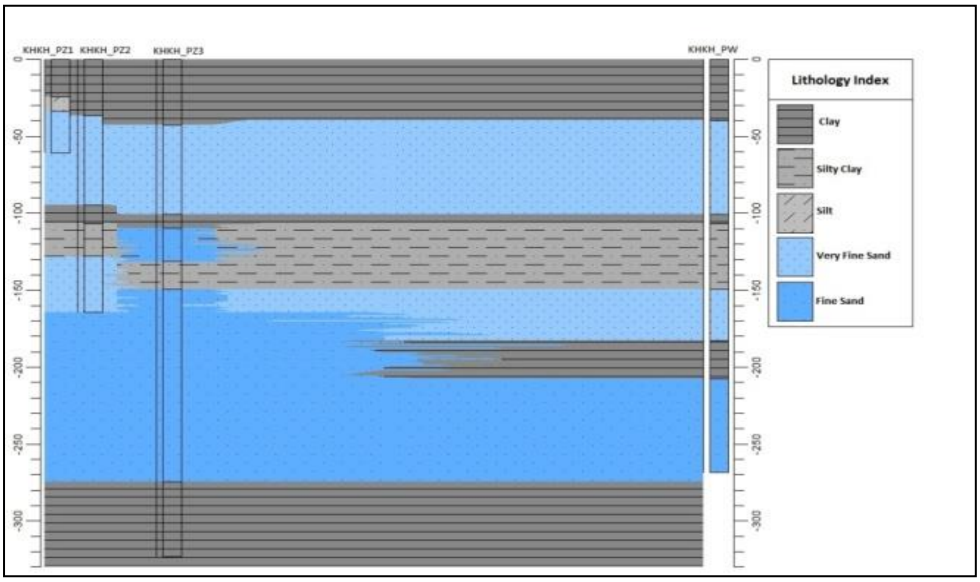



Figure 2.1: Lithologic Cross Section of Nested Wells at Khulna sadar, Khulna. (Source: BWDB, 2013)

The 2nd aquifer is encountered between depths of 150 to 270 m below surface consisting of gray very fine and fine sand underlain by gray clay aquitard till the investigated depth. The 2nd aquifer is confined to leaky confined in nature.

At Rupsha upazila the highest drilling depth for the deepest piezometer was 335 m. The borehole lithologic logs indicate that the aquifer continues till 280 m depth from the surface underlain by clay aquitard. The aquifer is unconfined in nature (Figure 2.2). The upper part of the aquifer sediment is composed of gray very fine sand and the lower part is dominated by gray fine sand, in places inter bedded with silty clay lenses.

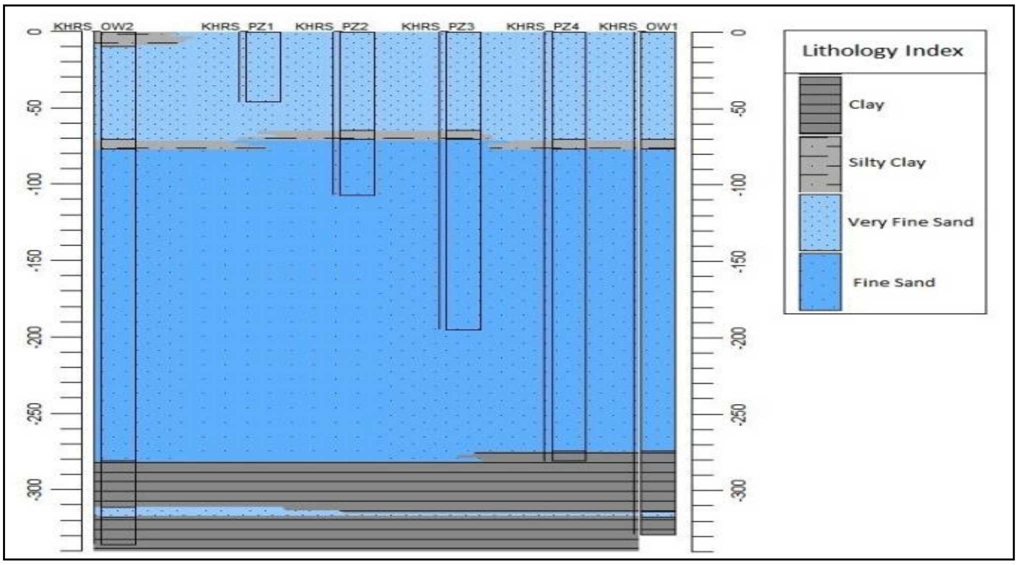



Figure 2.2: Lithologic Cross Section of Nested Wells at Rupsha, Khulna. (Source: BWDB, 2013)

At Botiaghata, Dakope, Dighalia, Dumuria, Koyra, Paikgacha, Rupsha and Terokhada upazila/thana areas under Khulna district, 40 piezometers were drilled in 8 lines upto 100 m depth. At all locations the upper or 1st aquifer exists till investigated depth of 100 m consists of gray fine to very fine sand and overlain by 5 to 45 m thick silty clay aquitards. At Terokhada area, 20 m thick upper silty clay and clay layer occurs while the highest thickness of an upper silty clay aquitard is 47 m in Dighalia area. At Rupsha area about 16 m thick silty clay lense is present and about 15 m thick silty clay aquitard is encountered below the 80 m thick aquifer. At Dumuria and Koyra about 7 m thick silt layer is interbeded in aquifer. The aquifers are semi confined in nature. (Zahid et al., 2013).

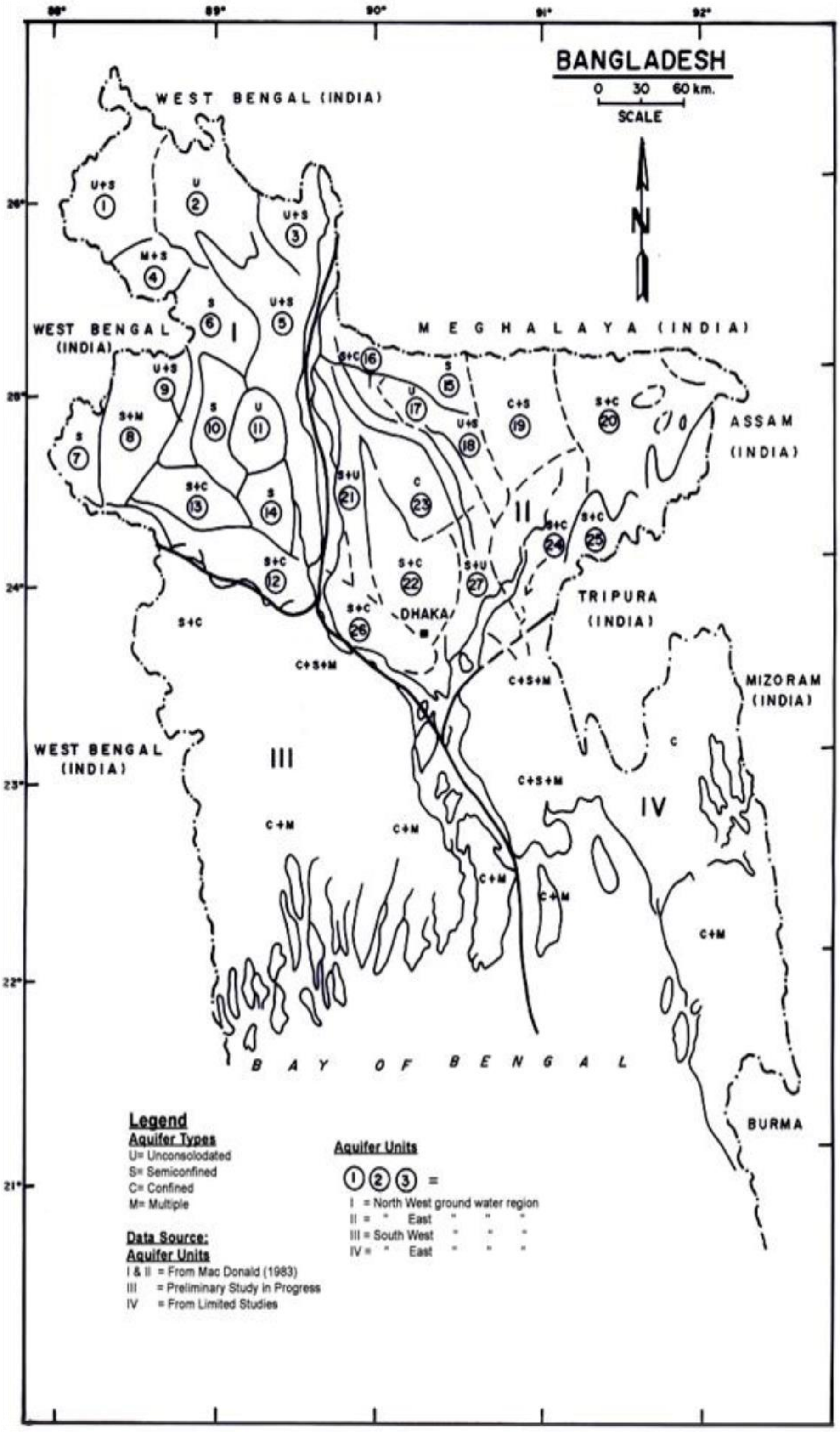



Figure 2.3: Aquifer Types in Different Regions of Bangladesh (Source: MPO, 1987).

## 2.4 SALINE WATER INTRUSION IN GROUND WATER

Groundwater in many parts of the world is under threat because of increasing demands, mismanagement and contamination. To cope with all these challenges, good planning and management practices are needed. A key to the management of groundwater is the ability to model the movement of fluids and contaminants in the subsurface (Bear and Cheng, 2010).

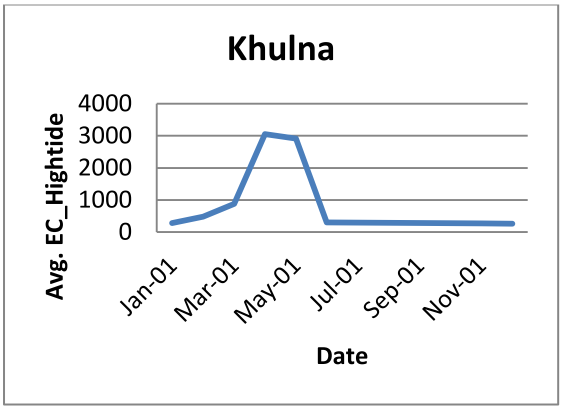
Models are the conceptual descriptions representing the real system. Groundwater flow models use mathematical equations based on the simplifying assumptions to describe flow and transport process. They also provide additional insight into the complex system behaviour and can assist in developing conceptual understanding. Furthermore, once they have been demonstrated to reasonably reproduce past behaviour, they can forecast the outcome of future ground water behaviour, support decision-making and allow the exploration of alternative management approaches (Kumar, 2013).

Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties in the values of data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions. Groundwater models, however, even as approximations are a useful investigation tool that groundwater hydrologists may use for a number of applications (Mandle, 2002).

### 2.4.1 Trend of Salinity Level of the Study Area

The groundwater in the coastal area is generally the Na–Cl type and the Na-Ca-Mg–$HCO_3$ type. The major ion trends of the Na–Cl type are Na+>$Ca_2$+>$Mg_2$+>K+ and $Cl^-$ >$HCO_3$->$SO_4^{2-}$. Salinization is the most widespread form of groundwater contamination in coastal aquifers, and is represented by the increases of total dissolved solids (TDS), Electric Conductivity (EC) and some specific chemical constituents such as $Cl^-$, $Na^+$, $Mg^{2+}$, and $SO_4^{2-}$.

In the coastal zone, salinity is extremely variable and changes abruptly over short distances. In most areas, the water is too saline for domestic and irrigation use due to either to connate salts or estuarine flooding. Salinity trend in the study area suggest that in the month of April and May salinity is maximum and it gradually decreases. The historical data collected from BWDB for past 11 years (Figure 2.4) shows the same trend. Keeping that in mind from the EC value salinity value was calculated and incorporated in the model.


Khulna
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Avg. EC_Hightide
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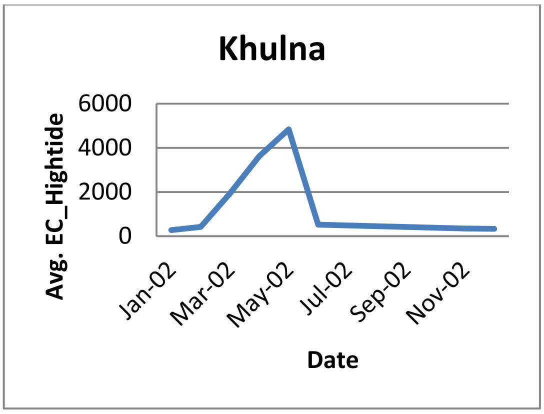
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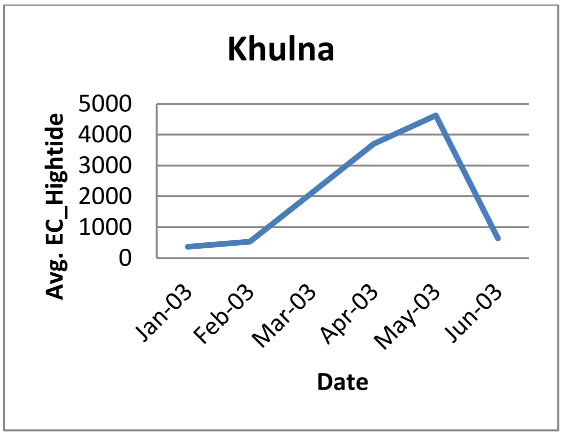
Jul-02
Sep-02
Nov-02
Date


Khulna
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May-03
Jun-03
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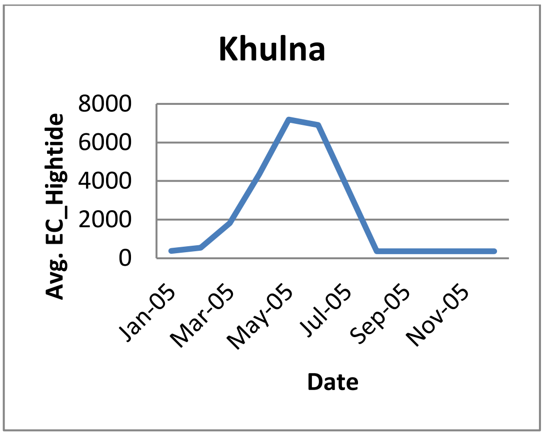
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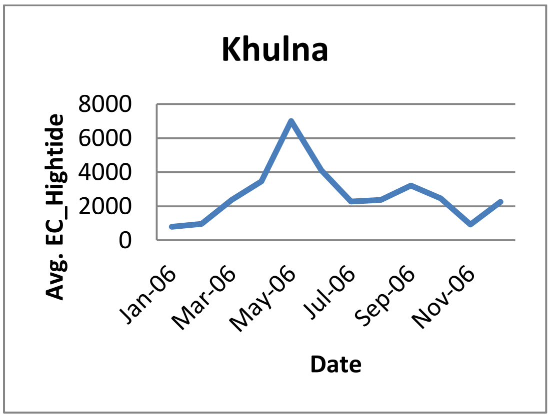
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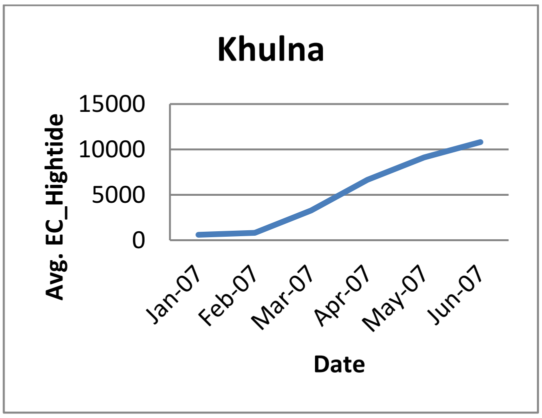
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Jun-07
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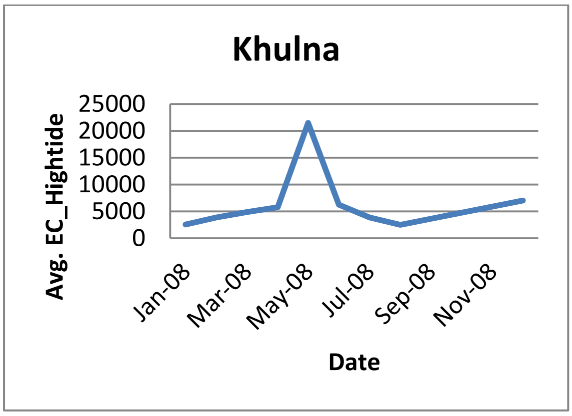
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Nov-08
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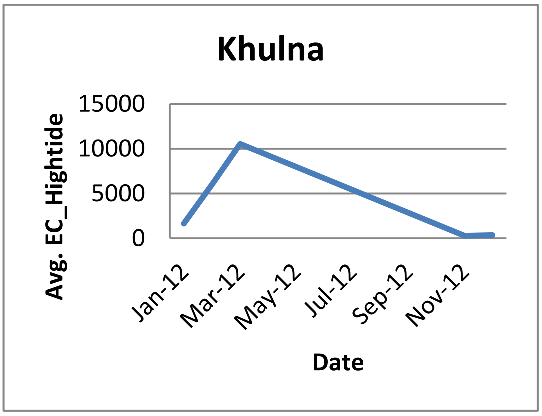
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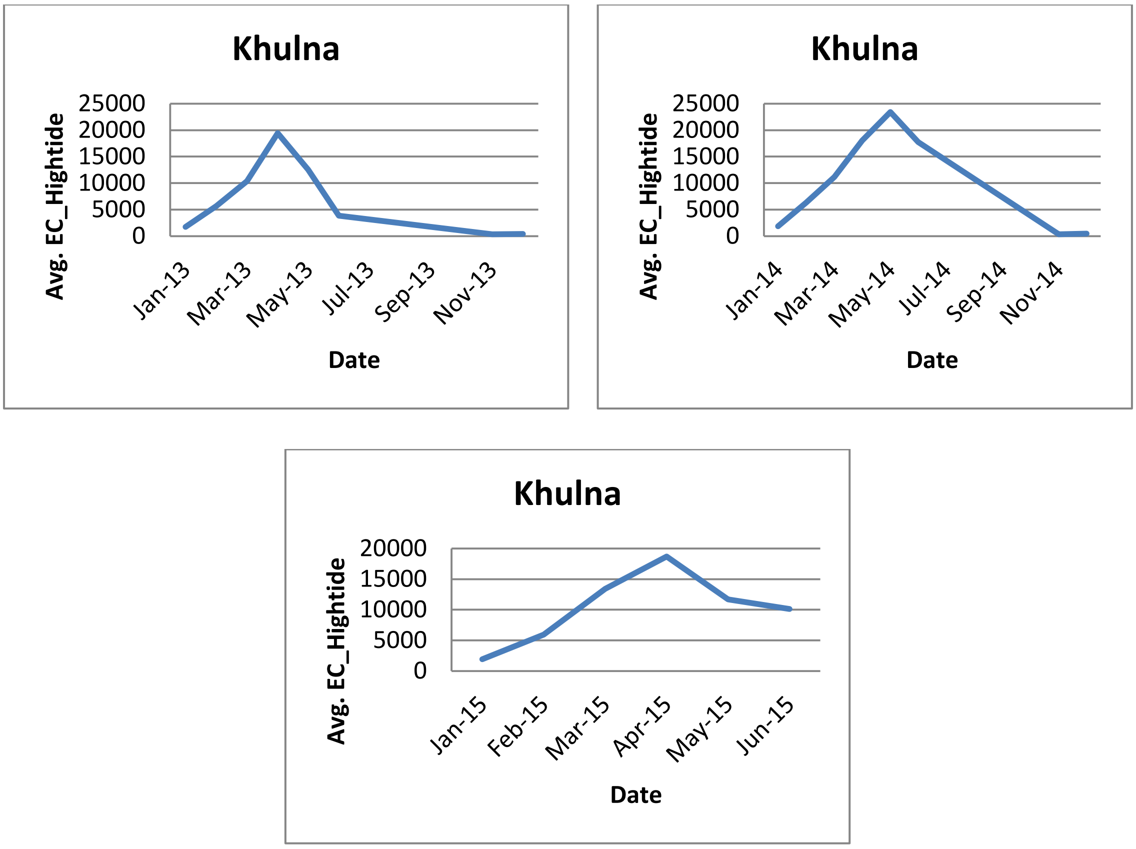
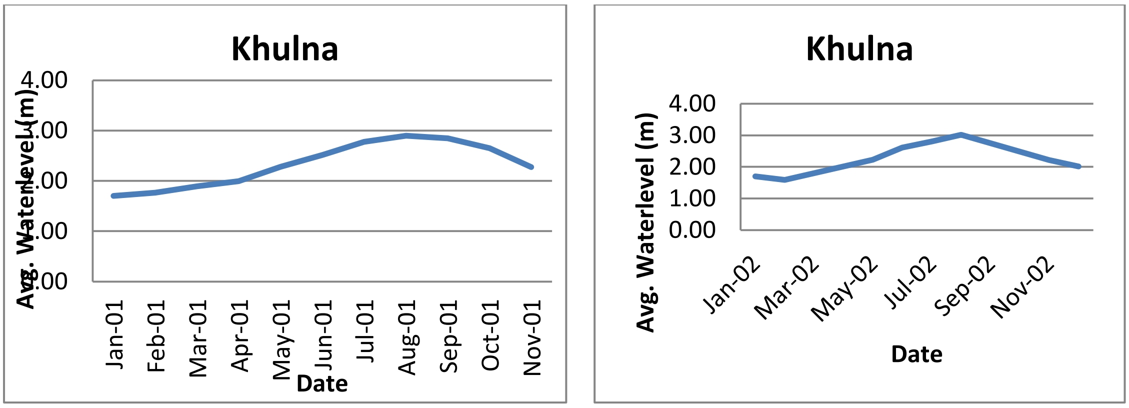
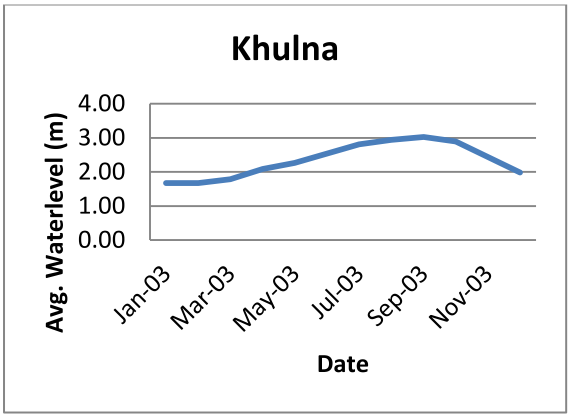
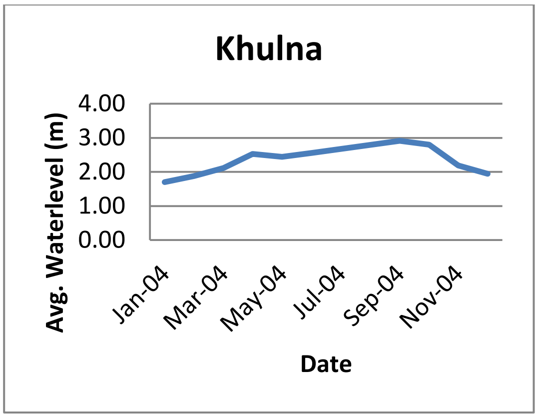



Figure 2.4: EC data of the study area (Source: BWDB).

### 2.4.2 Trend of GW Level in the study area




Khulna
Avg. Waterlevel (m)
4.00
3.00
2.00
1.00
0.00
Jan-03
Mar-03
May-03
Jul-03
Sep-03
Nov-03
Date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Avg. Waterlevel (m)
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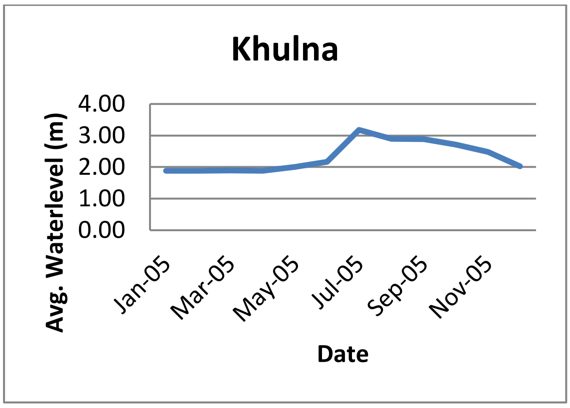
2.00
1.00
0.00
Jan-04
Mar-04
May-04
Jul-04
Sep-04
Nov-04
Date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Avg. Waterlevel (m)
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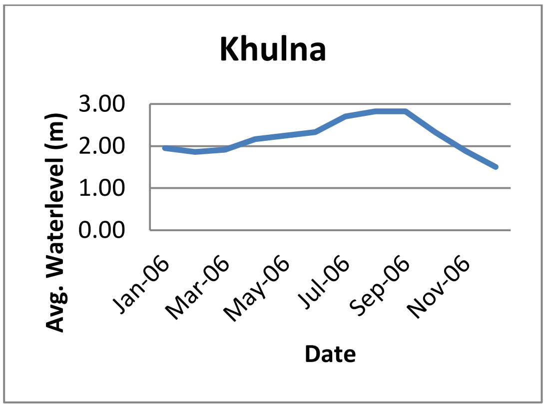
2.00
1.00
0.00
Jan-05
Mar-05
May-05
Jul-05
Sep-05
Nov-05
Date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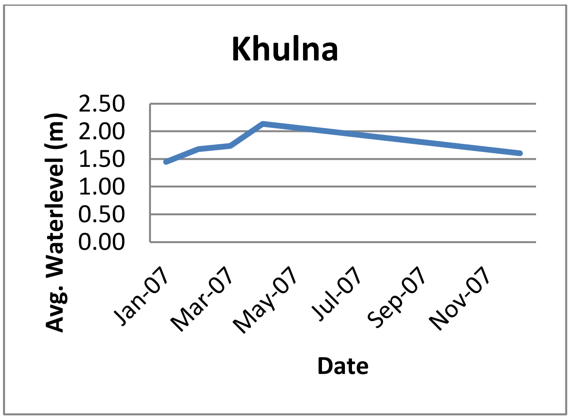
1.00
0.00
Jan-06
Mar-06
May-06
Jul-06
Sep-06
Nov-06
Date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Avg. Waterlevel (m)
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1.50
1.00
0.50
0.00
Jan-07
Mar-07
May-07
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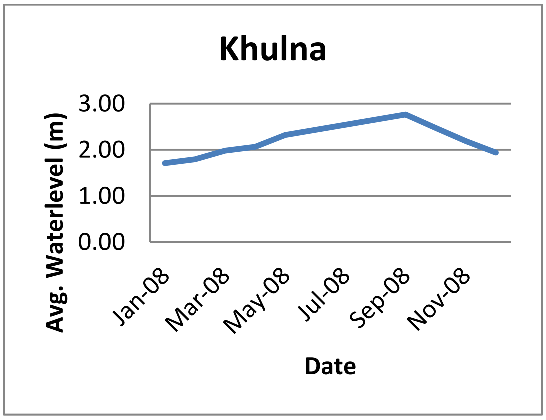
Sep-07
Nov-07
Date


Khulna
Avg. Waterlevel (m)
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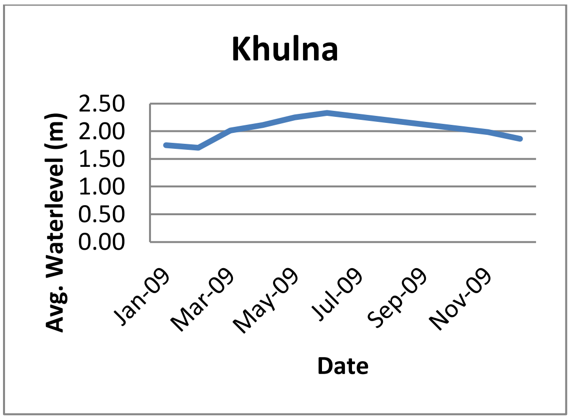
2.00
1.00
0.00
Jan-08
Mar-08
May-08
Jul-08
Sep-08
Nov-08
Date


Khulna
Avg. Waterlevel (m)
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1.50
1.00
0.50
0.00
Jan-09
Mar-09
May-09
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Sep-09
Nov-09
Date

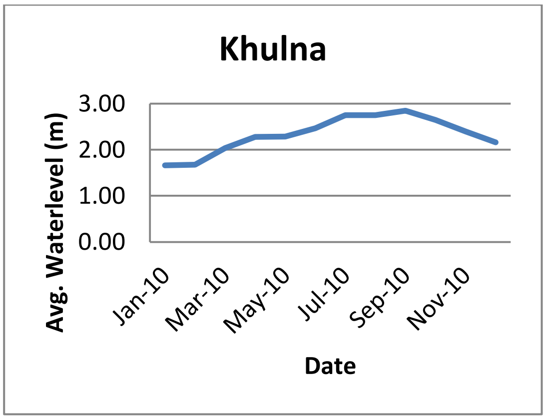

Khulna
Avg. Waterlevel (m)
3.00
2.00
1.00
0.00
Jan-10
Mar-10
May-10
Jul-10
Sep-10
Nov-10
Date


Figure 2.5: Water level data of the study area (Source: BWDB).

A long term water level graph (Figure 2.5) of a BWDB Station ID. SW241 is prepared and presented above. BWDB used to collect the groundwater level data from their country wide groundwater monitoring network wells.

From the graphs it is observed that the groundwater level of shallow aquifer (first aquifer) fluctuate from 0.56 m to 2.16 m below ground level of the well and replenished in all the respective years. Trend of this graph is similar in nature in all the years.

Alam & Umar, in 2013, studied a depleting aquifer in a fluvial region in India and performed groundwater modelling using Visual Modflow Flex 2015.1. The researchers addressed an issue of groundwater depletion caused by over irrigation and suggested that groundwater modelling is an integral part of sustainable groundwater management. The study also investigated the parameters to which the groundwater modeling by Modflow is dependent on. The study concluded that hydraulic conductivity and recharge values are the most influential parameters in the software.

Kafle *et al.* (2006) had presented the results of a basin scale rain fall runoff modelling on Bagmati basin in Nepal using the hydrologic model HEC-HMS in GIS environment. The model developed is a combination with the GIS extension HEC-GEOHMS, and used to convert the precipitation excess to overland flow and channel runoff. The Curve numbers are assigned based on the soil type and land use. The peak flow of the derived hydrograph was used as an input in hydraulic model to derive flood maps showing inundation area extent and flood depths.

Goswami (2000) studied five Rainfall Runoff models for continuous River flow simulation. The five rainfall runoff models which are used in this paper are simple linear model, seasonally based linear perturbation model, 7 wetness index based linearly varying gain factor model, artificial neural network model and conceptual soil moisture accounting and routing model. The authors used the Galway real-time river flow forecasting system software package to produce all the numerical results. They concluded that simpler models for continuous River flow simulation can surpass their complex counterparts in performance.

Sarangi (2007) dealt with the predictability of unit hydrograph models that are based on the concepts of land morphology and isochrones to generate direct runoff hydrograph. The models which were used by them are Exponential Distributed Geomorphologic Instantaneous Unit Hydrograph (ED-GIUH), GIUH based Clark model and Spatially Distributed Unit Hydrograph (SDUH). Five distinct rainfall events are used to evaluate the three models. These three models are evaluated based on morphology, flow path probability and travel time responses over land surfaces and through channels. In this study, ArcGIS is used to estimate the watershed morphological parameters.

Kalin (2004) identified the sediment source areas using optimization methods for two watersheds. The question of non-uniqueness is addressed 8 first by them. KINEROS model is used. Assumption made in this study is that the flow is Hortonian. Sedimentographs are generated using 13 rainfall events. The generated sedimentographs and unit sedimentograph resulting from rainfall event were taken as the inputs to the optimization model. Outcomes of the model revealed that sediment source areas could be reasonably identified as long as the number of sediment generating area is less than eight. When the number of sources exceeds eight, the uncertainty of source identification increased due to the non-uniqueness problem.

Fu (2007) developed and implemented a methodology to estimate the impacts of global climate change on hydrological regimes using ArcGIS Geostatistical Analyst. The methodology was applied to the Spokane River Watershed. From the results, they indicated that a 30% precipitation increase causes a 50% increase of stream flow when the temperature is normal. When the temperature is 1.5% higher than normal, then they indicated that only a 20-30% increase in stream flow. The results obtained by them can be used as reference conditions for long-term water management strategies under global warming scenarios.

Hea, Thomas E. Croley (2005) analyzed the application of a spatially distributed large basin runoff model. They discussed about the four essential components of operational hydrologic model development such as model structure, model input, model calibration and GIS model interface. The results obtained by them indicated that large scale operational hydrologic models that are based on mass continuity equations and include land surface, soil zones and groundwater components require fewer parameters and are less data demanding.

Angelica and Gutiérrez-Magness (2005) dealt with an Automatic calibration of complex models, which includes continuous hydrograph 9 models, requires sophisticated calibration methods. The authors also dealt with this model-independent-parameter estimator which requires complex objective functions to ensure that the final parameter values reflect the hydrologic flow components surface runoff, interflow and base flow that the models are designed to represent. They also showed that a multicomponent objective function should include components to represent each of the important physical processes represented in the model. The goal of the investigation was to develop a weighted multicomponent objective function and a method that can be used to provide estimates of the weights. For best calibration accuracy, the weights of the objective function should reflect the flow proportions of the stream flow record.

Mullem (1991) used the Green-Ampt infiltration model to predict runoff from 12 rangeland and cropland watersheds in Montana and Wyoming. Soil parameters derived from standard USDA soil surveys are used, and 99 rainfall events are modeled. The runoff distributions obtained from the model are then used with a hydrograph model to predict the peak discharge from the watershed. Procedures are applied that adjusted the Green-Ampt infiltration parameters for various cover and condition classes. The runoff volumes and peak discharges are compared with the measured values and with those predicted by the Soil Conservation Service (SCS) curve-number procedure. By using this model they have predicted both the runoff volume and peak discharge better than the curve-number model.

McCuen (2006) used the Nash–Sutcliffe efficiency index (Ef) which is a widely used and potentially reliable statistic for assessing the goodness of fit of hydrologic models. The factors that contribute to poor sample values are not well understood by the authors. Their research focused on the interpretation of sample values of Ef. The objectives were to present an approximation of the sampling distribution of the index; provide a method for 10 conducting hypothesis tests and computing confidence intervals for sample values; and identify the effects of factors that influence sample values of Ef. They have concluded that the Nash–Sutcliffe index can be a reliable goodness of-fit statistic if it is properly interpreted.

Uhlenbrook (1999) investigated the uncertainties arising from the problem of identifying a representative model structure and model parameters in a conceptual rainfall-runoff model. In this paper a conceptual model, the HBV model, was applied to the mountainous basin. In a first step, a Monte Carlo procedure with randomly generated parameter sets was used for calibration. For a ten-year calibration period, different parameter sets resulted in an equally good correspondence between observed and simulated runoff. A few parameters were well defined (i.e. best parameter values were within small ranges), but for most parameters good simulations were found with values varying over wide ranges. In a second step, model variants with different numbers of elevation and land use zones and various runoff generation conceptualizations were tested. They found that in some cases, representation of more spatial variability gave better simulations in terms of discharge. However, good results could be obtained with different and even unrealistic concepts. The computation of design floods and low flow predictions illustrated that the parameter uncertainty and the uncertainty of identifying a unique best model variant have implications for model predictions.

Megnounif (1984) analyzed a large amount of data on suspended solids transport in Algerian rivers. In this paper the author enabled a general study of erosion, sediment transport and silting of dams. The object of his study is to improve the understanding of erosion and sediment transport phenomena in a Mediterranean semiarid climate, and to develop simple and practical methods 11 for the data analysis necessary for planning, construction and management of water resources. This case study demonstrated the need to approach the problem at the level of individual flood events; to study the variables of suspended solids concentration and stream flow separately; and to relate a map of erosion forms and geomorphological factors to the hydrological analysis. The study also showed that a correlation exists between lithology and erosion forms, an average suspended solids content can be related to individual erosion forms, sediment transport primarily takes place in spring during floods which originate from the whole, saturated, basin; the contribution from autumnal localized storm floods.

## 2.5 PREVIOUS STUDIES IN BANGLADESH

### 2.5.1 The DPHE-Danida Study

With the support of DANIDA, DPHE carried out groundwater investigation in few areas of coastal districts. The findings reveals that potential aquifers in the coastal areas are mostly located at depths between 200 and 350 m, and heavy drilling equipment is required for the construction and testing of large diameter production wells to those depths. Also, special surface electrical resistivity survey equipment is recommended for identification of fresh water aquifers below the upper brackish water aquifers.

The major findings on potential aquifers in the coastal areas are described below.

Occurrence of Fresh Groundwater

The potential fresh water aquifers in the coastal areas are mostly located at depths of between 200 and 350 m and fresh water occurs in deep aquifers below a sequence of other aquifer layers containing saline or brackish groundwater. The density of fresh water (1000 kg/m3) is less than the density of saline water (1004 kg/m3 for a chloride content of 3000 mg/l), therefore, deep freshwater would normally be expected to rise above, or mix with, saline water. During the Holocene (the last 10000 years), the sea level gradually rose, the gradient of the major rivers decreased, and river sediments accumulated. The sea water started to penetrate the land via tidal rivers, and the salt content in shallow groundwater started to increase, partly through infiltration from the tidal rivers, but possibly also through the increase of soil in the land. Due to the density difference between fresh and saline water, the shallow brackish/saline water could penetrate deep into the aquifer layers, contaminating the fresh water, except where the deep fresh water was protected by more or less continuous clay layers. In many areas saline or brackish water is noticed in deep aquifers. The deep fresh water lenses may be considered as trapped by the sea level rise in the Holocene.

The DPHE-DANIDA study indicates that the erratic occurrence of small fresh water pockets at depth is reported all over the coastal belt. The fresh bodies do not seem to be connected with each other, which would be the case if they have been built up by groundwater flow from the hinter land. The protective clay layers is leaky or even absent in some places, so it does not provide the closed conduit necessary for flushing saline aquifers at a large distance from the recharge area.

# Chapter 3

# METHODOLOGY

## 3.1 INTRODUCTION

The prime objective of the study is to investigate the present salinity status of groundwater as well as surface water in the study area. Basically, a groundwater model is a simplified representation of the natural groundwater flow system. Numerical model is a useful and tested tool to understand the baseline and future changed conditions of river and coastal hydraulics along with its water quality variation. Investigation on the interaction of river /coastal water salinity to adjacent aquifer water and spatial-temporal variation has been assessed by using groundwater salinity intrusion model.

Salinity transport model has been used to assess the salinity intrusion towards upstream due to the increase of human activity, reduction of dry period flow and climate change within the project area.

Groundwater models are developed to simulate water movement and salt transport in the sea, river and through the porous medium of aquifer for a range of existing and possible future conditions. Seawater intrusion is a natural process, where the groundwater flow depends on hydraulic gradient and fluid density variation between freshwater and seawater and the transport mechanics includes convective and dispersive processes (Bear, et al, 1999).

A numerical model has been assessed showing the dynamism of groundwater in the coastal areas of Bangladesh (Khulna Division). The models will allow for simulation of both groundwater flow and the migration of saltwater in the subsurface. The models will help in understanding and assessing the salinity intrusion process for the present conditions and then in evaluating changes due to increased groundwater uses and sea-level rise. Accordingly, it has been established with a view to studying the hydrology, hydrogeology and aquifer system in the coastal belt of Bangladesh through the numerical modeling by addressing the issue of the movement of salinity front in rivers towards upland due to increase of human activities, reduced dry period flow and the movement of the fresh saltwater interface towards land in response to water-management factors.

## 3.2 EQUATIONS GOVERNING FLOW AND TRANSPORT PROCESSES

A general form of the equation governing the three dimensional non equilibrium movement of groundwater of constant density through porous, anisotropic, three dimensional and heterogeneous flow of groundwater may be described by the partial differential equation (Freeze and Cherry, 1979):

$$\frac{d}{dx}[Kxx\frac{dh}{dx}]+\frac{d}{dy}\ [Kyy\frac{dh}{dy}]+\frac{d}{dz}[Kzz\,\frac{dh}{dz}]-W=Ss\frac{dh}{dt} \quad \text{-----------------------------------------} \ (1)$$

Where,

$K_{xx}$, $K_{yy}$, $K_{zz}$ are components of the hydraulic conductivity along x, y and z axes (l/t),

h is potentiometric head (l),

W is the volumetric flux per unit volume and represents the sources and/or sinks of water per unit time (t-1),

$S_s$ is specific storage of the porous material (l-1),

and t is time (t).

The finite-difference equation is used to simulate the groundwater flow in the study area.

The partial differential equation for three dimensional transports of contaminants in groundwater is:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}[\mathrm{D}ij\,\frac{\partial C}{\partial x_i}] - \frac{\partial}{\partial x_i}(V_i\mathrm{C}) + \frac{q_s}{\theta}\mathrm{Cs} + \sum_{K=1}^{N} R_K \quad \text{----------------------------------------} \ (2)$$

Where,

C is the concentration of contaminant dissolved in groundwater,

t is the time (t),

$x_i$ is the distance along the respective Cartesian coordinate axis Dij is the hydrodynamic dispersion coefficient,

$V_i$ is the seepage or linear pore velocity,

$Q_s$ is the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative),

$C_s$ is the concentration of sources or sinks,

θ is the porosity of the porous medium, and,

$R_k$ is the chemical reaction term.

## Solution with Finite difference

The finite difference form of the partial differential in a discretized aquifer domain (represented using rows, columns and layers) is:

$$CR_{i,j-\frac{1}{2},k}\,(h^m_{i,j-1,k} - h^m_{i,j,k}) + CR_{i,j+\frac{1}{2},k}\,(h^m_{i,j+1,k} - h^m_{i,j,k}) +$$

$$CC_{i-\frac{1}{2},j,k}\,(h^m_{i-1,j,k} - h^m_{i,j,k}) + CC_{i+\frac{1}{2},j,k}\,(h^m_{i+1,j,k} - h^m_{i,j,k}) +$$

$CV_{i,j,k-\frac{1}{2}}(h^m_{i,j,k-1} - h^m_{i,j,k}) + CV_{i,j,k+\frac{1}{2}}\ (h^m_{i,j,k+1} - h^m_{i,j,k}) +$

$P_{i,j,k} h^m_{i,j,k} + Q_{i,j,k} - ss_{i,j,k}\ (\triangle r_j \triangle c_i\ \triangle_{vk}) \frac{h^m_{i,j,k} - h^{m-1}_{i,j,k}}{t^m - t^{m-1}}$

where

$h^m_{i,j,k}$ is the hydraulic head at cell *i,j,k* at time step *m*

*CV*, *CR* and *CC* are the hydraulic conductances, or branch conductances between node *i,j,k* and a neighboring node

$P_{i,j,k}$ is the sum of coefficients of head from source and sink terms

$Q_{i,j,k}$ is the sum of constants from source and sink terms, where $Q_{i,j,k} < 0{,}0$ is flow out of the groundwater system (such as pumping) and $Q_{i,j,k} > 0{,}0$ is flow in (such as injection)

$ss_{i,j,k}$ is the specific storage

$\triangle r_j \triangle c_i\ \triangle_{uk}$are the dimensions of cell *i,j,k*, which, when multiplied, represent the volume of the cell; and

$t^m$is the time at time step *m*

This equation is formulated into a system of equations to be solved as:

$CV_{i,j,k-\frac{1}{2}} h^m_{i,j,k-1} + CC_{i-\frac{1}{2},j,k}\ h^m_{i-1,j,k} + CR_{i,j-\frac{1}{2},k}\ h^m_{i,j-1,k} + (-CV_{i,j,k-\frac{1}{2}} - CC_{i-\frac{1}{2},j,k} -$
$CR_{i,j-\frac{1}{2},k} - CR_{i,j+\frac{1}{2},k} - CC_{i+\frac{1}{2},j,k} - CV_{i,j,k+\frac{1}{2}} + HCOF_{i,j,k}$
$)\ h^m_{i,j,k} + CR_{i,j+\frac{1}{2},k} h^m_{i,j+1,k} + CC_{i+\frac{1}{2},j,k} h^m_{i+1,j,k} + CV_{i,j,k-\frac{1}{2}} h^m_{i,j,k+1} = RHS_{i,j,k}$

Where,

$HCOF_{i,j,k} = P_{i,j,k} - \frac{ss_{i,j,k}\ \triangle r_j \triangle c_i \triangle_k}{t^m - t^{m-1}}$

$RHS_{i,j,k} = -Q_{i,j,k} - ss_{i,j,k} \triangle r_j \triangle c_i \triangle_{vk}\ \frac{h^{m-1}_{i,j,k}}{t^m - t^{m-1}}$

or in matrix form as:

Ah= q

where

*A* is a matrix of the coefficients of head for all active nodes in the grid

h is a vector of head values at the end of time step m for all nodes in the grid; and

q is a vector of the constant terms, *RHS*, for all nodes of the grid.

## 3.3 MODEL DESCRIPTION

MODFLOW simulates steady and non-steady flow in an irregularly shaped flow system in which aquifer layers are confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, is simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries are simulated as a head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modeled area at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary block. The geological formations, property model, and boundary conditions are all designed outside the model grid or mesh; this allows the flexibility to adjust your interpretation of the groundwater system before applying a discretization method and converting to a numerical model. With grid-independent data allows to maximize the use of existing GIS data and incorporate physical geology and geographic conditions before designing a grid or mesh. MODFLOW LGR package helps local grids around areas of interest, directly within the conceptual model environment. Calculated heads from a regional model can also be used as boundary conditions for local-scaled models. The grid-independent raw data is left intact and is not constricted by grid cells or mesh elements when modifying the data and project objective. This allows to generate multiple numerical models from the same conceptual model.

## 3.4 MODEL BOUNDARY CONDITION

The basic model boundary condition of the groundwater model is summarized in table 3.1 for the area. It includes essentially the following:

Table 3.1: Summary of Numerical Model for the study Area

| **Components of Numerical model** | **Description** |
|---|---|
| **Model framework and hydraulic properties** | |
| Domain | The model domain covers an area of approximately 350 km$^2$ |
| Hydrogeological Units | defined by three hydro-stratigraphic layers |
| Salinity | Groundwater salinity ranges between fresh (<500 mg/L) and hyper saline (32,000 mg/L) |
| Model Boundaries | **Northern boundary for upper shallow aquifer** – The observed groundwater level is used as Hydraulic Head Boundary.<br><br>**Southern boundary for upper shallow aquifer** – The surface water level of various ponds is used as Fluid Transfer Boundary.<br><br>**Eastern boundary for upper shallow aquifer** – The surface water level of Shibsa River is used as Fluid Transfer Boundary.<br><br>**Western boundary for upper shallow aquifer** – The surface water level of Rupsha River is used as Fluid Transfer Boundary. |

| Components of Numerical model | Description |
|---|---|
| | **Boundary for lower shallow aquifer** – The observed groundwater level is used a Hydraulic Head Boundary for the entire outer boundary.<br>**Boundary for deeper aquifer** – The observed groundwater level is used a Hydraulic Head Boundary for the entire outer boundary.<br><br>**Model base** – represents impermeable boundary.<br><br>**Model top** – represents recharge boundary.<br><br>**Salinity Concentration at Northern Boundary** – No concentration boundary is used.<br><br>Beside this the concentration of different river is used as Mass Transfer Boundary condition for upper shallow aquifer. Other than upper shallow aquifer no concentration boundary is use. |
| **Groundwater Recharge / Discharge** | Recharge due to infiltration of rainfall in the catchment area is estimated to range between 8 to 12% of rainfall. |

### 3.4.1 Boundary Conditions with Required Data

For simulations, MODFLOW requires the time element of the boundary conditions to be defined using Stress Period "counters" as opposed to using "real" times.

#### 3.4.1.1 Initial and Boundary Conditions

The concentration observation well location and head observation head well location of the area is shown in Figure 3-1 and 3-2. The area is regarded as a closed one with only flow across the boundaries in the eastern and western side. There are however, a few ephemeral surface streams, which take off the groundwater across the eastern boundary of the area. The aquifer has been assumed to be a single layer aquifer having a vertical recharge and has been modeled accordingly. The bottom of the aquifer is assumed to be impermeable bedrock. The numerical model was then used to simulate the groundwater flow under the current conditions. A steady state finite difference model, MODFLOW, is developed to quantify groundwater in the study using ground water data from five head observation wells (Table 3-2) and three concentration observation well (Table 3-3) and two pumping well (Table 3-4). The model simulates groundwater flow over an area of 350 $km^2$ with 40 rows and 40 columns, with three vertical layers. Based upon lithology, water levels aquifer was conceptualised as unconfined. The initial hydraulic head was given based on the observed water levels of 2013 and 2014.

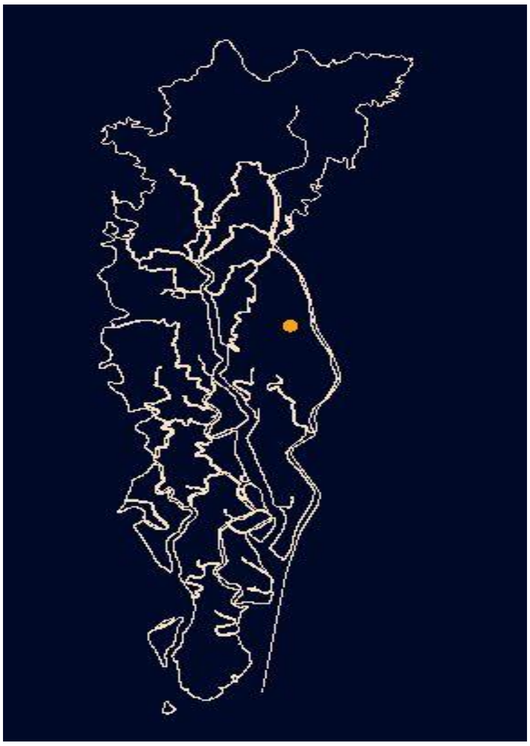


Figure 3-1 Conc. Observation

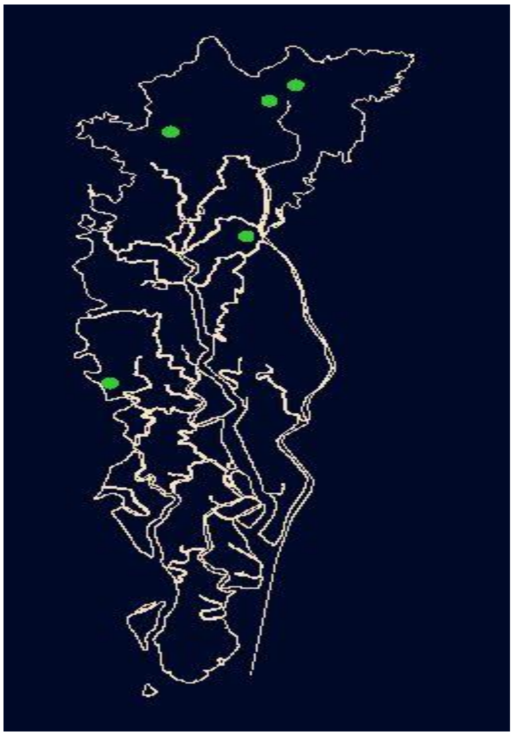


Figure 3-2 Obs. Head Well location

Table 3.2 Observed Head data from monitoring wells of the Coastal Region (Khulna)

| Well Id | X | Y | Elevation | Well bottom | Logger Id | Logger Z | Observed Head | Head observation date |
|---|---|---|---|---|---|---|---|---|
| OW-1 | 745304.492 | 2525579.096 | 120 | 0 | 1 | 100 | 91 | 05/12/2006 |
| OW-2 | 758804.328 | 2516939.292 | 110 | 0 | 1 | 100 | 92 | 06/12/2006 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| OW-3 | 756991.7775 | 2502504.399 | 115 | 0 | 1 | 100 | 88 | 07/12/2006 |
| OW-4 | 760592.5703 | 2532482.709 | 117 | 0 | 1 | 100 | 98 | 08/12/2006 |
| OW-5 | 735886.7447 | 2470038.085 | 112 | 0 | 1 | 100 | 91 | 09/12/2006 |

Source: Bangladesh Water Development Board (BWDB)

Table 3.3 Concentration observation Head data from wells of the Coastal Region (Khulna)

| **Well ID** | **X** | **Y** | **Logger Z** | **Logger Id** | **Concentration** | **Concentration observation date** |
|---|---|---|---|---|---|---|
| OW1 | 762436.4399 | 2484868.188 | 108 | A | 0.13 | 01/01/2000 |
| OW1 | 762436.4399 | 2484868.188 | 108 | A | 0.51 | 06/04/2001 |
| OW1 | 762436.4399 | 2484868.188 | 108 | A | 0.754 | 05/06/2002 |
| OW1 | 762436.4399 | 2484868.188 | 108 | A | 0.98 | 07/08/2003 |
| OW1 | 762436.4399 | 2484868.188 | 108 | A | 0.175 | 04/02/2004 |
| OW1 | 762436.4399 | 2484868.188 | 108 | A | 1.128 | 06/08/2005 |
| OW2 | 748692.9552 | 2442541.041 | 108 | A | 1.34 | 09/12/2006 |
| OW2 | 748692.9552 | 2442541.041 | 108 | A | 2.68 | 06/07/2007 |
| OW2 | 748692.9552 | 2442541.041 | 108 | A | 3.5 | 08/04/2008 |
| OW2 | 748692.9552 | 2442541.041 | 108 | A | 0.185 | 06/09/2009 |
| OW2 | 748692.9552 | 2442541.041 | 108 | A | 2.12 | 03/05/2010 |
| OW3 | 736781.8308 | 2478914.145 | 108 | A | 3.685 | 04/02/2011 |
| OW3 | 736781.8308 | 2478914.145 | 108 | A | 5.473 | 03/01/2012 |
| OW3 | 736781.8308 | 2478914.145 | 108 | A | 5.598 | 03/12/2013 |

Source: Bangladesh Water Development Board (BWDB)

The pumping well boundary condition is used to simulate wells that withdraw water at a constant rate during a stress period, where the rate is independent of both the cell area and head in the cell.

Table 3.4 Pumping well observation data of the Coastal Region (Khulna)

| Well Id | X | Y | Elevation | Well bottom | Screen Id | Screen top Z | Screen bottom Z | Pumping start date | Pumping end date | Pumping rate ($m^3/d$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Supply Well 1 | 771973.1074 | 2528218.473 | 60.97 | 0 | 1 | 57 | 48 | 01/01/2003 | 01/03/2003 | 500 |
| Supply Well 2 | 771970.1465 | 2528211.771 | 93.33 | 0 | 1 | 87 | 77 | 01/06/2005 | 01/07/2005 | 1000 |

Source: Bangladesh Water Development Board (BWDB)

### 3.4.2 Model conceptualization

The conceptual model of the system was arrived at from the detailed studies of geology, borehole lithology and water level fluctuations in wells. Groundwater of the study area was found at depth of 35 to 100 m. Hence, the upper part of the aquifer sediment is composed of gray very fine sand and the lower part is dominated by gray fine sand, in places inter bedded with silty clay lenses.

### 3.4.3 Wells

In the well drop-down menu choose to graphically add, delete or edit pumping well, head observation wells, concentration observation wells. Visual MODFLOW allows inputting field observations for head, concentration and relating this observation to model output values (Figure 3-3).

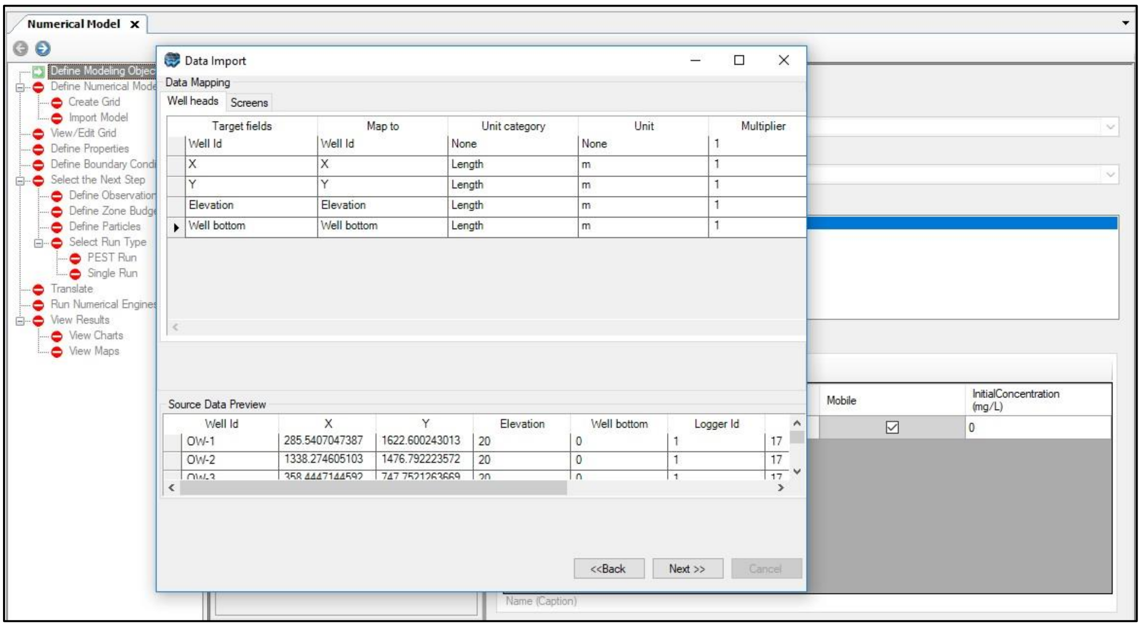



Figure 3-3: Input field observations for head in MODFLOW

### 3.4.4 Pumping wells

Well inventory is made on entire stretch of study area and their pumping rate. There are five observation wells is carried out of study and calculated start time, end time and rate. The pumping wells are located in the grid and the pumping rate is entered (Table 3-4). Positive rates are used for injection. Negative rates are used for pumping. In the study area there is no injection wells. However, ground water recharge structures are construed by BWDB to capture run off during rain. These structures are taken into consideration in the model input. MODFLOW considers a well in a cell to be located at the center of a cell. MODFLOW considers a well be screened across the entire layer it is located in, regardless of the screening interval assigned.

The first pumping rate in the pumping schedule is used as the pumping rate for steady-state simulations. The pumping rate is specified continuously for all stress periods. If a well cell goes dry during a simulation, the pumping rate of the well at that location will automatically be reduced.

### 3.4.5 Head observation wells

The Visual MODFLOW package saves the calculated heads at the locations of specified observation wells for every time step in a *.HVT (head vs. time) file. This allows to compare simulated heads with observed heads, produce calibration statistics, and produce hydrographs at observation wells without saving the entire MODFLOW solution at every time step. Observation well information is required for the calibration. Model saves hydraulic head and drawdown at every time step. BWDB monitors groundwater level in eleven shallows open wells and two bore wells spread in the Khulna district half yearly basis. Out of these five wells are falling within the study area. The location of these five wells (OW1–OW5) can be seen in the study area (Figure 3-2). A general observation of pumping data and water level data at monitoring wells, suggest that water tends to rise during the June–December to reach the highest peak and start declining from February onwards to end of August to September in each year. The rise and fall depend upon the amount, duration and intensity of rainfall, thickness of soil layer, specific yield of the formation and general slope of the aquifer bottom towards the drainage channel. BWDB monitoring wells are located in the grid using head observation wells menu and the water levels from year 2013 are entered. However these well data are used for over all analysis.

## 3.5 HYDRAULIC CONDUCTIVITY

In Visual MODFLOW hydraulic conductivity was the hydraulic conductivity along model rows. It was multiplied by an anisotropic factor that helped in obtaining the hydraulic conductivity along model columns. For flow simulations involving more than one layer, MODFLOW required the input of vertical transmission or leakage term, known as vertical leakance between two model layers. The software took the vertical hydraulic conductivities and thickness of layers to calculate the vertical leakance.

Based on the data from BWDB, hydraulic conductivity of first layer was assigned at 3 m/day and for the third layer, which is impervious clay; hydraulic conductivity of 1 m/day was assigned. Hydraulic conductivity for the second layer was estimated to vary between 13 and 18 m/day. The hydraulic conductivity values of the zones were increased to get a match between observed and calculated heads. Simulated hydraulic conductivity values vary between 11 to 29 m/day.

## 3.6 GROUNDWATER DRAFT THROUGH PUMPING

A borewells census from the BWDB was used for the existing wells data. Three types of wells were categorized on the basis of their yield. The local tube wells, having a discharge rate of 3 L/min. Private electric motor and diesel engine pump bore wells have discharge rates of 250 L/min and 1500 L/min, respectively. The duration of pumping mainly depends on electric power supply, tube well maintenance and season of the year. Simulated pumping rates of 500 $m^3$/day and 1000 $m^3$/day were used in the pumping well package.

# Chapter 4

# MODEL CONCEPTUALIZATION AND DEVELOPMENT

## 4.1 GROUNDWATER MODEL

Groundwater models are developed to simulate water movement and salt water transport in the land and river through the porous medium of aquifer for a range of existing and possible future conditions. Seawater intrusion is a natural process, where the groundwater flow depends on hydraulic gradient and fluid density variation between freshwater and seawater and the transport mechanics includes convective and dispersive processes (Bear, et al, 1999). FEFLOW which is a leading groundwater modelling environment and finite – element 3D saturated – unsaturated density – dependent code is used for this study to address the objectives of the study. The approach adopted for the groundwater model development is shown in Figure 4.1.

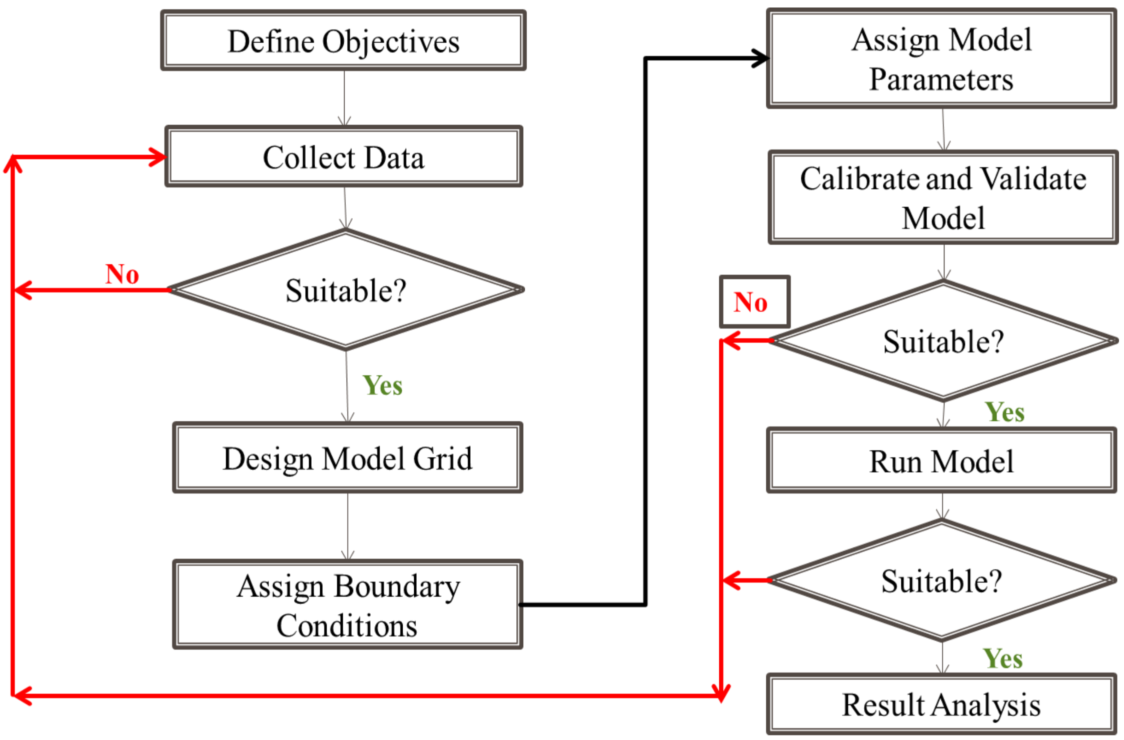



Figure 4.1: Simulation Steps of the Groundwater Modelling

### 4.1.1 Model Area

The model area lies in the district of Khulna. Upazilas are Batiaghata, Dacope, Dumuria, Dighalia, Koyra, Paikgachha, Phultala, Rupsha, Terokhada and Kotwali (Figure 4.2). The area lies approximately between $89.23^0\ 69^{/}\ 45^{//}$ E to $89.75^0\ 89^{/}\ 11^{//}$ E longitudes and $21.69^0\ 51^{/}\ 60^{//}$ N to $23.00^0\ 88^{/}\ 01^{//}$ N latitudes.

These areas are characterized by withdrawal of groundwater for agricultural and domestic purposes. Exposed coast have already met or crossed the threshold limit of the three parameters. The coastal zone is divided into three distinct coastal regions, namely, the western, central and eastern regions. The scope of this study was limited to the South-central coastal zone, situated between the eastern and western region, along the Meghna estuary. (ICZMP, 2013)

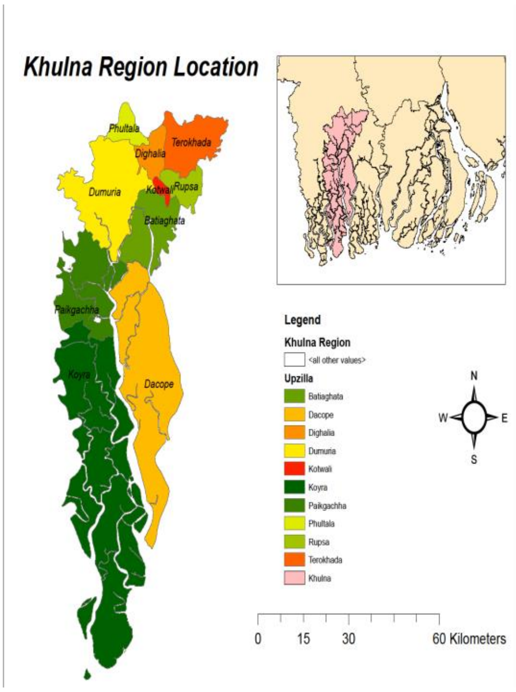



Figure 4.2: Regional Location Map of Bangladesh (Source: BWDB, 2004)

### 4.1.2 Climate

Climate of Khulna is classified as tropical. Khulna has an annual average temperature of 26.3ºC (79.3ºF) and monthly means varying between 12.4ºC (54.3ºF) in January and 34.3ºC (93.7ºF) in May. Rainfall during the monsoon season is caused by the tropical depressions that enter the country from the Bay of Bengal. (Wikipedia)

### 4.1.3 Topography

About 80% of the land in Bangladesh is flat, intersected by numerous rivers and their distributaries. The land area has a general slope from north to south (Figure 3.2). The flat deltaic lands in the coast are interlaced by an intricate river and tidal channel system which cuts the land into numerous areas. These channels carry flood water from the Ganges, the Brahmaputra, the Meghna and the other rivers and also act as drainage channels for rainfall and tide to the Bay of Bengal. Many of these separate land areas are saucer shaped basin lands with the higher elevations on natural banks adjacent to the river. During over bank flow heavy deposition of sediment occurs in the vicinity of the bank. This pattern is altered in cases where the rivers have recently changed the course and cut through the center of the 'saucer'. The land masses are generally at elevation slightly above sea level but are subject to inundation at the higher portion of the tidal cycle. Ground level varies from below sea level to 6 m or more above sea level. However more usual maximum level seldom exceeds 3 m.

In Khulna district, the land is exceptionally flat and includes numerous low-lying areas called "Beels". The area in this district is separated from the Bay of Bengal by mangrove swamp forests known as "The Sundarbans" which form a protective belt from 15km to 25 km wide along the southern part of the district. (Climate Change Trust Fund, MoEF)

## 4.2 MODEL SETUP FOR PROJECT AREA

Model setup includes identification of the model area domain (area to be modeled), river line that would be included in the model, identification of pumping stations, identification of geological layers and their hydraulic properties, identification of boundary conditions, land use and preparation various hydro-meteorological input data, identification of head observation stations and concentration observation stations.

### 4.2.1 Geological Information of the Study Area

Geological study of the selected area has been defined by three hydro-stratigraphic layers. Elevations of these layers are used in the model to define the geological formations. To define the geology of the upper aquifer data is taken from the bore log data collected for the study. Using the data collected from BWDB, the geological layer for the model has been defined. In the study area the elevations of the layer are defined top and bottom of the model layers. In Visual MODFLOW Flex, for the study area we used varying layer elevations defined from Surface data objects. Surfaces data objects was imported from Surfer .GRD. In this study, we import 4 surfaces (from Surfer .GRD files), then use these to define the layer elevations.

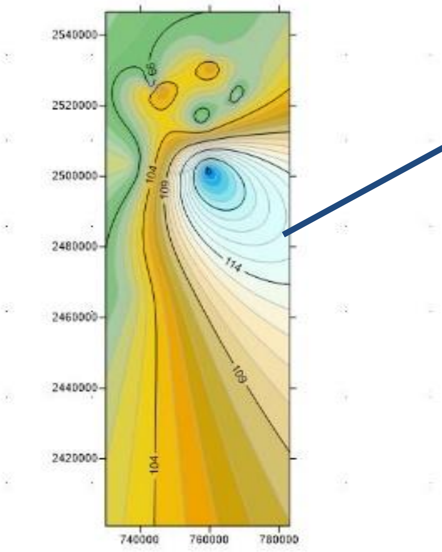



Figure 4.4 Ground Surface Top

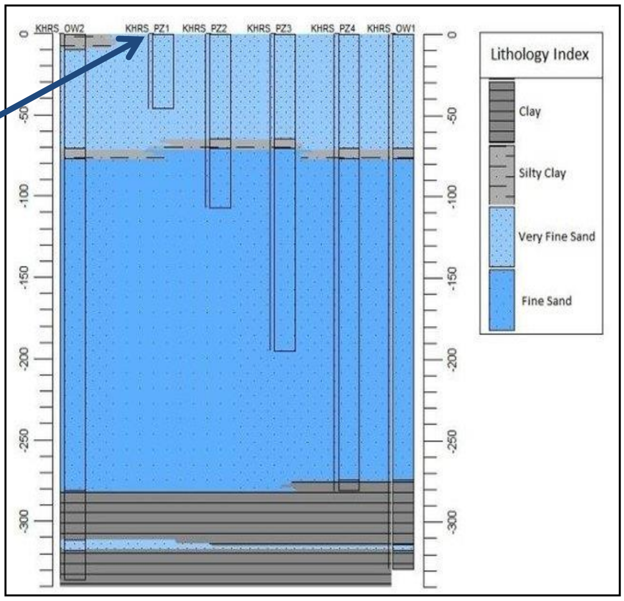



Figure 4.3: Cross Section of Nested Wells at Rupsha, Khulna

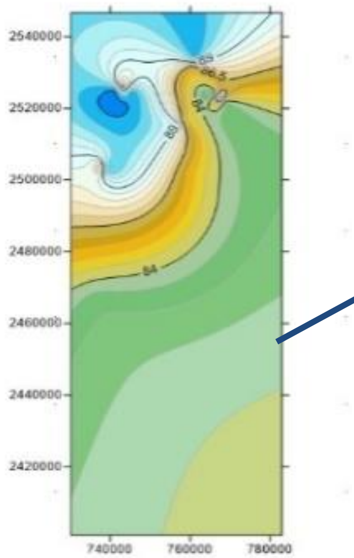



Figure 4.5 Layer 2 Top

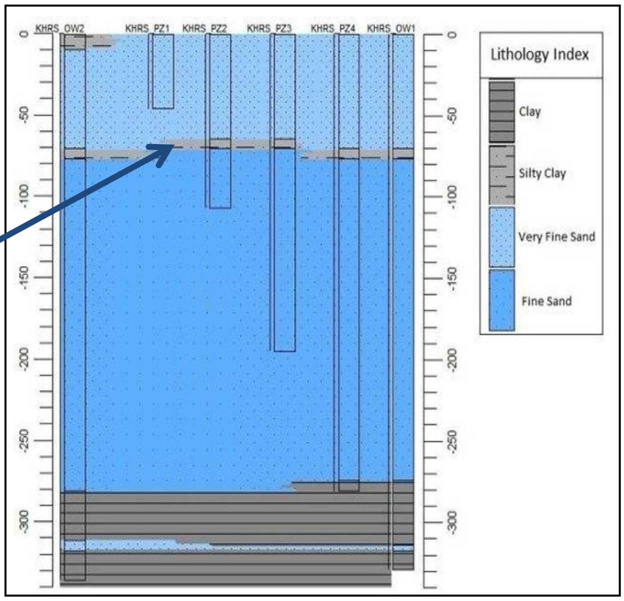
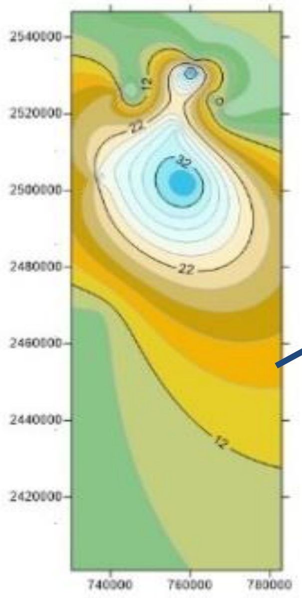



Figure 4.3: Cross Section of Nested Wells

at Rupsha, Khulna



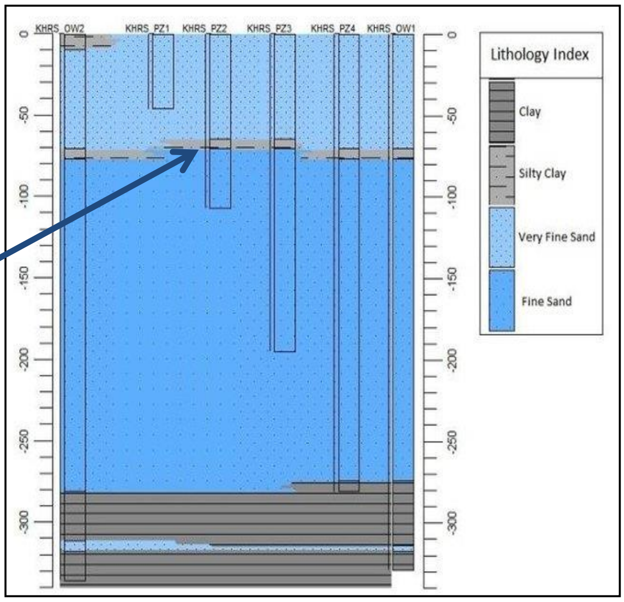
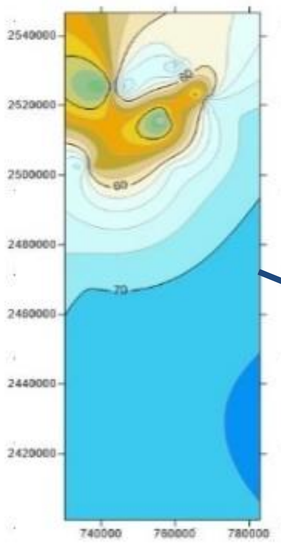




Figure 4.6 Layer 3 Top

Figure 4.3: Cross Section of Nested Wells at Rupsha, Khulna



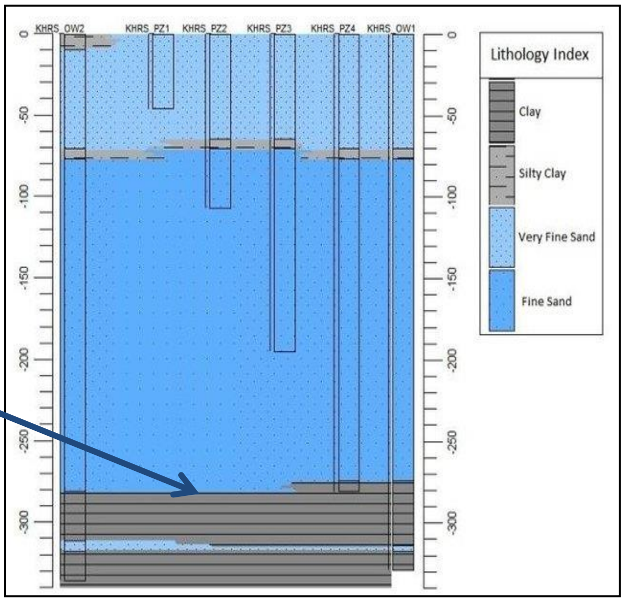




Figure 4.7: Layer 3 Bottom

Figure 4.3: Cross Section of Nested Wells at Rupsha, Khulna

### 4.2.2 Simulation Specification

The Start Date of the model corresponds to the beginning of the simulation time period. It is taken from January 2000 to 2015 as field measurements from BWDB (Observed heads and Pumping schedules) is defined with absolute date measurements, which is within the simulation time period. The time step control and computational control parameters for overland flow (OL), unsaturated zone (UZ) and Saturated Zone (SZ) have been used for entire simulation period.

### 4.2.3 Model Domain and Grid Size

The study area has been discretized into 40 square grids as shown in the horizontal plan of the Figure . The finite difference method involves fitting the numerical model to one or more finite difference grids. Once converted, the resulting numerical model can be viewed/edited and then simulated in the VMOD Flex environment. The finite element method involves fitting the numerical model to a finite element mesh. Once translated, a FEFLOW ASCII .FEM file is created, which can then be opened and simulated using FEFLOW. The model grid was refined around the water supply wells and area of the aquifer. Each grid is a numerical presentation of soil/aquifer condition of the study area when assigned with properties. The values on the x-y axes represented maximum and minimum value of the longitude and latitude of the selected study area. The co-ordinate system was used UTM45N. The reason for refining the grid is to get more detailed simulation results in areas of interest.

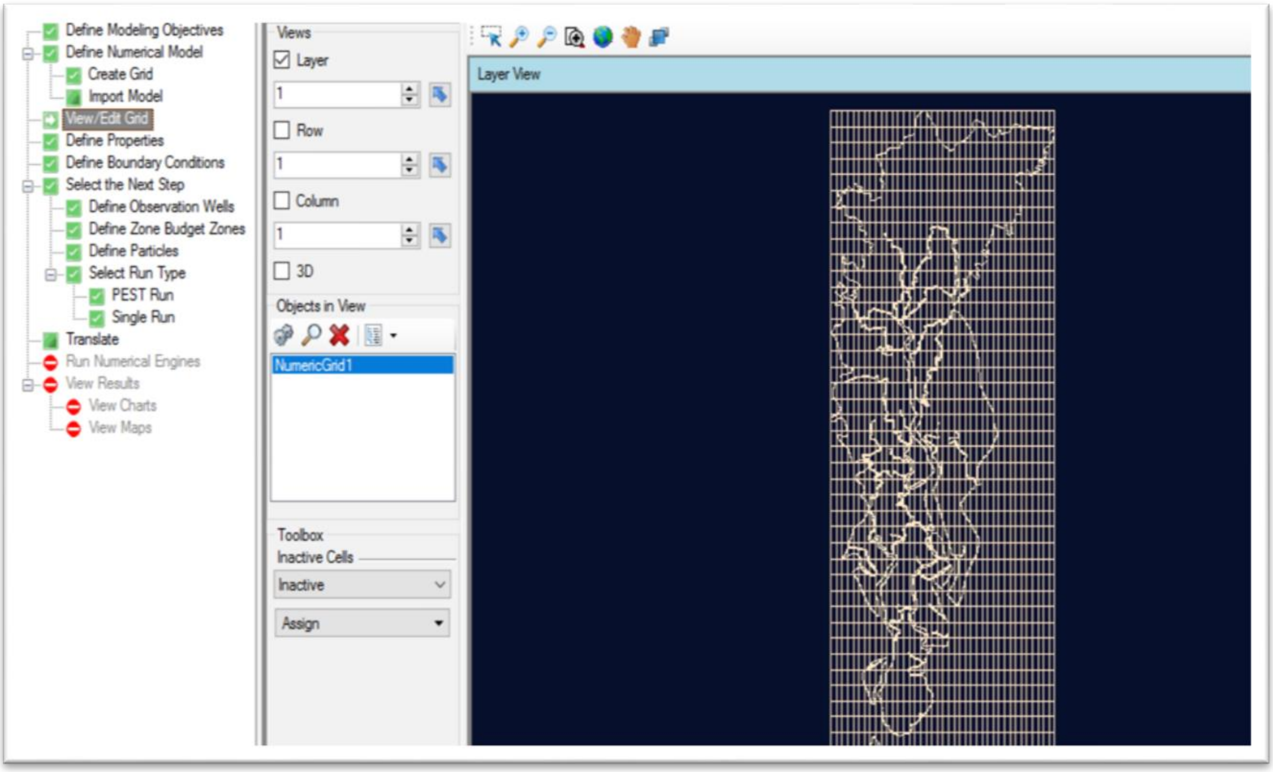



Figure 4-8: Groundwater Model Domain in 40m x 40m Grid Cells

## 4.3 MODEL PARAMETERS FOR FLOW MODELS IN VMOD FLEX

A flow model requires Conductivity, Storage, and Initial Heads property values for the flow simulation. For visual MODFLOW the flow and transport parameter values are assigned to every grid cell in the model domain which ensures the model has the minimum data required to run the simulation. For the flow and transport model properties remain uniform throughout the entire model domain.

Heterogeneous model property values are supported by Visual MODFLOW using either Constant Value Property Zones, or Distributed Value Property Zones. These two different approaches are described below.

### 4.3.1 Flow Properties

This flow model has Conductivity, Storage, and Initial Heads property values for each active grid cell for running a flow simulation. For this model Constant Value Property Zone approach was used which is the most simple and straight forward, and can be used for all model properties supported by Visual MODFLOW. Different model properties are accommodated by grouping grid cells sharing the same property values into "property zones". Each property zone will (normally) contain a unique set of property values, and is represented by a different grid cell color. For this model, an aquifer were considered where a pumping test data and slug test data indicating a range of horizontal conductivity values from $1x10^{-4}$ cm/s to $5x10^{-4}$ cm/s at different locations within the aquifer. The model would assign a uniform Kx and Ky value of $2.5x10^{-4}$ cm/s to the entire aquifer.

### 4.3.2 Constant Value Property Zones

The Constant Value Property Zones approach is the most simple and straight forward, and can be used for all model properties supported by Visual MODFLOW. Different model properties are accommodated by grouping grid cells sharing the same property values into "property zones". Each property zone will (normally) contain a unique set of property values, and is represented by a different grid cell color.

The Constant Value Property Zones approach requires the development of a Numerical model, whereby each hydro stratigraphic unit of the model is assigned a uniform set of property values. For example, consider an aquifer where there is pumping test data and slug test data indicating a range of horizontal conductivity values from $1x10^{-4}$ cm/s to $5x10^{-4}$ cm/s at different locations within the aquifer. The numerical approach would assign a uniform Kx and Ky value of $2.5\times10^{-4}$ cm/s to the entire aquifer. This value would be adjusted up or down for calibration purposes within the range of values reported. If a reasonable calibration cannot be achieved using this conceptual model, it may be necessary to sub-divide this region into several zones to accommodate local irregularities in the flow pattern.

### 4.3.3 Distributed Value Property Zones

The Distributed Value Property Zones approach is currently only available for Conductivity, Storage, Initial Heads, Initial Concentrations, and Dispersivity properties. This approach is a little more complicated because it involves linking a property zone to one or more parameter distribution arrays containing data interpolated from scattered observation points. When a property zone is linked to distribution array, the property values assigned to each grid cell within that zone are calculated by multiplying the zone parameter value with the corresponding value from the parameter distribution array. If the grid spacing from the model does not match the grid spacing from the distribution array, a bivariate interpolation scheme is used to calculate the appropriate parameter value at the center of the model grid cell using the four nearest data nodes in the parameter distribution array.

### 4.3.4 Conductivity

Kx - Hydraulic conductivity in the direction of the model X-axis

Ky - Hydraulic conductivity in the direction of the model Y-axis

Kz - Hydraulic conductivity in the direction of the model Z-axis

These Conductivity parameters may be defined on a cell-by-cell basis using constant property values and/or distributed property values. When importing or assigning the Conductivity property zones, VMOD Flex will require valid data for each of the above parameters.

### 4.3.5 Anisotropy

The reason Visual MODFLOW prompts for both Kx and Ky is because there are two options for defining the horizontal anisotropy of the Conductivity property zones:

1. Anisotropy by layer
2. Anisotropy as specified

If the Anisotropy by layer option is used, the Kx value will determine the conductivity in the X direction, and the specified anisotropy ratio (Ky/Kx) for each layer will be used to calculate the Ky value for each grid cell.

If the Anisotropy as specified option is used, the model will use the Kx and Ky values defined for each property zone.

### 4.3.6 Storage

Ss - specific storage

Sy - specific yield

Eff. Por - effective porosity

Tot. Por - total porosity

Specific Storage (Ss) is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head due to aquifer compaction and water expansion. Using Specific Storage, Visual MODFLOW determines the primary storage coefficient (sf1) for MODFLOW. The primary storage coefficient is calculated by Visual MODFLOW to be equal to the specific storage multiplied by the layer thickness (Specific Storage x thickness = Storage coefficient).

Specific Yield (Sy) is known as the storage term for an unconfined aquifer. It is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area per unit decline in the water table. For sand and gravel aquifers, specific yield is generally equal to the porosity. MODFLOW uses Ss or Sy depending on the layer type assigned by the user. For an unconfined layer, MODFLOW uses Sy to determine storage volumes. For a confined layer, Ss is used. For a variable layer, MODFLOW will check the head value of the cell to determine if it is confined or not.

Effective Porosity (Eff. Por) is the pore space through which flow actually occurs, and is used by MODPATH to determine the average linear groundwater velocities for use in time dependent capture zones and time markers along path lines. This term is not used for MODFLOW simulations.

Total Porosity (Tot. Por) is the percentage of the rock or soil that is void of material, and is used by MT3D to determine the chemical reaction coefficients, and for calculating the average linear groundwater flow velocity in the particle tracking solution schemes. A different porosity is used for MT3D than for MODPATH because MT3D accounts for additional transport and reactive processes, such as dispersion. The total porosity term is not used for These Storage parameters may be defined on a cell-by-cell basis using constant property values and/or distributed property values.

### 4.3.7 Initial Heads

In order to start solving the flow simulation, MODFLOW requires an initial “guess” for the head values in the model. A good initial guess for the starting heads of the simulation can reduce the required run time significantly. The Initial Head values are also used to calculate the drawdown values, as measured by the difference between the starting head and the calculated head.

### 4.3.8 Boundary Conditions

Steady-State vs. Transient Flow Boundary Conditions For transient simulations, MODFLOW requires the time element of the boundary conditions to be defined using Stress Period “counters” as opposed to using “real” times. As a result, each time interval for a transient model must be determined in terms of Stress Periods before any boundary condition data is defined. Unfortunately, accommodating this format is quite tedious because the data collected for rainfall and groundwater recharge doesn’t always follow the same time schedules as data collected for other boundary conditions like well pumping rates and surface water levels. This approach also makes it difficult to utilize raw field data collected and recorded in terms of real times.

In Visual MODFLOW, a Time Period is similar to a Stress Period, but with two important exceptions:

A Time Period is defined using real times and real time units, and Each boundary condition grid cell may contain different Time Periods The advantage of this approach is the ability to clearly see the magnitude of time for each Time Period (as opposed to interpreting data such as “from Stress Period 1 to Stress Period 2”), and it facilitates more convenient methods for importing raw data from different boundary condition types.

Each group of boundary condition grid cells requires a minimum of one Time Period of data containing a Start Time, a Stop Time, and a complete set of data for the selected boundary condition type (the required data for each boundary condition type are described later in this section). For steady-state simulations, Visual MODFLOW requires data for only a single Time Period, while for transient simulations; Visual MODFLOW can accommodate an unlimited number of Time Periods.

For steady-state simulations the Stop Time value is irrelevant because the term “steady state” indicates that the model results are not changing with time. Therefore, a Stop Time value of 1 time unit is commonly used. However, if the model is going to be used to evaluate a transient simulation in the future, it is probably a better idea to give it a more realistic value corresponding to the potential time frame of interest.

If a steady-state simulation is run using a model containing transient boundary condition data, only the data from the first Time Period of each grid cell will be used for the steady-state conditions.

## 4.4 MODFLOW SETTINGS

Specify the property package (LPF or BCF)

### 4.4.1 Steady-State or Transient

If the Steady-State Flow option is selected, VMOD Flex will prepare the data set for a steady state flow simulation, and will automatically use the data from the first time period (only) of each boundary condition and pumping well defined in VMOD Flex to run the model to achieve flow equilibrium (i.e. a time-independent solution since all inputs are constant).

If the Transient Flow option is selected, VMOD Flex will prepare the data set for a transient flow simulation. During this process, VMOD Flex will automatically merge all of the different time period data defined for each pumping well and boundary condition into the stress period format required by the different versions of MODFLOW. This creates a time-dependent flow solution, as the model is being run with different inputs at different times

Specify the steady state simulation time.

**The Time Steps** option is only available when running a transient model (i.e. when Transient Flow run type is selected). For transient flow simulations, VMOD Flex will automatically merge all of the different time periods defined for all of the different pumping wells and boundary conditions into the uniform stress period format required by MODFLOW. A stress period is defined as a time period in which all the stresses (boundary conditions, pumping rates, etc.) on the system are constant. Unfortunately, the data collected for each modeling site is rarely synchronized in terms of stress periods, so VMOD Flex merges the time schedules for all pumping wells and boundary conditions to determine the length of each stress period for a transient simulation. As a result, the user cannot directly modify the number of stress periods or the length of each stress period.

The Time step options window (as shown in the following figure) is used to define the number of Time steps in each stress period and the time step Multiplier is used to increment each time step size.

The Period # column indicates the stress period number while the Start and Stop columns indicate the start time and stop time, respectively, for each stress period.
Each stress period is divided into a user-defined number of Time steps whereby the model will calculate the head solution at each time step. The default value for Time steps is 10.

The time step Multiplier is the factor used to increment the time step size within each stress period (i.e. it is the ratio of the value of each time step to that of the preceding time step). The default value is 1.2. A time step Multiplier value greater than 1 will produce smaller time steps at the beginning of a stress period resulting in a better representation of the changes of the transient flow field. Thus increasing the number of time steps in a simulation may result in smoother head or drawdown versus time curves.
The Steady-state column indicates if the stress period is transient or steady-state. This option is available if MODFLOW-2000, MODFLOW-2005 and MODFLOW-SURFACT is selected as the numeric engine for the flow model. These engines allow individual stress periods in a single simulation to be either transient or steady state

instead of requiring the entire simulation to be either steady state or transient. Steady-state and transient stress periods can occur in any order. Commonly the first stress period may be run as steady state, to produce a solution that is used as the initial condition for subsequent transient stress periods

### 4.4.2 Solvers

VMOD Flex with a choice of different solvers to use in solving the numerical equations for the flow simulation:

Preconditioned Conjugate-Gradient Package (PCG2)

Strongly Implicit Procedure Package (SIP)

Slice-Successive Over relaxation Package (SOR)

WHS Solver for VMOD Flex (WHS)

Geometric Multigrid Solver (GMG)

Algebraic Multigrid Methods for Systems (SAMG)

And Algebraic Multigrid Solver (AMG)

These solvers and their individual settings can be accessed by selecting MODFLOW/Solver from the Run section of VMOD Flex. A Solver Setting window will appear, with a list for choosing the desired Solver and a listing of the settings for the selected Solver.

#### 4.4.2.1 PCG Solver

PCG2 uses the preconditioned conjugate-gradient method to solve the simultaneous equations produced by the model. Linear and non-linear flow conditions may be simulated. PCG2 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 PCG2 Package is described in Water-Resources Investigations Report 90-4048 of the USGS, (by Mary Hill, 1997), which is included in the MODFLOW reference manual on your VMOD Flex media, in the Manual folder.

The PCG2 solver works on a two-tier approach to a solution at one time step, inner and the outer iterations. Outer iterations are used to vary the preconditioned parameter matrix in an approach toward the solution. An outer iteration is where the hydrogeologic parameters of the flow system are updated (i.e., transmissivity, saturated thickness, storativity) in the preconditioned set of matrices. The inner iterations continue until the user-defined maximum number of inner iterations are executed, or the final convergence criteria are met. The Outer iterations continue until the final convergence criteria are met on the first inner iteration after an update.

The following is a description of the solver parameters for the PCG method:

Maximum Number of Outer Iterations: [Default = 25]

This parameter provides an upper limit on the number of outer iterations to be performed. The maximum number of iterations will only be used if a convergent solution is not reached beforehand. Twenty five iterations should be adequate for most problems. However, if the maximum number of outer iterations is reached and an appropriate mass balance error is not achieved, this value should be increased.

Maximum Number of Inner Iterations: [Default = 10]

This parameter provides an upper limit on the number of inner iterations to be performed. This number of iterations will only be used if a convergent solution for the current set of matrices in the "outer" iteration is not reached beforehand. Ten inner iterations should be adequate for most problems. More than ten iterations will not usually improve the solution, as the solution is updated again when it returns to the outer iterations.

Head Change Criterion for Convergence: [Default = 0.01]

After each outer iteration has completed, the solver checks for the maximum change in the solution at every cell. If the maximum change in the solution is below a set convergence tolerance (set here in the working units feet or meters) then the solution has converged and the solver stops, otherwise a new outer iteration starts.

A solution accurate to 0.01 [ft. or m] will normally be sufficient for most problems, unless the maximum head difference across the modeled domain is less than one foot or meter. If an appropriate mass balance is not achieved and the number of inner and outer iterations are within the maximums declared above, this value can be decreased by an order of magnitude, e.g. 0.001.

Residual Criterion for Convergence: [Default = 0.01] While the head change criterion is used to judge the overall solver convergence, the residual criterion is used to judge the convergence of the inner iterations of the solver. If the maximum absolute value of the residual at all nodes is less than the tolerance specified here (units of length3/time) then the solver will proceed to the next outer iteration.

If you notice that only a few inner iterations are being performed for all outer iterations, and an appropriate mass balance is not achieved, the Residual Criterion value can be decreased by one or more orders of magnitude. (Visual Modflow Flex User Manual, 2012)

#### 4.4.2.2 GMG Solver

The GMG solver, based on the preconditioned conjugate gradient algorithm, has been developed by the USGS for solving finite-difference based flow models. As opposed to AMG, the preconditioning in GMG is based on a solver method known as geometric multigrid. The GMG solver has been demonstrated to greatly reduce model run times relative to other solvers using a comparable amount of memory. Detailed information about the GMG solver, including comparisons with the AMG solver, can be found in the GMG Linear Equation Solver Package PDF documentation (located in the Manual folder of your VMOD Flex installation media).

The solver parameters for the Geometric Multigrid Solver are described below using excerpts from the GMG Linear Equation Solver Package PDF documentation (located in the Manual folder of your VMOD Flex installation media):

Max. Outer iterations (MXITER): The maximum number of outer iterations. For linear problems, MXITER can be set to 1. For nonlinear problems, MXITER needs to be larger, but rarely more than 100. The maximum number of iterations will only be used if a convergent solution is not reached beforehand.

Max. Inner iterations (IITER): The maximum number of PCG iterations for each linear solution. A value of 100 is typically sufficient. It is frequently useful to specify a smaller number for nonlinear problems so as to prevent an excessive number of inner iterations. This number of iterations will only be used if a convergent solution for the current set of matrices in the "outer" iteration is not reached beforehand.

Adaptive Damping Control (IADAMP): IADAMP is a flag that controls adaptive damping. If IADAMP = 0, then the value assigned to DAMP is used as a constant damping parameter. If IADAMP = 0, then the value of DAMP is used for the first nonlinear iteration. The damping parameter is adaptively varied on the basis of the head change, using Cooley's method for subsequent iterations.

Head change criterion (HCLOSE): After every outer iteration is completed, the solver checks for the maximum change in the solution at every cell. If the maximum change in the solution is below a set convergence tolerance (set here in the working units of feet or metres) then the solution has converged and the solver stops, otherwise a new outer iteration is started. A solution accurate to 0.01 [ft. or m] will normally be sufficient for most problems unless the maximum head change throughout the modeled domain is less than 1 foot or metre. If an appropriate mass balance is not achieved and the number of inner and outer iterations is within the maximums, this value can be decreased by an order of magnitude.

Residual criterion (RCLOSE): RCLOSE is the residual convergence criterion for the inner iteration. The PCG algorithm computes the l2-norm of the residual and compares it against RCLOSE Typically, RCLOSE is set to the same value as HCLOSE (see below). If RCLOSE is set too high, then additional outer iterations may be required due to the linear equation not being solved with sufficient accuracy. On the other hand, a too restrictive setting for RCLOSE for nonlinear problems may force an unnecessarily accurate linear solution. This may be alleviated with the IITER parameter or with damping.

Relaxation parameter (RELAX): The RELAX parameter can be used to improve the spectral condition number of the ILU preconditioned system. The value of RELAX should be approximately one. However, the relaxation parameter can cause the factorization to break down. If this happens, then the GMG solver will report an assembly error and a value smaller than one for RELAX should be tried. This item is read only if ISC = 4.

Upper bound of estimate (NPBOL): IOUTGMG is a flag that controls the output of the GMG solver. The possible values of IOUTGMG and their meanings are as follows: If IOUTGMG = 0, then only the solver inputs are printed. If IOUTGMG = 1, then for each linear solve, the number of PCG iterations, the value of the damping parameter, the l2norm of the residual, and the max-norm of the head change and its location (column, row, layer) are printed. At the end of a time/stress period, the total number of GMG calls, PCG iterations, and a running total of PCG iterations for all time/stress periods are printed. If IOUTGMG = 2, then the convergence history of the PCG iteration is printed, showing the l2-norm of the residual and the convergence factor for each iteration. IOUTGMG = 3 is the same as IOUTGMG = 1 except output is sent to the terminal instead of the MF2K LIST output file. IOUTGMG = 4 is the same as IOUTGMG = 2 except output is sent to the terminal instead of the MF2K LIST output file.

Multigrid Preconditioner (ISM): ISM is a flag that controls the type of smoother used in the multigrid preconditioner. The possible values for ISM and their meanings are as follows: If ISM = 0, then ILU(0) smoothing is implemented in the multigrid preconditioner. This smoothing requires an additional vector on each multigrid level to store the pivots in the ILU factorization. If ISM = 1, then Symmetric Gauss Seidel (SGS) smoothing is implemented in the multigrid preconditioner. No additional storage is required for this smoother; users may want to use this option if available memory is exceeded or nearly exceeded when using ISM = 0. Using SGS smoothing is not as robust as ILU smoothing; additional iterations are likely to be required in reducing the residuals. In extreme cases, the solver may fail to converge as the residuals cannot be reduced sufficiently.

Semi coarsening Control in the Multigrid Preconditioner (ISC): A flag that controls semi coarsening in the multigrid preconditioner. The possible values of ISC and their meanings are given as follows: If ISC = 0, then the rows, columns and layers are all coarsened. If ISC = 1, then the rows and columns are coarsened, but the layers are not. If ISC = 2, then the columns and layers are coarsened, but the rows are not. If ISC = 3, then the rows and layers are coarsened, but the columns are not. If ISC = 4, then there is no coarsening. Typically, the value of ISC should be 0 or 1. In the case that there are large vertical variations in the hydraulic conductivities, then a value of 1 should be used. If no coarsening is implemented (ISC = 4), then the GMG solver is comparable to the PCG2 ILU(0) solver described in Hill (1990) and uses the least amount of memory.

Damping factor (DAMP): This factor allows the user to reduce (dampen) the head change calculated during each successive outer iteration. For most "well posed" and physically realistic groundwater flow problems, the dampening factor of one will be appropriate. This parameter can be used to make a non-convergent (oscillating or divergent) solution process more stable such that a solution will be achieved. This is done by decreasing the damping factor to a value between 0 and 1 (only rarely < 0.6). This parameter is similar to "acceleration parameters" used in other solvers. (Visual Modflow Flex User Manual, 2012)

#### 4.4.2.3 WHS Solver

The WHS Solver uses a Bi-Conjugate Gradient Stabilized (Bi-CGSTAB) acceleration routine implemented with Stone incomplete decomposition for preconditioning of the groundwater flow partial differential equations. This solver, as all iterative solvers, approaches the solution of a large set of partial differential equations iteratively through an approximate solution. Because the matrix equation for groundwater flow is initially "ill-conditioned", effective preconditioning of these matrices is necessary for an efficient solution.

The WHS solver works on a two-tier approach to a solution at one time step. Outer iterations are used to vary the factorized parameter matrix in an approach toward the solution. An outer iteration is where the hydrogeologic parameters of the flow system are updated (i.e., transmissivity, saturated thickness, storativity) in the factorized set of matrices. Different levels of factorization allow these matrices to be initialized differently to increase the efficiency of solution and model stability. Inner iterations are used to iteratively solve the matrices created in the outer iterations.

The solver parameters for the WHS method are described below:

Maximum Number of Outer (non-linear) Iterations: [Default = 50]

This parameter provides an upper limit on the number of outer iterations to be performed. The maximum number of iterations will only be used if a convergent solution is not reached beforehand. Fifty iterations should be adequate for most problems. However, if the maximum number of outer iterations is reached and an appropriate mass balance error is not achieved, this value should be increased.

Maximum Number of Inner Iterations: [Default = 25]

This parameter provides an upper limit on the number of inner iterations to be performed. This number of iterations will only be used if a convergent solution for the current set of matrices in the "outer" iteration is not reached beforehand. Twenty-five inner iterations should be adequate for most problems. However, if the maximum number of inner iterations was used for all outer iterations and an appropriate mass balance error was not achieved, this value can be increased.

Head Change Criterion for Convergence: [Default = 0.01]

After every outer iteration is completed, the solver checks for the maximum change in the solution at every cell. If the maximum change in the solution is below a set convergence tolerance (set here in the working units of feet or metres) then the solution has converged and the solver stops, otherwise a new outer iteration is started. A solution accurate to 0.01 [ft. or m] will normally be sufficient for most problems unless the maximum head change throughout the modeled domain is less than 1 foot or metre. If an appropriate mass balance is not achieved and the number of inner and outer iterations is within the maximums, this value can be decreased by an order of magnitude.

Residual Criterion for Convergence: [Default = 0.01]

While the head change criterion is used to judge the overall solver convergence, the residual criterion is used to judge the convergence of the inner iterations of the solver. If the change in successive inner iterations is less than the tolerance specified here (in working units of feet or metres), then the solver will proceed with the next outer iteration. The residual criterion for convergence of 0.001 should be appropriate for most problems. However, if you notice that only a few inner iterations are being performed for every outer iteration and an appropriate mass balance is not achieved, this parameter value can be decreased by one or more orders of magnitude.

Damping Factor for the Outer Iterations: [Default = 1]

This factor allows the user to reduce (dampen) the head change calculated during each successive outer iteration. For most "well posed" and physically realistic groundwater flow problems, the dampening factor of one will be appropriate. This parameter can be used to make a non-convergent (oscillating or divergent) solution process more stable such that a solution will be achieved. This is done by decreasing the damping factor to a value between 0 and 1 (only rarely < 0.6). This parameter is similar to "acceleration parameters" used in other solvers.

Relative Residual Criterion: [Default = 0]

This parameter provides another method of checking for convergence of the inner iteration. This method compares the residual from the most recent inner iteration to the residual from the initial inner iteration. Once the most recent inner iteration residual is below the initial inner iteration residual times the relative residual criterion, the current outer iteration is completed and a new outer iteration will be started.

Factorization Level: [Default = 0] There are two “levels” of factorization available with the WHS solver, 0 and 1. Level 0 requires more outer iterations but less memory. Level 1 requires fewer outer iterations but more memory. While convergence of the solver requires fewer iterations with a factorization level of 1, the memory required to run the solver increases with this factorization level. Also, the work per iteration increases with the level 1 factorization such that the total solution time may not be less than the solution time using level 0 factorization. (Visual Modflow Flex User Manual, 2012)

#### 4.4.2.4 SIP Solver

The Strongly Implicit Procedure, also known as SIP, is a method for solving a large system of simultaneous linear equations by iterations. The advantage of the SIP solver is that it is very stable and generally converges to a solution, but often very slowly. It is not as fast as the PCG method, but it requires less memory to compute the final solution. Because each equation involves up to seven unknown values of head, and because the set of unknown values changes from one equation to the next throughout the grid, the equations for the entire grid must be solved simultaneously at each time step. This package is described in Chapter 12 of the MODFLOW manual included with your VMOD Flex media, in the Manual folder.

The solver parameters for the SIP method are described below:

Maximum Number of Iterations: [Default = 200]

This is the upper limit on the number of iterations to be performed. The maximum number of iterations will only be considered if a convergent solution is not reached beforehand. Two hundred iterations should be adequate for most problems. However, if the maximum number of iterations is reached and an appropriate mass balance error is not achieved, this value should be increased.

Number of Iteration Parameters: [Default = 5]

The finite difference equations describing the groundwater flow system can be put into matrix form as [A] {h}={q}. Where [A] is the coefficient matrix, {h} is the heads array and {q} is the flux array. The number of iteration parameters indicates the number of parameters that will be used to transform the initial coefficient matrix [A] to a similar matrix that can be decomposed into two lower and upper triangular matrices [L] and [U], respectively. The default value of 5 is generally sufficient.

Acceleration Factor: [Default = 1]

The acceleration factor controls the magnitude of head change between iterations. The acceleration factor must be positive. Values larger than one will result in larger head changes between iterations; the solution may be approached faster but it may also overshoot the solution more easily. Values less than one will result in smaller head changes, requiring more iterations to reach a solution.

Head Change Criterion for Convergence: [Default = 0.01]

After each iteration is completed, the solver checks for the maximum change in the solution at every cell. If the maximum change in the solution is below a set convergence tolerance (set here in the working units of feet or metres) then the solution has converged and the solver stops, otherwise a new iteration is started. A solution accurate to 0.01 [ft. or m] will normally be sufficient for most problems unless the maximum head change throughout the modeled domain is smaller than one foot or metre. If an appropriate mass balance is not achieved and the maximum number of iterations is not reached, this value can be decreased by an order of magnitude.

Printout Interval: [Default =10]

The printout interval is the number of iterations after which the maximum head change (and residual) of the solution is written to the listing (. LST) file.

User Seed Value: [Default = 0.01]

There are two options: either the user can enter the seed, or the seed will be calculated at the start of the simulation from problem parameters. The iteration parameter ‘seed’ is used as a basis for determining the sequence of w values. The w multiplies each term on the right side of the equation; and must be cycled through a series of values in successive iterations to achieve satisfactory rates of convergence. The more strongly diagonal the coefficient matrix, the less important the choice of seed will be. (Visual Modflow Flex User Manual, 2012)

#### 4.4.2.5 SOR Solver

Slice-Successive Over-Relaxation is a method for solving large systems of linear equations iteratively. It is implemented in the SOR Package by dividing the finite difference grid into vertical slices, and grouping the node equations into discrete sets, each set corresponding to a slice. In every iteration, these sets of equations are processed in turn, resulting in a new set of estimated head values for each slice. As the equations for each slice are processed, they are first expressed in terms of the changes in computed heads between successive iterations. The set of equations corresponding to the slice is then solved directly by Gaussian elimination, treating the terms for adjacent slices as known quantities. The values of head change computed for the slice are then each multiplied by an acceleration variable, T. The results are taken as the final values of head change in that iteration for the slice. This procedure is repeated for each slice in sequence until all of the slices in the three dimensional array have been processed, thus completing a domain iteration. The entire sequence is then repeated, until the differences between the head values computed in successive iterations are less than the chosen criterion at all nodes in the mesh. The SOR Package is described in detail in Chapter 13 of the MODFLOW reference manual included with your VMOD Flex media, in the Manual folder.

The solver parameters for the SOR method are described below:

Maximum Number of Iterations: [Default = 50]

This parameter provides an upper limit on the number of iterations to be performed. The maximum number of iterations will only be used if a convergent solution is not reached beforehand. 50 iterations should be adequate for most problems. However, if the maximum number of outer iterations is reached and an appropriate mass balance error is not achieved, this value should be increased.

Acceleration Factor: [Default = 1]

The acceleration factor controls the magnitude of head changes between iterations. The acceleration factor must be positive. Values larger than one will result in larger head changes between iterations; the solution may be approached faster but it may also overshoot the solution more easily. Values less than one will result in smaller head changes, thus, requiring more iterations to reach a solution.

Head Change Criterion for Convergence: [Default = 0.01]

After each iteration is completed, the solver checks for the maximum change in the solution at every cell. If the maximum change in the solution is below a set convergence tolerance (set here in the working units of feet or metres), then the solution has converged and the solver stops, otherwise a new iteration is started. A solution accurate to 0.01 [ft. or m] will normally be sufficient for most problems unless the maximum head change throughout the model domain is less than 1 foot or metre. If an appropriate mass balance is not achieved and the number of iterations is less than the maximum, this value can be decreased by an order of magnitude.

Printout Interval: [Default =10]

The printout interval is the number of iterations after which the maximum head change (and residual) of the solution is written to the listing (. LST) file. (Visual Modflow Flex User Manual, 2012)

#### 4.4.2.6 SAMG Solver

Visual MODFLOW supports the Algebraic Multigrid Methods for Systems Solver (SAMG) Package developed by the Fraunhofer Institute for Algorithms and Scientific Computing (FhGSCAI). Please note that the SAMG solver is only available with the MODFLOW-2000, 2005 and LGR flow engine.

The Algebraic Multigrid (AMG) Package solver may be obtained from the Fraunhofer Institute for Algorithms and Scientific Computing (FhG-SCAI) for research purposes only. Although most users will not have any difficulty running Visual MODFLOW with the AMG solver, Schlumberger Water Services unfortunately cannot provide technical support for users who choose to manually add the AMG solver to their Visual MODFLOW software.

The SAMG solver package is a complete multi-level framework, designed to overcome the high memory requirements of previous AMG-based solvers, while maintaining the scalability and rapid execution times. Testing of the SAMG solver vs. the PCG2 solver using several models generated using Visual MODFLOW demonstrated solution times to be faster by a factor of between 2.4 and 11.3. The SAMG Package has some distinct advantages over other solvers available with MODFLOW for problems with large grids (more than about 40,000 cells) and/or a highly variable hydraulic-conductivity field. The advantages of multigrid methods over the other iterative solvers mentioned are (1) the effectiveness of the multigrid solver is not dependent on the initial head distribution, and (2) for many problems of interest, the rate of convergence scales approximately linearly with the size of the domain, unlike the other solvers where the rate of convergence increases nonlinearly (Demmel, 1997).

The Solver settings window contains a number of user-defined solver settings which can influence the speed and effectiveness of the AMG solver.

Max. Iterations (MXITER): [Default = 50]

MXITER is the maximum number of times that the AMG routines will be called to obtain a solution. MXITER is never less than 2, and rarely more than 50. MXITER often equals 2 when the problem is linear (all layers are confined, and no boundary conditions are nonlinear; the Evapotranspiration, Drain, and River Packages, for example, produce nonlinear boundary conditions). For nonlinear problems, MXITER generally is 50 or less; however values near 50 and sometimes even larger are needed for more severely nonlinear problems.

Max. Cycles (MXCYC): [Default = 50]

For each call to the solver, AMG cycles through one or more sequences of coarsening and refinement. The solver is limited to a maximum of MXCYC cycles per call to the solver. For most problems, convergence for each iteration is achieved in less than 50 cycles, so that generally MXCYC can be less than 50. For highly nonlinear problems, however, better performance may be achieved by limiting the solver to a small number of cycles, and increasing the maximum number of iterations (MXITER). This prevents the solver from needlessly finding very accurate solutions at early iterations of these highly nonlinear problems.

Residual Convergence Criterion (RCLOSE) for the inner iteration. Typically RCLOSE is set to the same value as HCLOSE. If RCLOSE is set too high, then additional outer iterations may be required due to the linear equation not being solved with sufficient accuracy. Likewise, a too restrictive setting for RCLOSE for nonlinear problems may force an unnecessarily accurate linear solution. This may be alleviated with the MXCYC parameter or with damping.

Note: In the new SAMG package, RCLOSE and HCLOSE replace BCLOSE

Damping Factor (DAMP): [Default = 1]

The damping factor can be used to restrict the head change from one iteration to the next, which commonly is useful in very nonlinear problems. DAMP makes the solution change slowly, thus avoiding spurious deviations prompted by nonlinear effects at intermediate solutions. Values of DAMP less than 1.0 restrict the head change (under-relaxation), while values greater than 1.0 accelerate the head change (over-relaxation). For linear problems, no damping is necessary, and DAMP should be set equal to 1.0. For non-linear problems, restricting the head change (DAMP < 1.0) may be necessary to achieve convergence, and values of DAMP between 0.5 and 1.0 are generally sufficient.

For some nonlinear problems, imposing a fixed value of DAMP for every iteration can hinder convergence. One remedy for this condition is to adjust the amount of damping depending on how the head solution progresses. The AMG Package provides two adaptive damping strategies; (1) Cooley's method with Huyakorn's modification, and (2) the relative reduced residual method. These methods are described in detail in the U.S. Geological Open-File Report 01-177. A DAMP value of -1 will utilize the first method, and a DAMP value of -2 will utilize the second method.

Max. Damping Factor (DUP): [Default = 1]

The upper limit for DAMP when an adaptive damping strategy is used.

Min. Damping Factor (DLOW): [Default = 0.2]

The lower limit for DAMP when an adaptive damping strategy is used

Head Change Convergence Criterion (HCLOSE), similar as described for previous solvers

Perform Conjugate Gradient Iterations (ICG): [Default = checked]

In some cases, AMG can perform poorly as a result of a small number of error components that are not reduced during the AMG cycling. A few iterations of a conjugate gradient solver can often reduce these error components and thus help convergence (Cleary and others, 2000). In these cases, the parameter ICG can be set to 1 to perform conjugate gradient iterations at the end of each multigrid cycle. Activating this option can decrease execution times for some problems, but it will also increase the amount of memory used by the solver.

The Print Flag (IOUTAMG) frame allows you to select between various print options.

CONTROL Parameter [Default = 2]

1 - reuse of the setup phase is not used

2 - reuse of the setup phase will be used (Recommended)

3 - reuse of the setup phase will be used, and SSC will be used

(Visual Modflow Flex User Manual, 2012)

## 4.5 RECHARGE

The Recharge zone distribution can be applied to any of the user-specified model Layers. If the recharge is assigned to the top grid layer, and some cells in the top layer become dry during the course of the simulation, or if some cells in the top layer are designated as no-flow cells, the MODFLOW program allows the recharge to be applied to the grid cells in the upper most active (wet) layer in the model. The Recharge settings are shown in the following Recharge options window and these are described below.

Recharge is only applied to the top grid layer: If any grid cells in Layer 1 are dry, or if they are designated as no-flow cells, the recharge values assigned to these grid cells will NOT be carried down to the underlying active (wet) grid cells. In this case, the inactive or dry cells act like an impermeable barrier to the recharge.

Recharge is applied to the specified layer: It allows the user to assign the recharge values to any of the specified model layer

Recharge is applied to the uppermost active layer: If any grid cells in Layer 1 are dry, or if they are designated as no-flow cells, the recharge values assigned to these grid cells will be carried down to the upper most active (wet) grid cell in the same vertical column of grid cells.

## 4.6 EVAPOTRANSPIRATION

The Evapotranspiration distribution can be applied to any of the user-specified model Layers. If assigned to the top grid layer, and some cells in the top layer become dry during the course of the simulation, or if some cells in the top layer are designated as no-flow cells, the MODFLOW program allows the Evapotranspiration to be applied to the grid cells in the upper most active (wet) layer in the model. The Evapotranspiration settings are shown in the following Evapotranspiration Options window and these are described below.

Evapotranspiration is only applied to the top grid layer: If any grid cells in Layer 1 are dry, or if they are designated as no-flow cells, the Evapotranspiration values assigned to these grid cells will NOT be carried down to the underlying active (wet) grid cells. In this case, the inactive or dry cells act like an impermeable barrier to the Evapotranspiration.

Evapotranspiration is applied to the specified layer: It allows the user to assign the Evapotranspiration values to any of the specified model layers.

Evapotranspiration is applied to the uppermost active layer: If any grid cells in Layer 1 are dry, or if they are designated as no-flow cells, the evapotranspiration values assigned to these grid cells will be carried down to the upper most active (wet) grid cell in the same vertical column of grid cells.

## 4.7 LAYER TYPES

The Layer Type Settings window is used to set the LAYCON value and the LAYAVG variables required by the MODFLOW numeric engine.

The LAYCON value is the layer-type index array recognized by MODFLOW. MODFLOW has four different Layer Types to choose for LAYCON values as described below:

Type 0 - Confined: Transmissivity and storage coefficients of the layer are constant for the entire simulation.

Type 1 - Unconfined: Transmissivity of the layer varies and is calculated from the saturated thickness and hydraulic conductivity. The storage coefficient is constant; valid only for Layer 1.

Type 2 - Confined/Unconfined: Transmissivity of the layer is constant. The storage coefficient may alternate between confined and unconfined values.

Type 3 - Confined/Unconfined: [Default setting] Transmissivity of the layer varies. It is calculated from the saturated thickness and hydraulic conductivity. The storage coefficient may alternate between confined and unconfined values. Vertical leakage from above is limited if the aquifer becomes desaturated.

The LAYAVG value determines the method of computing interblock transmissivity.

Following are the five methods used in assigning the LAYAVG value.

0 - Harmonic mean interblock transmissivity [Default setting for MODFLOW-96 and MODFLOW-2000].

10 - Arithmetic mean interblock transmissivity.

20- Logarithmic mean interblock transmissivity.

30 - Arithmetic mean saturated thickness times logarithmic mean hydraulic conductivity.

40 - Harmonic mean interblock hydraulic conductivity introduced in BCF4 package [Default (Required) setting for MODFLOW-SURFACT].

Note that the LAYAVG values are two digits with a factor of ten. For example, a LAYCON value of 21 represents an unconfined layer where the interblock transmissivity is calculated using a logarithmic mean.

The Layer column in the Layer Settings window (see following figure) is the layer number which is automatically numbered as one row for each layer of the model grid.

The LAYCON column is the Input LAYCON value, which includes the first digit (tens) stored as the LAYAVG value (Interblock transmissivity), and the second digit (ones) stored as the LAYCON value (Layer type). Thus the one Input LAYCON value holds the identification for each layer of the model grid.

The Interblock transmissivity column displays the LAYAVG value and descriptive name associated with each layer of the model. The available LAYAVG settings can be chosen from a pick list by clicking the down arrow key, or you can scroll through the options by clicking the spin buttons on the left (as shown in the following figure).

The Layer type column displays the Layer Type associated with each layer of the model. The available layer types can be chosen from a pick list by clicking the down arrow on the right, or you can scroll through the options by clicking the spin buttons on the left. (Visual Modflow Flex User Manual, 2012)

## 4.8 OUTPUT CONTROL

Each MODFLOW simulation can produce three binary output files and one ASCII output file:

Binary head file (model name. HDS)

Binary drawdown file (model name. DDN)

Binary flow file (model name. BGT)

ASCII listing file (model name. LST)

The binary files contain head, drawdown, and flow exchange values for each grid cell, while the ASCII listing file contains all relevant information on the operation of MODFLOW, and the simulation results. The listing (.LST) file is useful if errors occur during a simulation and you want to know how far MODFLOW progressed, or if you want to examine head or drawdown values at given intervals.

For a steady-state simulation, only one set of values for each grid cell are written to these files. However, for transient simulations, each grid cell may contain simulation results for each time step, resulting in file that can become unnecessarily large. By default, the information is saved in the binary files at the end of each stress period, and at the end of the simulation in the listing (.LST) file.

The first two columns list the available stress periods and associated time steps for the entire simulation (only one stress period and time step will be listed for steady-state simulations). The remaining columns indicate the information which can be written and saved to the various MODFLOW output files. To select an output option, click in the appropriate checkbox and a checkmark (¸) will appear to indicate that the selected information will be written for the selected time step.

The columns labeled Save to Binary will save the output information to the binary files as described below.

Heads: Saves the heads in the binary heads file (.HDS).

DDown: Saves the drawdown in the binary drawdown file (.DDN).

F.Term: Saves the cell-by-cell flow terms in the binary budget (.BGT) file. Note: The Zone Budget program uses the.BGT file for calculating the flow between zones. Therefore, to change the frequency at which the Zone Budget information is saved, select the desired F.Term intervals.

The columns labeled Print to .LST will save the output information to the listing file as described below.

Heads: Saves the heads in the listing file.

DDown: Saves the drawdown in the listing file.

F.Term: Saves the flux terms (cell by cell flow terms) in the listing file.

Budget: Saves the budget information in the listing file. Note: MODFLOW only allows the flow terms (F.Term) to be stored once, in either the binary budget file (.BGT) or the listing file (.LST). Be aware that this setting can be lost if MODFLOW is being run together with MODPATH, because MODPATH requires the flow terms to be written to the .BGT file, and not to the .LST file.

The checkbox labeled Save.FLO file will save the cell-by-cell flow terms required by MT3D, when MT3D is not being run at the same time as MODFLOW. (Visual Modflow Flex User Manual, 2012)

# Chapter 5

# RESULTS AND DISCUSSION

## 5.1 MODEL CALIBRATION

The purpose of model calibration is to achieve an acceptable agreement with measured data by adjusting the input parameters within acceptable range. A groundwater model contains huge number of input data, the parameters to adjust during the calibration could be numerous. During the calibration it is therefore important to adjust the parameters within the acceptable range determined from field measurements, and also to minimize the number of adjusted parameters. In this study, the initial input parameters have been obtained from field measurements. The model has been calibrated for the year 2013. In the present model, calibration has been done against groundwater levels. During calibration vertical hydraulic conductivity, storage coefficient and river leakage coefficient have been adjusted.

To check the model accuracy the comparison of the measured and simulated values are done. Figure 5.1 shows the diagram for the groundwater heads. It can be seen, that the points are mostly located in the range of deviations less than ±0.25 m. At about 83% of the suitable observation points, the simulated head deviate less than ±0.25 m from the measured heads.

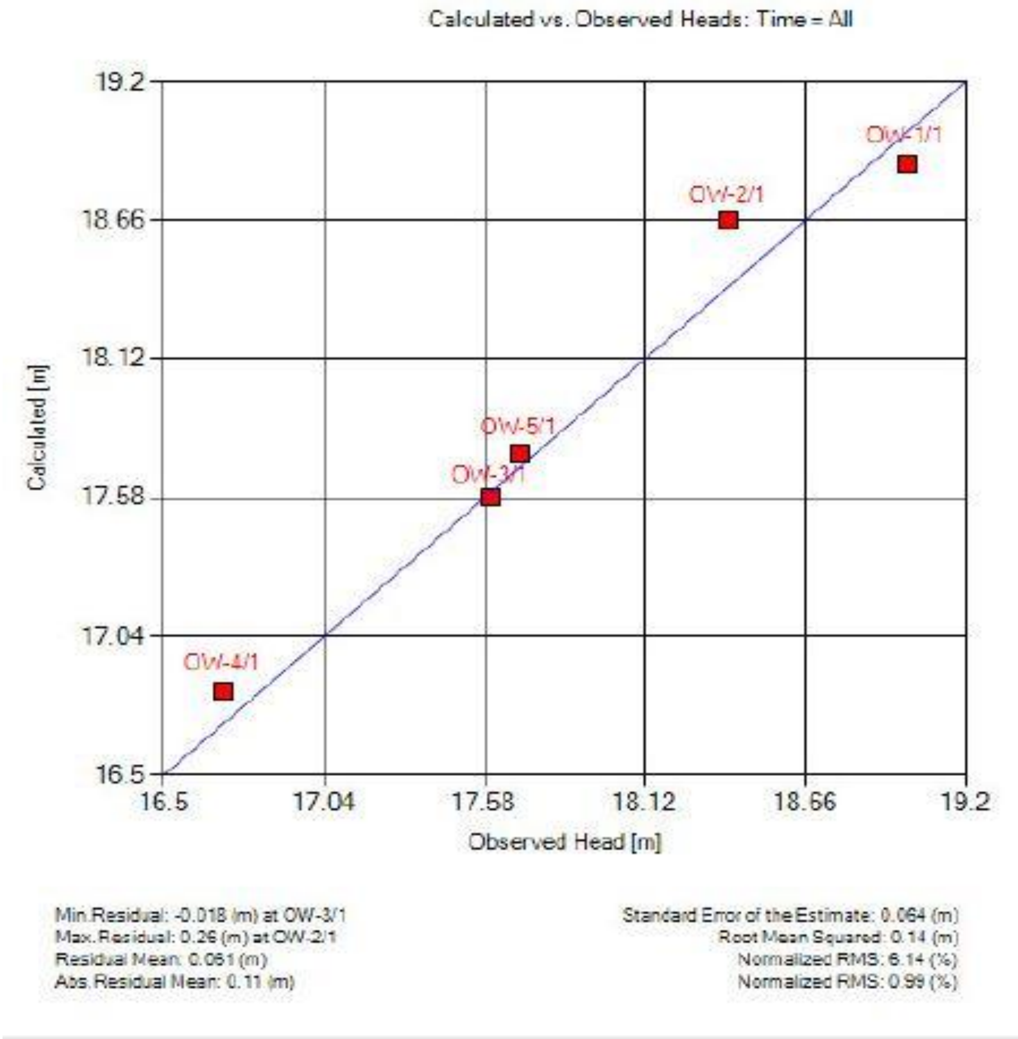



Figure 5.1: Calibration Curve for Observed Head vs. Calculated Head

## 5.2 MODEL VALIDATION

Validation of a groundwater model refers to the testing of a calibrated groundwater model against a new set of historic groundwater conditions for which measurement data of water levels or groundwater flow is available, but that have not been used for the calibration process.

A data collection program was undertaken by Iftakher in the year of 2013, during that time field samples were collected and from there various groundwater quality parameters like pH, temperature, Electrical Conductivity (EC), total dissolved solids (TDS) and Eh were measured (Table 5.1). Electrical Conductivity (EC) was measured in the field and from there salinity was calculated by using a factor of 0.6. It is established that 1 μS/ cm of EC =0.6 mg/l of salinity. Graphs have been prepared with the collected data (Table 5.1) and data got from the model to show the model validity in the same time frame with same location.

Table 5.1: Physical parameters of representative samples.

| Well ID | Upazila | Temperature (°C) | pH | Eh | **EC (μS/ cm)** | TDS (mg/l) |
|---|---|---|---|---|---|---|
| KHBGLW-1 | Batiaghata | 27.6 | 7.08 | -6.5 | **9777** | 5123 |
| KHBGLW-2 | Batiaghata | 28.4 | 7.44 | -23.9 | **6447** | 3447 |
| KHBGLW-3 | Batiaghata | 27.1 | 7.32 | -21.2 | **7030** | 4274 |
| KHBGLW-4 | Batiaghata | 28.6 | 7.69 | -35 | **7112** | 3852 |
| KHBGLW-5 | Batiaghata | 27.1 | 7.39 | -24.5 | **4464** | 2332 |
| KHDKLW-1 | Dacope | 30.6 | 6.55 | 26.8 | **6763** | 4163 |
| KHDKLW-2 | Dacope | 28.7 | 6.45 | 33.1 | **7368** | 3825 |
| KHDKLW-3 | Dacope | 28.4 | 6.43 | 34.3 | **7850** | 4152 |
| KHDKLW-4 | Dacope | 28.9 | 6.41 | 34.9 | **9284** | 5807 |
| KHDKLW-5 | Dacope | 27.8 | 6.41 | 35.3 | **6902** | 3569 |
| KHDLLW-1 | Dighalia | 28.1 | 7.35 | -12 | **1546** | 843 |
| KHDLLW-2 | Dighalia | 30.3 | 7.37 | -13.1 | **5458** | 3981 |
| KHDLLW-3 | Dighalia | 26.9 | 7.43 | -23.7 | **4760** | 2694 |

| | | | | | | |
|---|---|---|---|---|---|---|
| KHDLLW-4 | Dighalia | 26.4 | 7.4 | -18 | **432** | 233 |
| KHDLLW-5 | Dighalia | 26.5 | 7.57 | -436 | **394** | 228 |
| KHDRLW-1 | Dumuria | 27.1 | 6.32 | 40.4 | **5503** | 2949 |
| KHDRLW-2 | Dumuria | 27.9 | 6.39 | 36.7 | **1619** | 1143 |
| KHDRLW-3 | Dumuria | 27.4 | 6.37 | 37.4 | **6468** | 4294 |
| KHDRLW-4 | Dumuria | 27.8 | 6.39 | 36.5 | **5027** | 3183 |
| KHDRLW-5 | Dumuria | 28.1 | 6.43 | 34 | **716** | 417 |
| KHKRLW-1 | Koyra | 27.6 | 8.52 | -55.4 | **1781** | 926 |
| KHKRLW-2 | Koyra | 28.1 | 7.45 | -2.7 | **2700** | 1406 |
| KHKRLW-3 | Koyra | 28 | 7.44 | -21.8 | **5400** | 2800 |
| KHKRLW-4 | Koyra | 27.9 | 7.52 | -32.3 | **3350** | 1982 |
| KHKRLW-5 | Koyra | 28 | 7.8 | -40.6 | **2230** | 1159 |
| KHPGLW-1 | Paikgacha | 29.9 | 6.51 | 29.1 | **1288** | 984 |
| KHPGLW-2 | Paikgacha | 26.9 | 6.4 | 36.4 | **7062** | 4530 |
| KHPGLW-3 | Paikgacha | 27.3 | 6.37 | 37.4 | **604** | 321 |
| KHPGLW-4 | Paikgacha | 27.5 | 6.4 | 36.1 | **1231** | 871 |
| KHPGLW-5 | Paikgacha | 27.6 | 6.45 | 32.6 | **6555** | 4030 |
| KHRSLW-1 | Rupsa | 27.3 | 7.41 | -22.8 | **5727** | 3913 |
| KHRSLW-2 | Rupsa | 28.3 | 7.55 | -26.7 | **4793** | 2509 |
| KHRSLW-3 | Rupsa | 27.7 | 7.4 | -28.2 | **3739** | 2474 |
| KHRSLW-4 | Rupsa | 27.3 | 7.27 | -18 | **2146** | 1361 |
| KHRSLW-5 | Rupsa | 27.9 | 7.51 | -29.3 | **4341** | 2468 |
| KHTKLW-1 | Terokhada | 28.2 | 7.61 | -29.7 | **5835** | 2540 |
| KHTKLW-2 | Terokhada | 27.1 | 7.5 | -32.4 | **5761** | 2492 |

| | | | | | | |
|---|---|---|---|---|---|---|
| KHTKLW-3 | Terokhada | 28.8 | 8.23 | -69.4 | **1325** | 952 |
| KHTKLW-4 | Terokhada | 28.5 | 7.85 | -54.6 | **2680** | 1441 |
| KHTKWL-5 | Terokhada | 27.7 | 8.02 | -55 | **2619** | 1399 |

According to final report by IWM on Khulna Water Supply Project in March 2011, water quality data was collected and the EC value was measured (see **Appendix A**). From that EC value salinity for the study area was calculated and validated by comparing model results with measured data. Table 5.2 shows the validation of model by comparing model results with measured data.

Table 5.2: Validation of model by comparing model results with measured data and data from published report

| Ser. No | Year | Result from Developed Model Salinity (mg\l) | Final Report on Khulna Water Supply Project by IWM, 2011 Salinity (mg\l) | Remarks |
|---|---|---|---|---|
| 1 | 2010 | 1000-1700 | 660-2160 | |

The model data and published report by IWM for 2010 of the study area in the same location shows that they have striking similarities.

### 5.2.1 Model Validation Graphs of the Study area

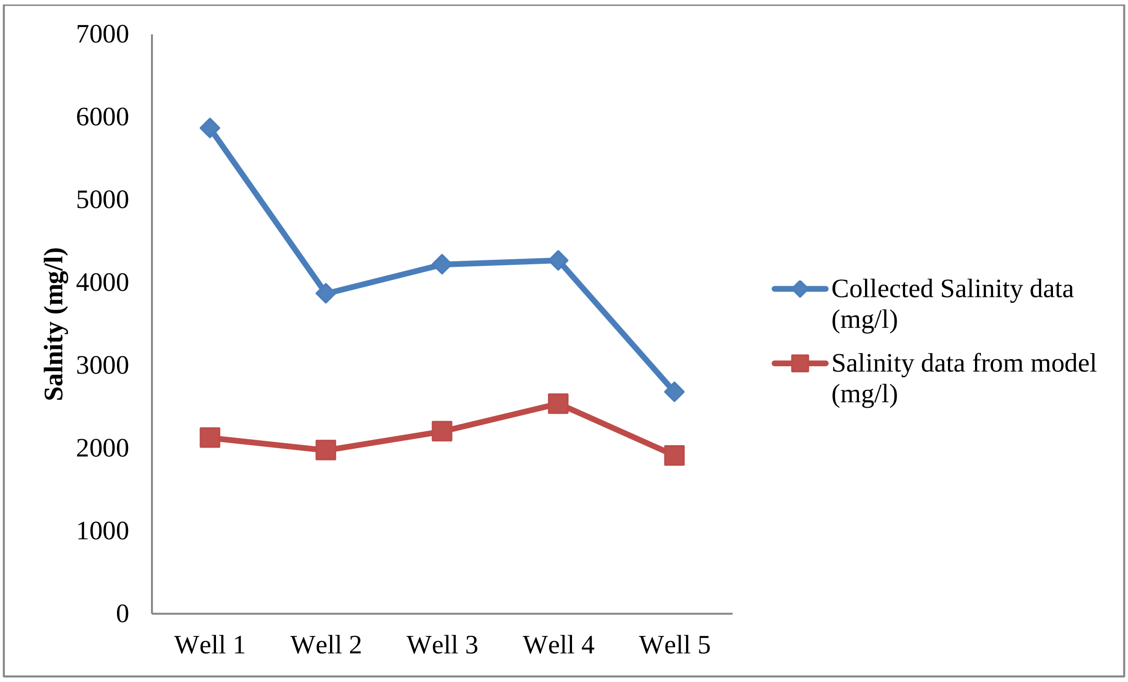



Figure 5.2: Salinity comparison in Batiaghata area in 2013

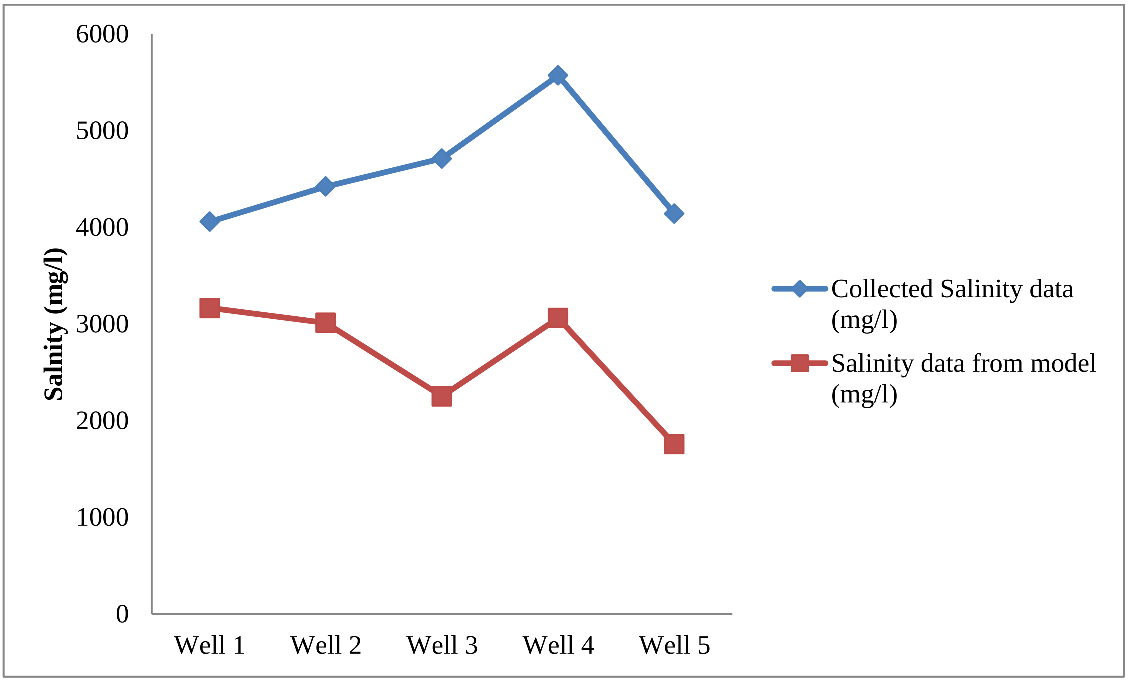



Figure 5.3: Salinity comparison in Dacope area in 2013

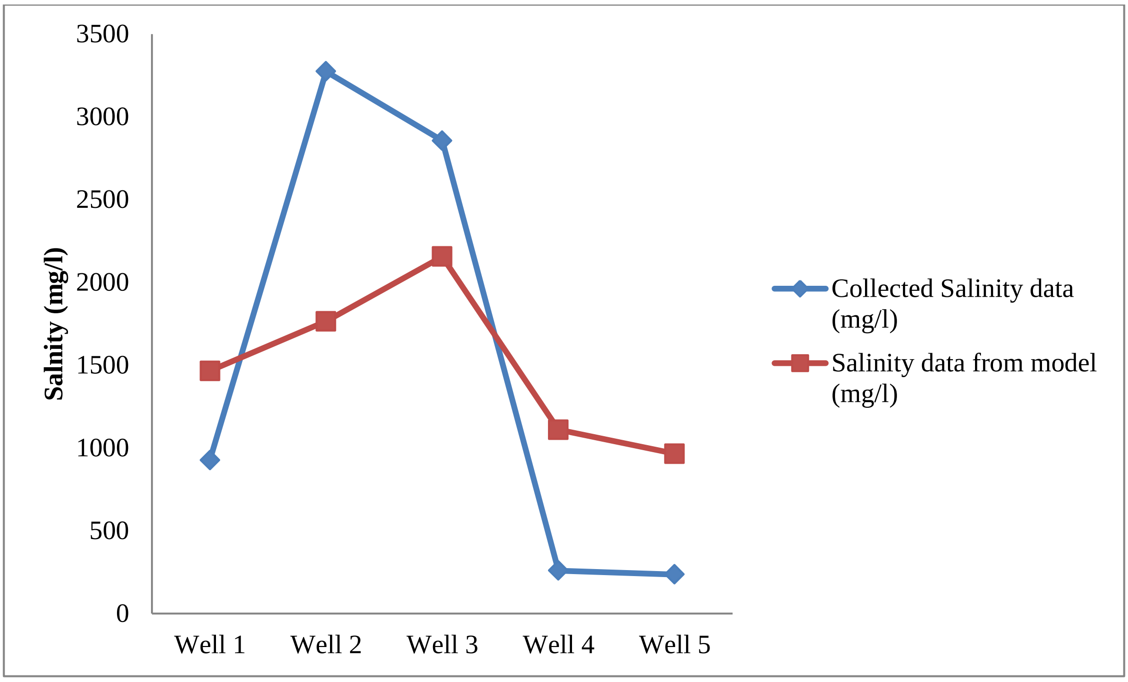



Figure 5.4: Salinity comparison in Dighalia area in 2013

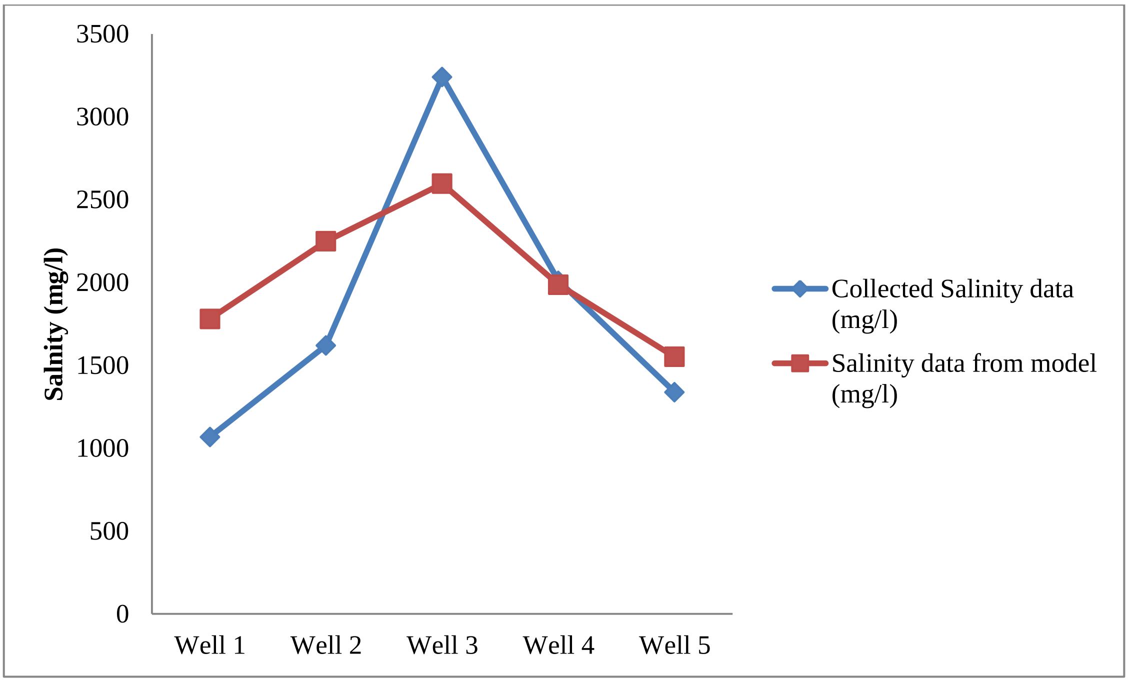



Figure 5.5: Salinity comparison in Koyra area in 2013

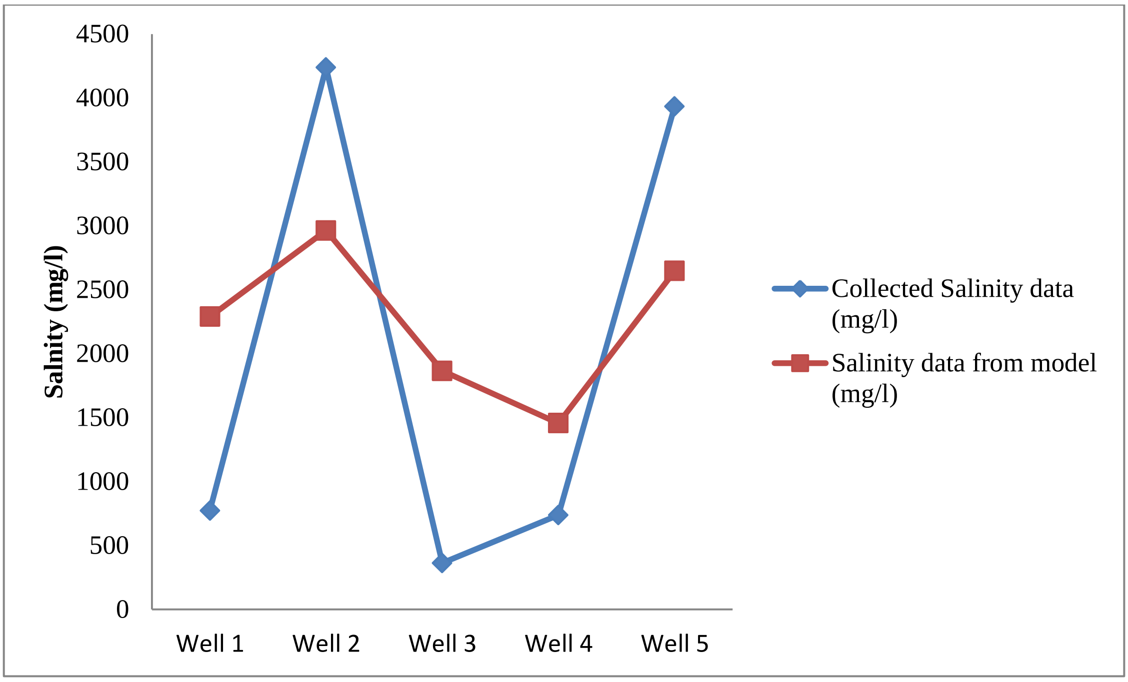



Figure 5.6: Salinity comparison in Paikgacha area in 2013

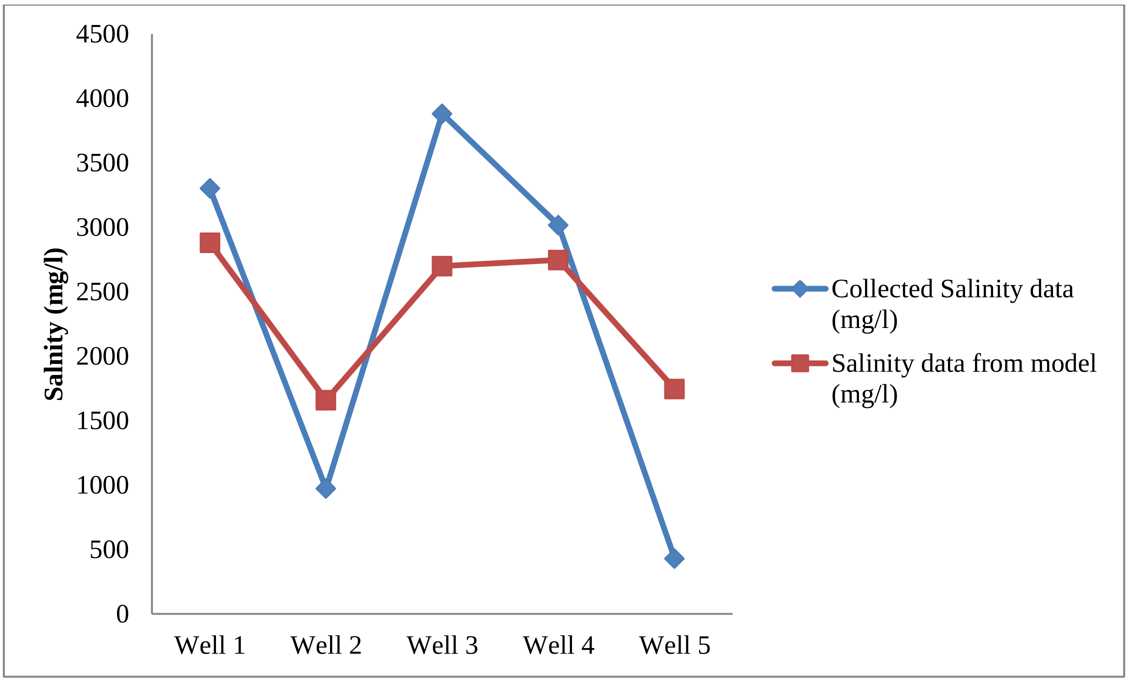



Figure 5.7: Salinity comparison in Dumuria area in 2013

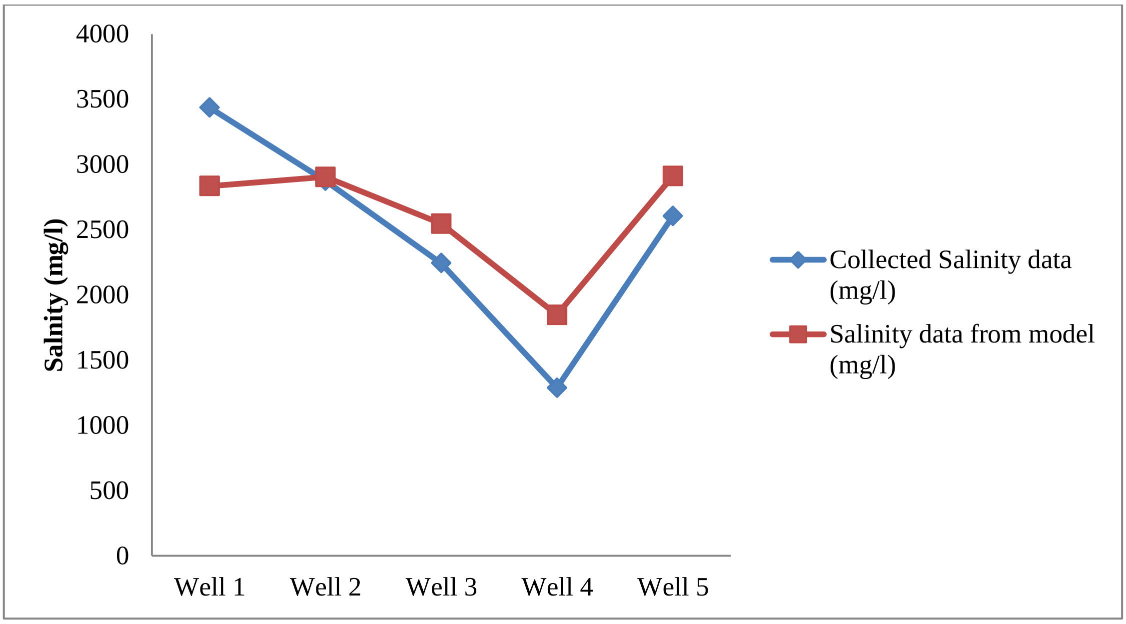



Figure 5.8: Salinity comparison in Rupsa area in 2013

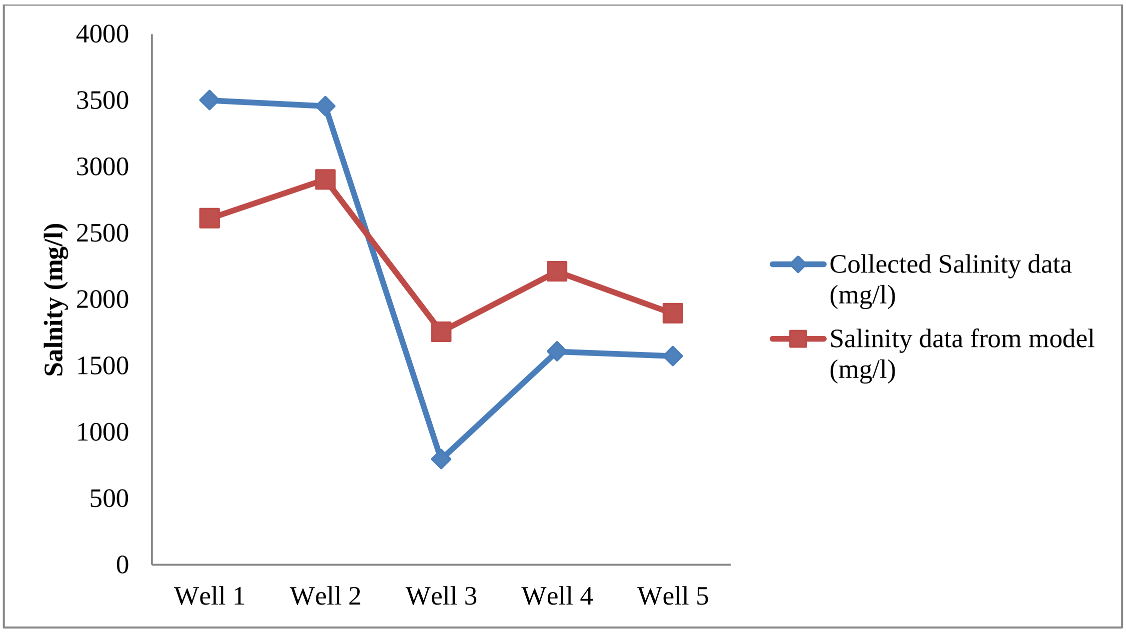



Figure 5.9: Salinity comparison in Terokhada area in 2013

From graphs it is established that the collected data for salinity in 2013 in the study areas are very close to the predicted data of the VISULA MODFLOW in the similar location of the study area for the year 2013.

## 5.3 MODEL STABILITY

The Courant number represents the number of cells a particle will be allowed to move through in any direction, in one transport step, when the MOC, MMOC and HMOC methods are used. Generally, the Courant Number is between 0.5 and 1.0; however, values in excess of 1.0 can be used with caution. In Courant number for MODFLOW lower time step to lower Courant number and raise time step to increase Courant number. This phenomenon indicates the model stability.

From the developed model using MT3DMS Engine with the following steps the Courant number was found against the selected time steps.

MT3DMS/Solution Method: from the top menu bar of MODFLOW window a Solution Method window will appear, In the Solution Method dialogue select advection term frame, using the Upstream Finite Difference solution method with the Generalized Conjugate Gradient (GCG) solver. The Upstream Finite Difference method provides a stable solution to the contaminant transport model in a relatively short period of time.

Though the Upstream Finite Difference method and the Implicit GCG Solver are computationally efficient, the model simulation tracks contaminant transport over a 20 year period. Boundary condition is taken same as the outer boundary. After checking the grid and the boundary condition type the following information in the fields at the bottom of the window. The output window will show the Courant number against the selected time step. A graph (Figure 5.10) is given below showing the Courant number got from the model against the time step.

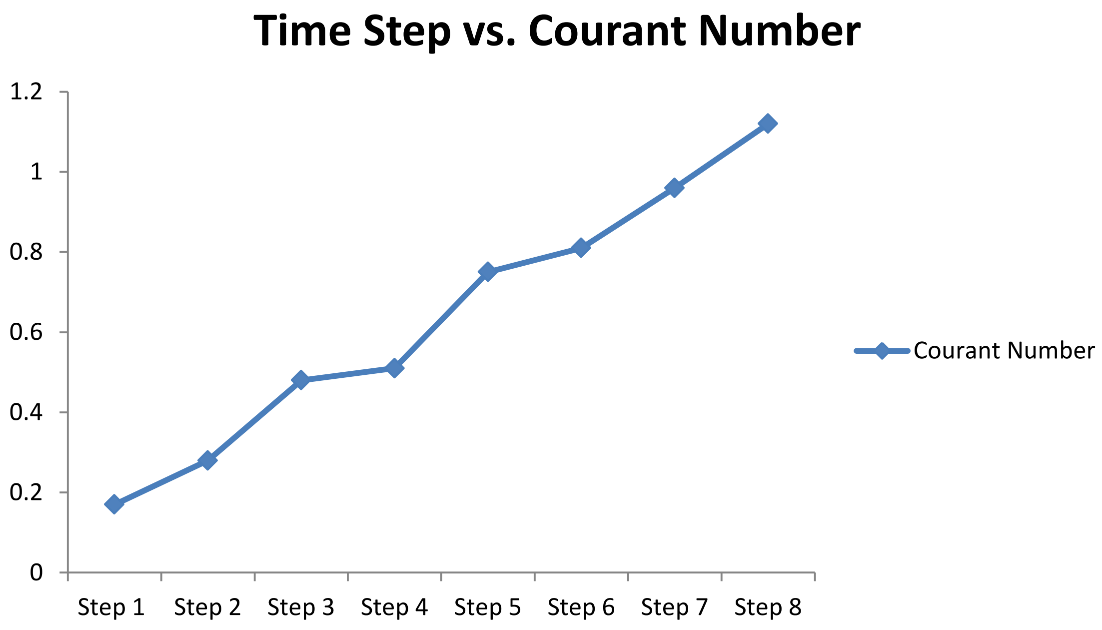



Figure 5.10: Time Step vs. Courant Number

It is observed that the Courant number of the developed model against its time step reflects a stable model. With the increase in time steps the Courant number also increases and also stays within the prescribed range of Courant number.

## 5.4 SALINITY TRANSPORT

From visual MODFLOW, concentration heads will be shown in the Maps view. For this Concentration head needs to be active, turn off Heads from the model explorer, and set "Concentrations" to be visible (Figure 5.11).

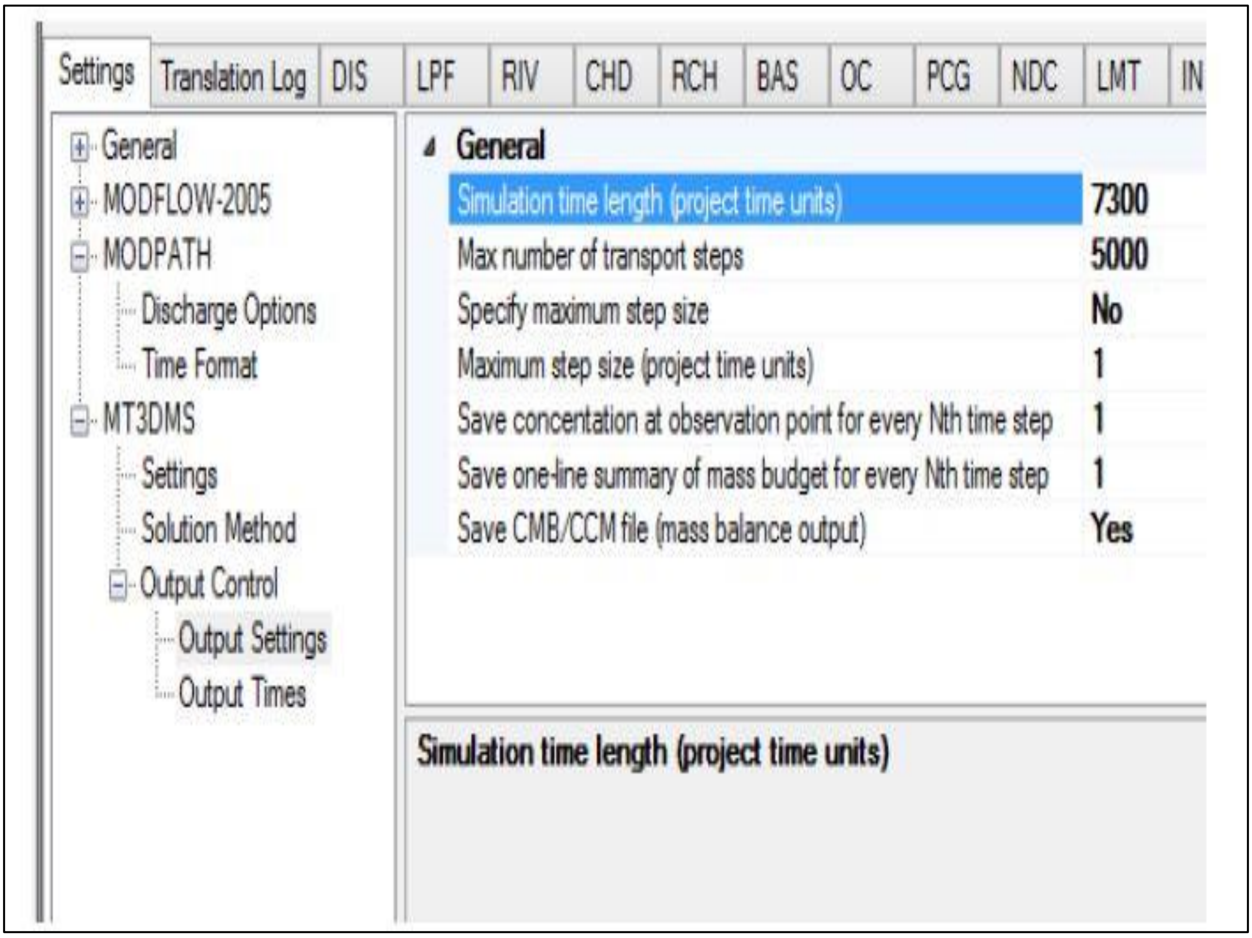



Figure 5.11: Simulation Time Settings

Then locate the Output node on the model tree and remove the checkbox beside heads, add a checkbox beside "Concentrations". The concentration contours will be plotted for the first transport output time in this case the first transport output time is 1 day (Figure 5.12).

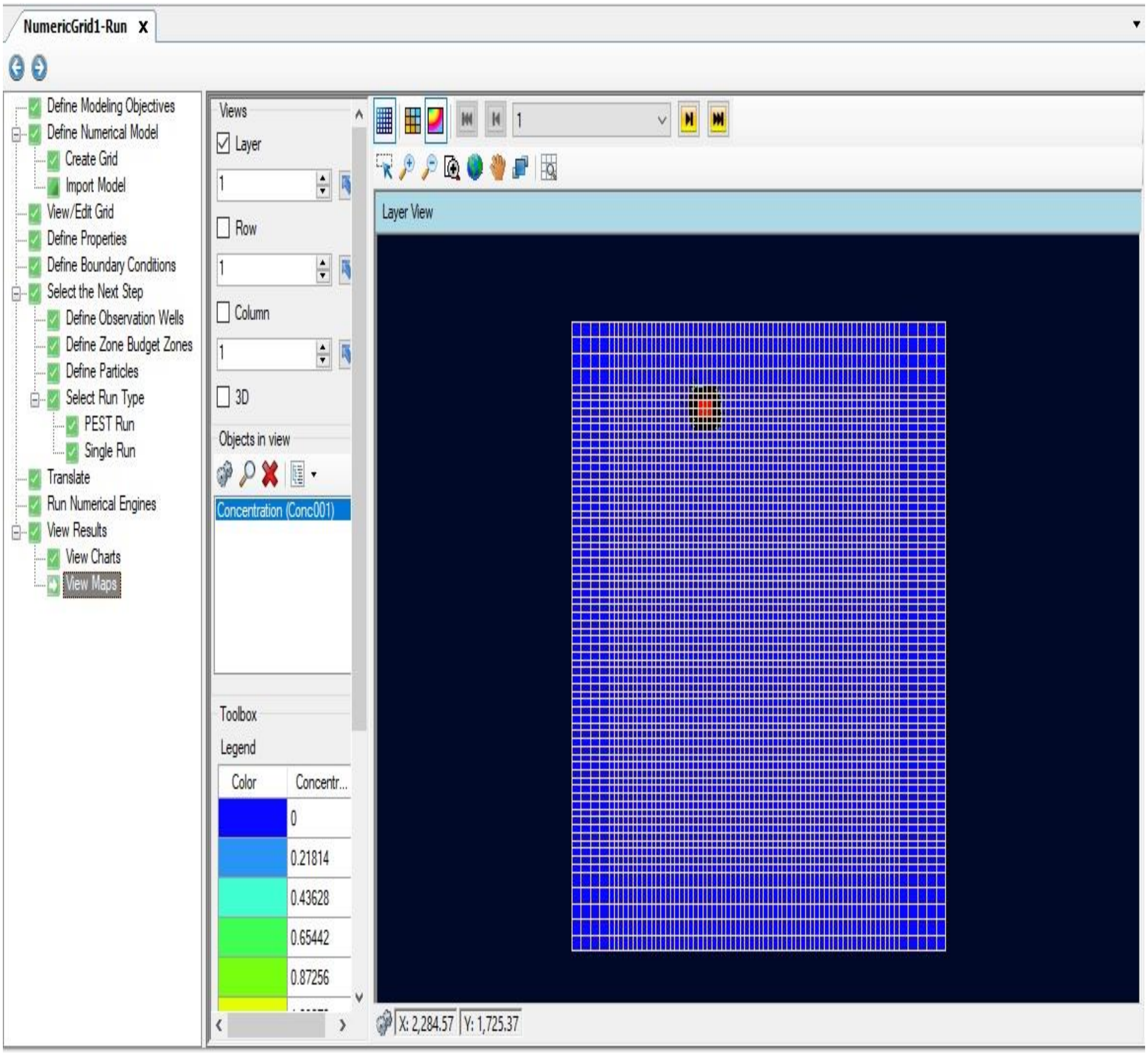



Figure 5.12: Contamination transport in day 1

For day 1, saline water is stagnant and ground water flow movement is yet to begin.

For next concentration output advance the output time for that click on the "Next Time Step" button located on the toolbar above the Layer view. Alternately, expand the list of output times, and navigate directly to the desired output time. This display will then update with a plot to plot concentration contours for selected output time.

Now advanced to the second output time, 1460 days (Figure 5.13):

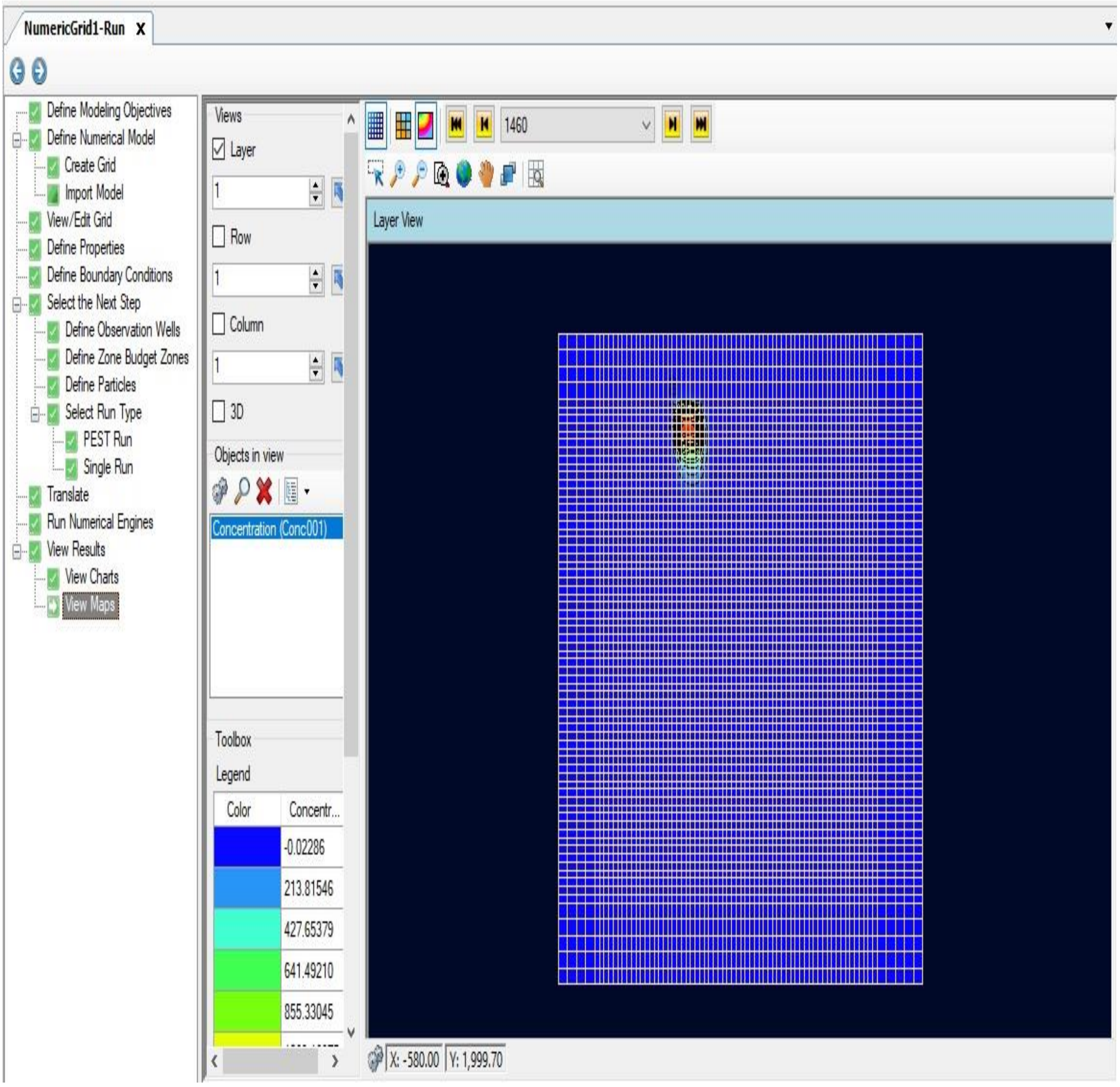



Figure 5.13: Contamination transport in day 1460

Now advanced to the third output time, 2190 days, it is observed that the saline water starts transporting from Dacope to Dumuria (Figure 5.14).

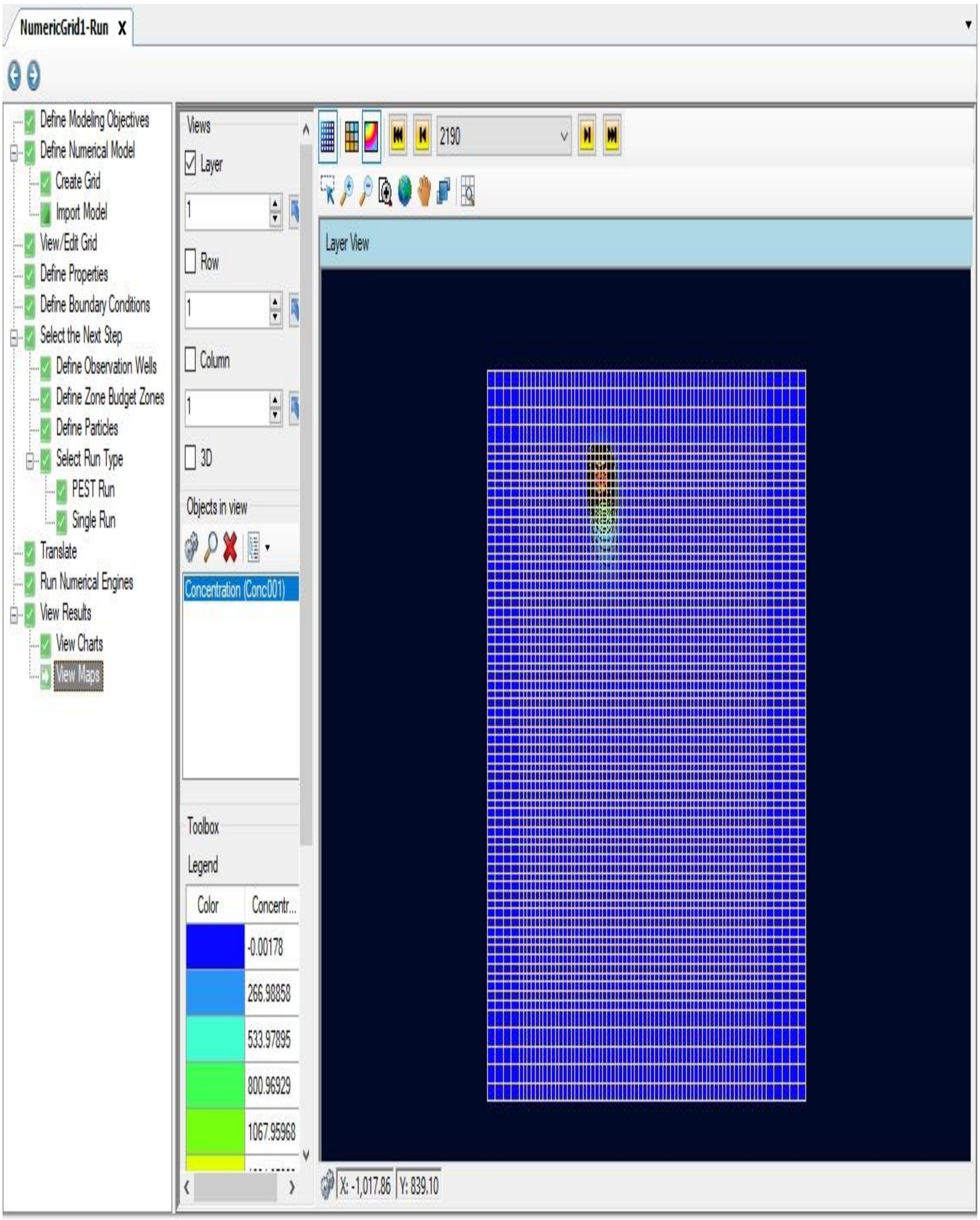



Figure 5.14: Contamination transport in day 2190

Again advanced to the fourth output time, 2920 days, it shows further saline water transport towards inland (Figure 5.15):

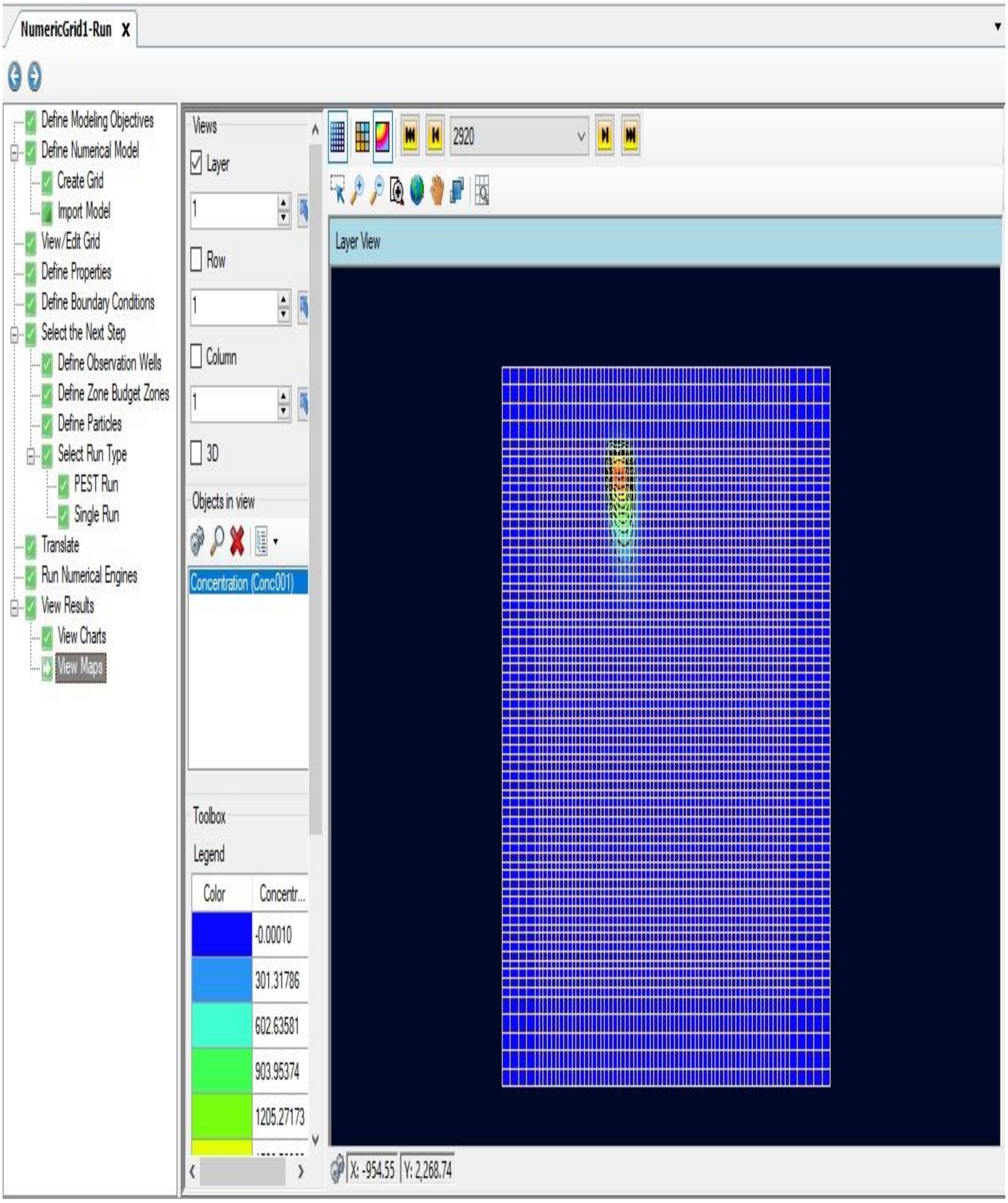



Figure 5.15: Contamination transport in day 2920

Now advanced to the fifth output time, 3650 days (Figure 5.16):

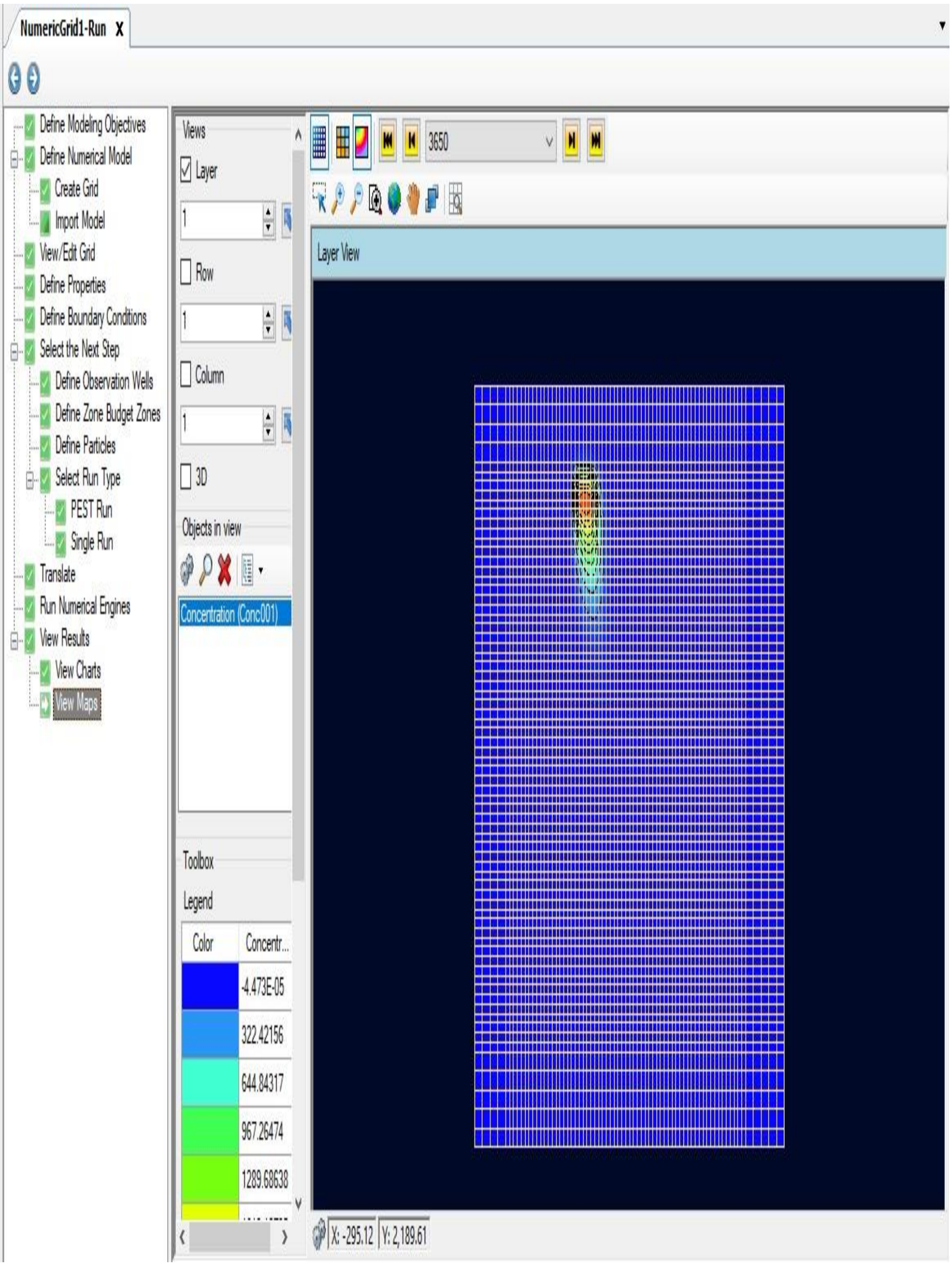



Figure 5.16: Contamination transport in day 3650

Again advanced to the sixth output time, 5475 days (Figure 5.17):

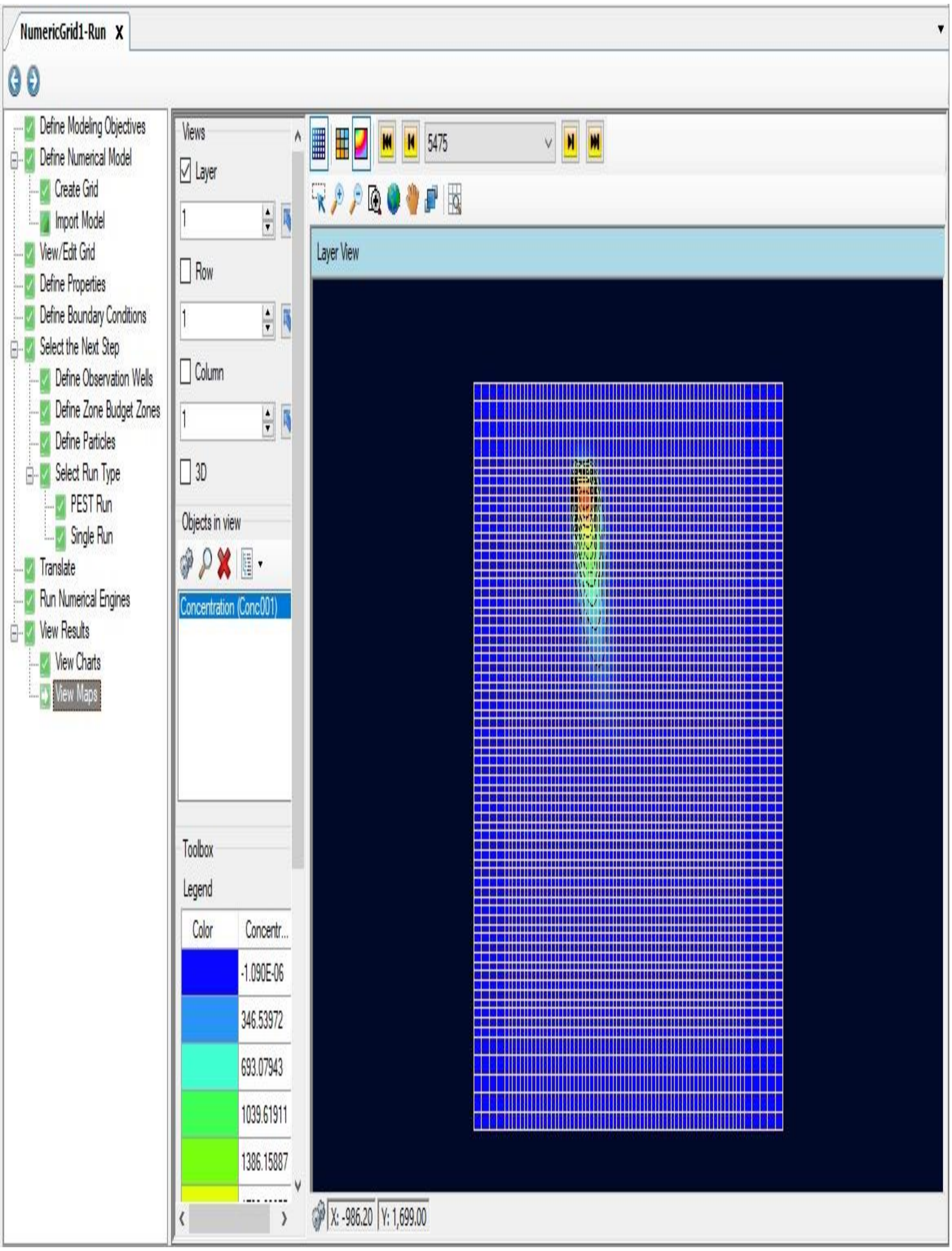



Figure 5.17: Contamination transport in day 5475

Now advanced to the final output time, 7300 days (Figure 5.18):

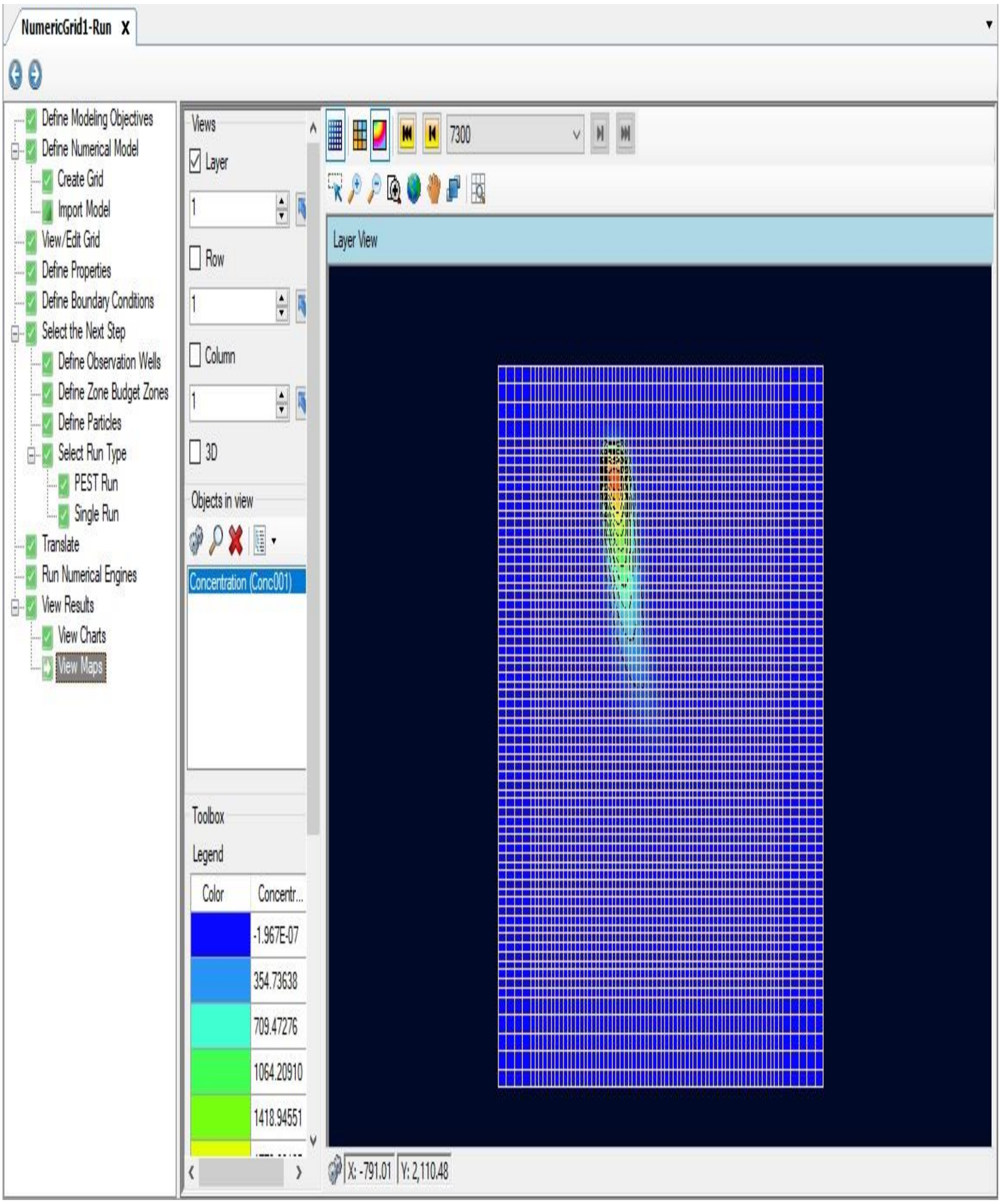


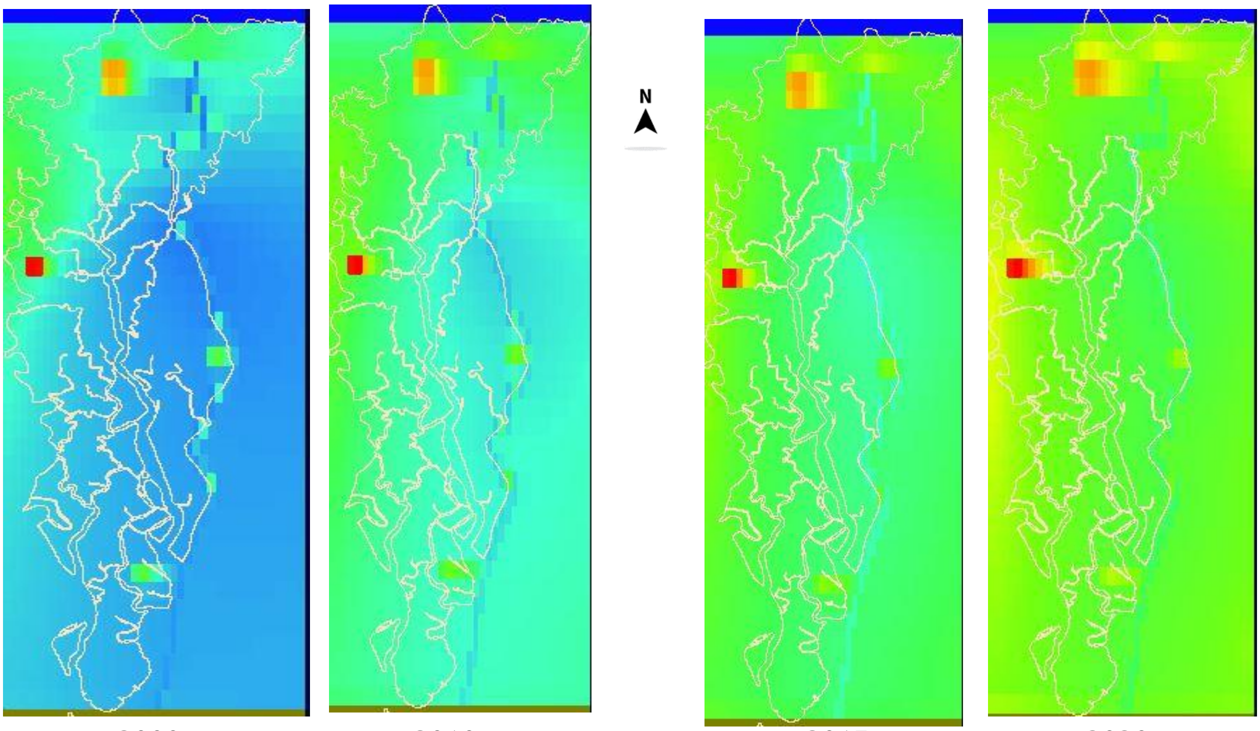

Figure 5.18: Contamination transport in day 7300

• After 7300 days of simulation time it is clear that the plume has migrated from Dacope to Dumuria a total length of about 45-46 km.

## 5.5 SALINITY DISTRIBUTION IN THE SUB-SURFACE LAYERS

The distribution of salinity was simulated for a period of twenty years in terms of chloride concentration. This simulation of salinity distribution was subject to some boundary conditions. The simulation took into consideration the presence of chlorides in the surface water (such as rivers and ponds) and also groundwater abstraction wells. In this regard, several ponds with saline water were identified in the study area, whose co-ordinates were mapped and inducted into the shape file for the study area and the levels of chloride concentration being noted. Local River like the Rupsha River in Khulna was identified. Although river salinity data in dry seasons for Rupsha River was available, little or no river salinity data was available for rainy season. Hence, for rainy season the primary source of saline water was considered to be the ponds and the groundwater abstraction wells. The interaction of these surface water bodies and groundwater wells was achieved by applying a groundwater head of 90 meters flowing in the north to south direction. The MT3DMS engine in combination with MODFLOW computes the salinity fronts in the sub-surface layers. Active transport was assumed for the movement of salinity front through the subsurface and groundwater layers; meaning the salinity/chlorides was transported with a linear velocity similar to that of the groundwater flow. For this model, the simulation time is 7300 days (20 years).

**Salinity Distribution in Khulna**




2000 2010 2015 2020

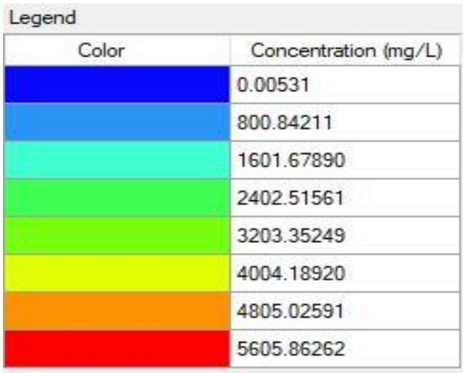



Figure 5.19: Simulation of Salinity Distribution (in mg/L of chlorides) in the Sub-surface layers of Khulna; for a period of 20 years

The Figures 5.19 are pictorial presentation of salinity distribution and transport in Khulna. The salinity concentration in the sub-surface layers appears to increase by about 3.75 times in a span of 20 years; due to the occurrence of surface water-groundwater interaction. Present value of salinity concentration has a value of nearly 800 mg/L while in another twenty years the concentration is expected to reach a maximum of approximately 3200 mg/L.

CHAPTER 6

# CONCLUSION AND RECOMMENDATION

## 6.1 SUMMARY AND CONCLUSION

The study to understand the salinity intrusion process in the coastal aquifer has been conducted using MODFLOW groundwater modelling tool which is coupled with MT3DMS transport modeling tool. Three major modeling activities such as salinity model, salinity transport model and groundwater model have been developed and calibrated to achieve the study objectives. The following conclusions may be drawn from this study:

- From the saline transport model it was observed that the saline water from the point source reached to the studied aquifer in Dacope within first 2 years (730 days) of the simulation time (Figure 6.1).

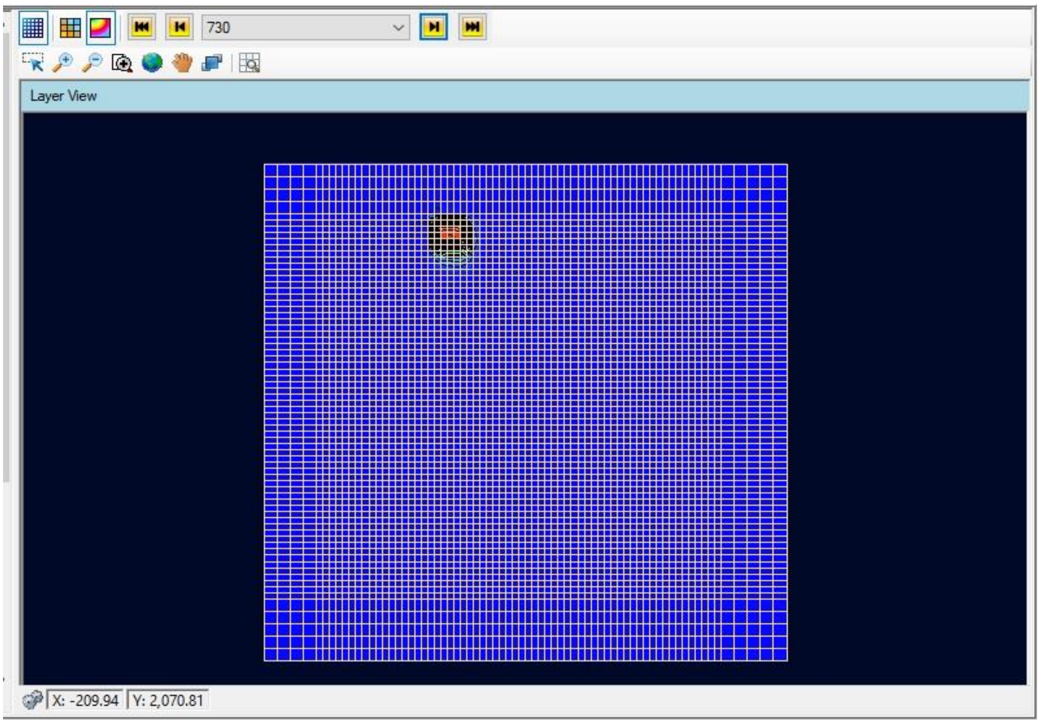



Figure 6.1 Salinity transport in day 730 in Dacope area

- It was found from the model that after 20 years of simulation time the salinity reached from Dacope to Dumuria a total length of about 45-46 km.

- Maximum salinity was found to be in Dacope upazila 3116 mg/l, which is near to coast.

- From the model, after 20 years of simulation time salinity of Dumuria will be 1926 mg/l.

- It was found from simulation results that in the month of March and April the salinity variation is maximum in the study area due to less rain fall.

- It was observed from the model that salinity distribution in the study area increase from 800 mg/L to about 3200 mg/L in a span of 20 years from year 2000 to 2020.

- The shallow groundwater of Dacope was found too saline for domestic or irrigation use.

## 6.2 LIMITATIONS OF THE STUDY

The salinity intrusion process is very difficult to identify as because of the complexity of hydrogeology of the costal aquifer here in Bangladesh. The dynamics of saline water movement depends on a lot of parameters which are not readily available. IWM and BWDB have initiated such a complex study which is a continuous process of understanding the dynamics with the updated data. During the study period a lot of limitations were noticed as illustrated below.

- The data to identify the boundary conditions, initial conditions and information about the salinity concentration and salinity development process is not sufficient. Long time series data needed primarily to achieve the real decision.

- Aquifer properties data is not quite sufficient to describe the geological properties.

- The climate change scenario itself contains a lot of uncertainties which may bias the model results.

- Calibration parameters for salinity model such as dispersion rate, density ratio are still needed to be justified with field measured data.

## 6.3 RECOMMENDATIONS

- Extensive ground water salinity data collection by automatic EC meter including data logger should be introduced in the study area.

- The change in seasonal variation of concentration of salinity can be thoroughly investigated as it produces an impact on the seasonal crop and economic condition.

- A better understanding of pumping schedules and rates would allow a more sophisticated analysis of ground water modeling and salinity transport.

- Collect and store all monitoring data in a central database. A centrally organized and publicly available database with data regarding: geology, hydraulic properties of the ground, groundwater levels, groundwater quality and well location is needed.

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# *APPENDIX A*