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Model Simulation of Groundwater Contamination by Cs-137 at Al-Tuwaitha Site

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BY

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[وَأَنْزَلْنَا مِنَ السَّمَاءِ مَاءً
بِقَدَرٍ فَأَسْكَنَّاهُ فِي الْأَرْضِ وَإِنَّا
عَلَى ذَهَابٍ بِهِ لَقَادِرُونَ]

[المؤمنون: 18]

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DEDICATION

I dedicate this work to God almighty for making
everything possible

And

To my dear father

To my dear mother

To my dear sisters

To my dear brothers

To all those who love me

With my love and respect for providing
opportunities for me and supporting me

Rasha.....

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Firstly, all the thanks and praise be to ALLAH for enabling me to achieve this research.

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Abstract

This study simulates the groundwater movement and the transfer of Cs-137 contaminants of the aquifer system for Nuclear Research Center at Al-Tuwaitha site, using processing MODFLOW software package version 5.3. The site is located in south of the province of Baghdad near the Tigris river and contaminated with radiation as a result of exposure for bombing and acts of vandalism and looting in 2003. MODFLOW model was used to determine the groundwater movement and the impact of change of water surface elevation of the Tigris river on layers of aquifer system as well as to evaluate the ability of the proposed pumping well on the changing movement of water and contaminant in steady-state. In addition, MT3D model was used to study the contaminant distribution in aquifer and its change with time.

The model calibration gave a relatively good agreement between the calculated and observed heads for six observed wells which were chosen for this study. Through the calibration process, an increase of 5% of the hydraulic head for the layers of the aquifer was found whenever the horizontal hydraulic conductivity of the third layer increases. The parameters used as input in model after the final calibration were $2x10^{-6}$, $7x10^{-5}$, and $3x10^{-4}$ m/s as values of the horizontal hydraulic conductivity, 0.1, 0.26, and 0.32 as values of the effective porosity, and $1x10^{-9}$, $1x10^{-8}$ and $5x10^{-8}$ m^2 /s as values of the diffusion coefficient for the first, second and third layers, respectively.

The results indicated that any increase in the water elevation of the Tigris river leads to increase in levels of existing wells in the region by taking in consideration that other input variables in the model are constant. In addition, the use of pumping well has reduced the groundwater level and intercepted groundwater movement.

The results of transport model showed that the spread of Cs-137 contaminate increased with time and its direction with the ground water movement. The migration of contaminants in horizontal direction is low which the seepage velocity for the first, second and third layer were 0.0357, 0.51, and 1.76 m/year, respectively, with approximately oval shape based on the ratio of longitudinal dispersion and diffusion coefficients. A distance of 690 m that the plume moved during 20 years of the simulation towards the pumping well existing in the direction of the water of the Tigris river. It was a relationship between the surface water (Tigris river), groundwater and the nature of the soil, a change in one of those elements may affect the others.

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LIST OF SYMBOLS

Symbol	Definition	Dimension
$a_{i,j,k,n}$	Represents Flow from the Nth External Source into Cell i,j,k.	L^3T^{-1}
C	The Concentration of Contaminant Dissolved in Groundwater.	ML^{-3}
$CC_{i-\frac{1}{2},j,k}$	Conductance in Column j and Layer k Between Nodes i-1/2,j,k and i,j,k.	$L^2\ T^{-2}$
$CR_{i,j-1/2,k}$	Conductance in Row i and Layer k Between Nodes i,j-1,k and i,j,k.	L^2T^{-1}
C_S	The Concentration of the Source.	$M\ L^{-3}$
Cs-137	Cesium 137	/
$CV_{i,j,k-\frac{1}{2}}$	Conductance in Rowi and Column Between Nodes i,j,k-1/2 and i,j,k.	$L^2\ T^{-2}$
D_{ij}	The Hydrodynamic Dispersion Coefficient	L^2T^{-1}
DOS	The US. Department of State	
h	Head	L
h_c	Calculated Hydraulic Head	L
$h_{i,j,k}$	Head at Node i,j,k.	L
$h_{i,j-1,k}$	Head at Node i,j-1,k.	L
h_o	Observed Hydraulic Head	L
k_d	Partition Coefficient	$L\ M^{-1}$
$kR_{i,j-\frac{1}{2},k}$	Hydraulic Conductivity Along the Row Between Nodes i,j,k and i,j-1,k.	LT^{-1}
k_{xx}, k_{yy}& k_{zz}	Values of Hydraulic Conductivity Along X, Y, and Z Coordinates Axes.	$L\ T^{-1}$
MAE	Mean Absolute Error	L
ME	Mean Error	L
MOC	Method of Characteristics	/

MODFLOW	Modular Three-dimensional Finite-difference Groundwater Model	
MT3D	Modular Three-dimensional Transport Model	
n	The Porosity of the Porous Medium	/
n_e	The Effective Porosity	/
$P_{i,j,k}$	Constant	L^2T^{-1}
PMPATH	Advective Transport Model	
PMWIN	Processing MODFLOW for Windows Software	
Q_i	Flow Rate into the Cell	L^3T^{-1}
$q_{(x,y,z)}$	Darcy Spead Along x,y,z Axises.	L / T
R_c	Chemical Reaction	/
RMSE	Root Mean Square Error	L
SNL	Sandia Atonal Laboratories	
S_S	Specific Storage of the Porous Material	L^{-1}
$SS_{i,j,k}$	Represents the Specific Storage of Cell i,j,k.	L^{-1}
t	Time.	T
T	Transmissivity	$L^2\ T^{-1}$
w	Volumetric Flux Per Unit Volume Representing Sources (W Is Negative) and/ or Sinks (W Is Positive) of Water	T^{-1}
ρ_d	Bulk Density For Aquifer	ML^{-3}
α_L	Longitudinal Dispersivity	L
α_T	Transverse Dispersivity	L
α_v	Vertical Dispersivity	L
$\Delta r_j \Delta c_i \Delta v_k$	The Volume of Cell I,j,k.	L^3
Δh	Change in Head Over a Time Interval of Length Δt.	L

$\Delta \boldsymbol{h}_{i,j,k}/\Delta \boldsymbol{t}$	Finite-difference Approximation for the Derivative of Head with Respect to Time.	LT^{-1}
$\Delta \boldsymbol{r}_{j-1/2}$	Distance Between Nodes i,j,k and i,j-1,k.	L
$\Delta \boldsymbol{r}_j \Delta \boldsymbol{C}_i \Delta \boldsymbol{v}_k$	Volume of Cell i,j,k.	L^3
$\Delta \boldsymbol{v}$	The Volume of the Cell	L^3

Chapter One

Introduction

CHAPTER ONE

Introduction

1.1 General

Generally, groundwater is a renewable resource which (if managed correctly) ensures supply of water for the long term decreases the impacts of anticipated climate changes. Groundwater is closely interrelated to other components of the environment. This leads to the advent of simulation models which are used to provide a predictive capability that can be used to evaluate the groundwater behavior in reply to future stresses due to climatic change or land use, etc. (Guzha, 2008).

1-2 Groundwater Contamination and Modeling

However, many of the materials may contaminate groundwater and leave it unfit for consumption by pollutants seeping through the soil, either directly or indirectly via surface water. Contaminants that can dissolve in groundwater will move along with the water, and pollute very large volumes and areas of groundwater. contamination may cause degradation in water quality, and can create hazards to public health through toxicity or spread of disease. The most dangerous pollutants in groundwater are radioactive and heavy materials. Radiological pollution may result from the dissolving of the components aquifer, or as a result of nuclear explosions, where the soil absorbs the radiation that will be seeping into the groundwater (Pepper et al., 2011). Radioactive contaminants cause a significant risk for health that could impact future generations, including cancers and birth defects, and this is what presumably happened in Iraq (Rasheed, 2013). Aquifers of groundwater may be overlapping with each other, or the direction of flow may be in a river or the sea. So the effective management of water sources requires a comprehensive knowledge of hydrologic processes and impacts of pollution source (Huyakorn, 2000).

The model of groundwater is a clear representation of a groundwater system (a real phenomenon) and it is simplified with maintaining the required accuracy and the high reliability of the results. The models incorporate restrictive assumptions, such as dimensionality, spatial variability, and interaction of various components of flow and transport processes. One of the most popular models is mathematical models, they include analytical and numerical models. Groundwater modeling has been broadly used to simulate and foresee the status of aquifers. It solves the distribution of hydraulic heads, describes flow, and distributes solute concentration due to dispersion, advection, and chemical reactions (Kresic, 2006).

In this study, 3D model was applied to model the flow and contaminant transport by using Processing MODFLOW software version 5.3.1. MODFLOW model was used to estimate and distribute the hydraulic heads, and PMPATH model was used to show the flow direction, while MT3D model was used to simulate and distribute the (Cs-137) concentrations of the aquifer in Al-Tuwaitha (Nuclear Research Center). Al-Tuwaitha is located near Baghdad, Iraq, which was established in about 1960 and became the principal nuclear facility in Iraq. It was heavily damaged in 1981, 1991and 2003 by aerial bombings, which led to the pollution of the environment, as well as groundwater by one way or another, as a result of leakage of heavy radioactive materials into the soil (Tawfiq et al., 2011).

The assessment, decontamination, and dismantlement of various buildings in Nuclear Research Center were commenced in 2004. While groundwater studies began at Al-Tuwaitha in 2002 with the installation of six groundwater monitoring wells, then groundwater monitoring was resumed at the facility in 2011 (Copland, 2013).

This study aims to simulate groundwater movement and distribution of contaminants with groundwater movement, to evaluate the effect of Cs-137 which is considered a radiological contaminant hazardous which spreads in aquifer and affects the Tigris river.

1.3 Problem of This Study

Iraq was one of the clean environments, but it has suffered many destructive wars in the past which led to pollute the environment of Iraq in terms of air, water and soil. Several studies have been conducted by taking samples from different parts of Iraq. Iraq's environment has been contaminated with radioactive materials and heavy material as a result of wars and their consequences.

In addition, Nuclear Research Center was subjected to looting, sabotage, shelling and destruction in some of its buildings, especially after the 2003 war. The radiological contaminants in Al-Tuwaitha site are Cs-137, Co- 60, Pu-239, U-235, and U 238 (Copland, 2013). As a result of those actions, amounts of radioactive materials include Cs-137 leaked into soil and groundwater.

Most of the buildings of Nuclear Research Center were contaminated by radioactive materials, as in Table (1-1) (Abbas et al., 2010), and there is the possibility of leakage from those buildings to groundwater aquifer. Figure (1-1), and Figure (1-2) show the site of contaminated soil samples by radioactive materials in Al-Tuwaitha region (Al-Taii et al., 2012) and (Zaboon et al., 2013).

Table (1-1) The contaminated buildings of Nuclear Research Center at Al-Tuwaitha site (Abbas et al., 2010)

Building Number	**Facility Name**	**Building Number Potential to Impact Groundwater**
Building 9	Radiochemistry laboratory	High
Building 13	IRT-5000 research reactor	High
Building 22	LAMA U metallurgy	Low
Building 24	Tammuz-1 and Tammuz -2 research reactors	High
Building 35	RWTS	High
Building 36	French radioactive storage silo	Low
Building 40	Russian silos	High
Building 64	Uranium metal production	Low
Building 73	Fabrication lab	High
Building 85	Technology hall uranium preparation	Low
Building 86	Polonium 210 production	Low

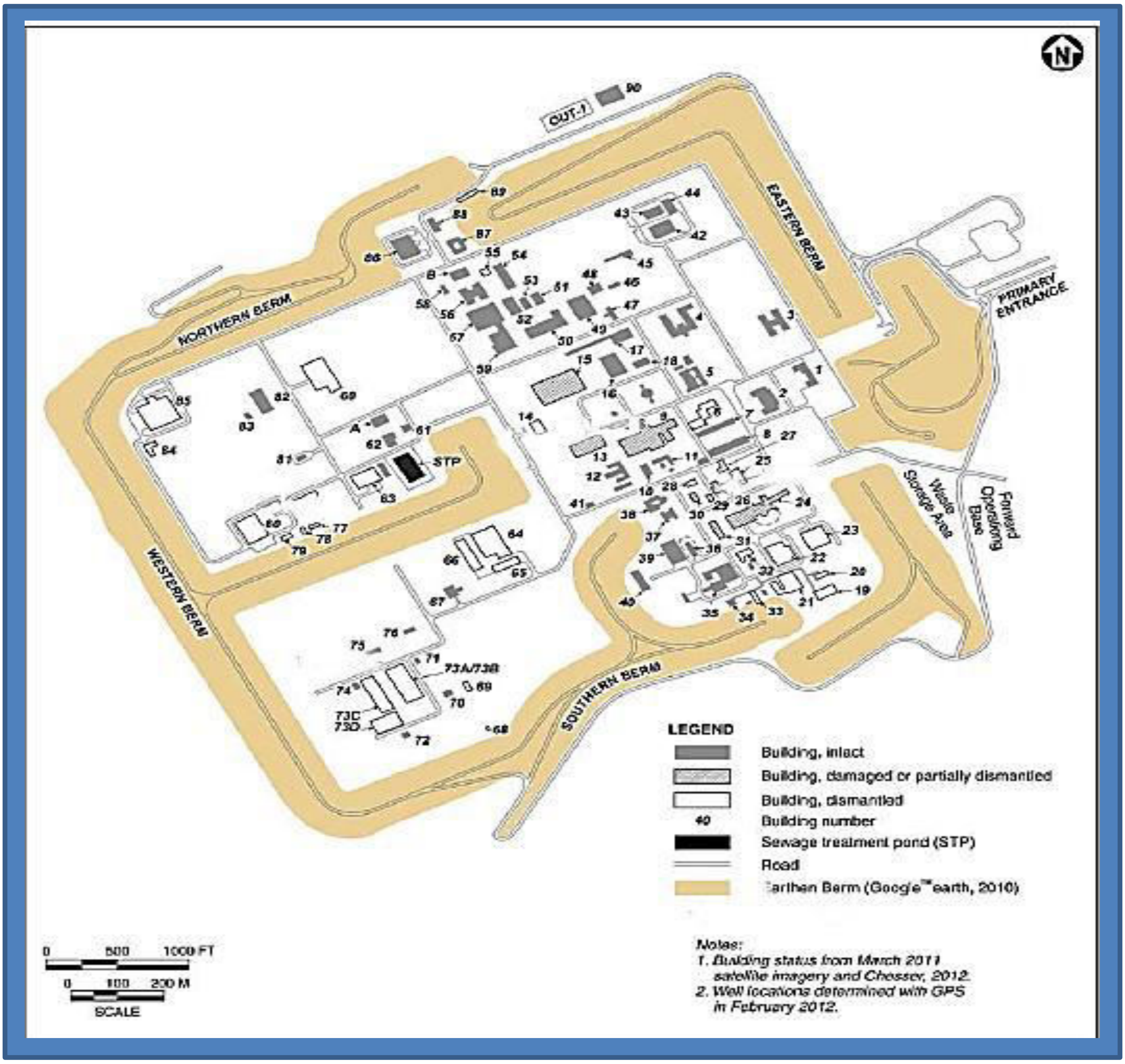

Fig. (1-1) Buildings located at Al-Tuwaitha Nuclear Research Center site (Copland et al., 2013)

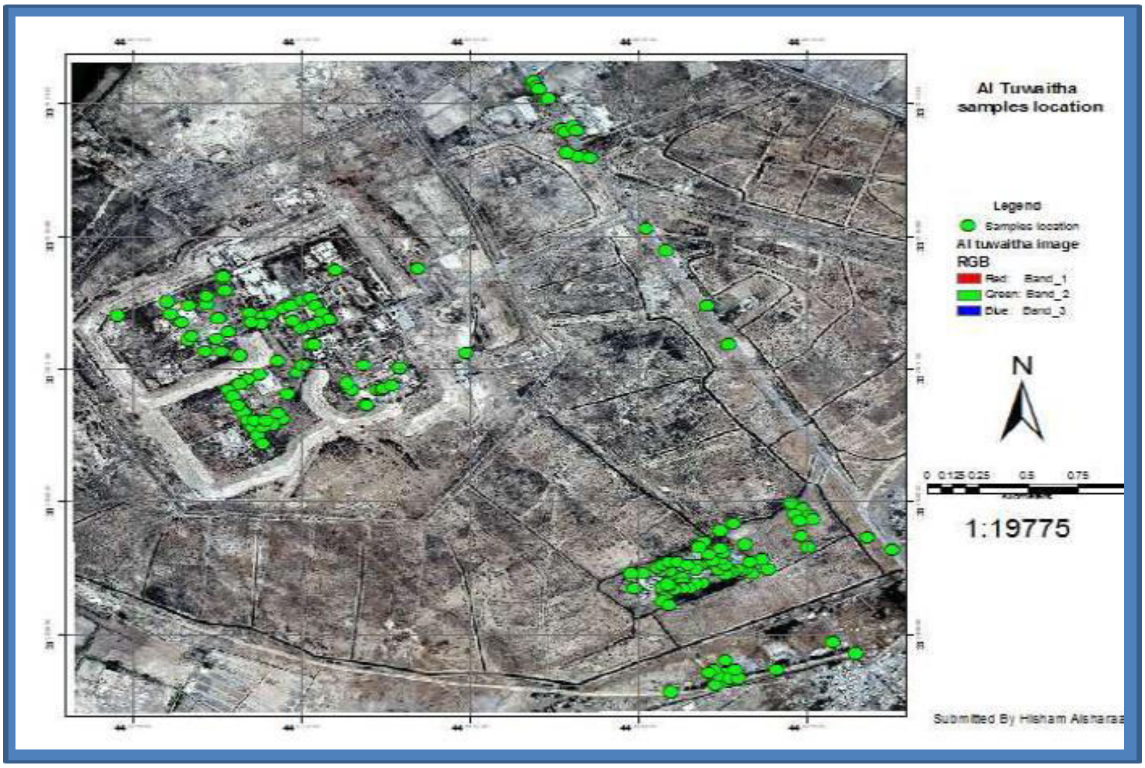

Fig. (1-2) Soil pollution samples locations (Zaboon et al., 2014)

This research investigates groundwater contamination by applying groundwater model to simulate flow and contaminant transport to help future decontaminating or to limiting the migration of contaminates.

1.4 Objectives of the Study

A groundwater model of the aquifer in the study area using Processing MODFLOW Package has been applied in this work to:

1- Estimate the distribution of hydraulic heads for soil layers of the aquifer system.
2- Assess the impact of rising water elevation of the Tigris river on the groundwater level of wells in the study area.
3- Simulate solute with the transport model (MT3D) to evaluate the distribution of (Cs-137) concentrations based on the variation of concentration with time in the aquifer at Al-Tuwaitha (Nuclear Research Center) region.

1.5 Limitations and Assumptions

All numerical groundwater flow models have limitations and assumptions that are usually associated with the quantity and quality of input data.

- The model squared area was 10 km^2, and it included three layers of soil, based on the characteristics of the aquifer system.
- Six observation wells were selected to simulate the groundwater model.
- Steady-state condition was assumed for groundwater flow patterns and contamination transport.
- The vertical hydraulic conductivity was assumed 10% of horizontal hydraulic conductivity (Todd et al., 2005).
- Three values for the water surface elevation of the Tigris river 27.6, 28.7, and 29.8 (m.a.s.l) for the period (2002-2010) were adopted (Ministry of Water Resources Iraq, 2014).
- Specific parameters, such as dispersion, and diffusion coefficients were assumed based on the previous studies because no measurements were conducted in this study.
- The concentration of Cs-137 which was assumed the only source of was 7.06 $\mu g/m^3$(Zaboon et al., 2014).

Chapter Two

Literature Review

CHAPTER TWO

Literature Review

2.1 General

In recent years, the attention to study the groundwater has increased as a result of the urgent need and the growing demand for water, especially when the climatic conditions are changeful. In the dry and semi-dry areas, groundwater is considered one of the most important sources of water. A number of scholars and researchers tried to study the problems of groundwater.

This chapter provides some of the previous studies on groundwater modeling with MODFLOW model, carried out in Iraq and other countries, and groundwater pollution.

2.2 Previous Studies

Several investigations contributed to the development of groundwater modeling are summarized in this chapter. Table (2-1) shows previous studies carried out in Iraq, while Table (2-2) shows previous studies carried out in developed countries.

Table (2-1) Previous works on groundwater model in Iraq

Investigators and Year	Model	Model Description (Approach)	Study Objective	Conclusion
Hasan et al., (2006) / Mosul City, Iraq.	MODFLOW software	The study area covered 528 km^2, which divided into 7380 cells with a cell size of (275m x 275m) to simulate groundwater flow.	Describe and simulate the groundwater movement.	Hydraulic conductivity values were found to range between (4 to 28) m/day. The actual reason behind the increasing in groundwater elevations in Mosul city belongs to the unbalance occurs in the study area through the increasing in the feeding sources to groundwater noted from the simulation process indicated.
Al-Ajaaj, (2007) / Mosul city, Iraq.	Visual MODFLOW V.4.2	Three-dimensional with 89 columns and 72 rows for steady-state, single layer was a semi-confined aquifer.	Develop an application of a groundwater flow model of the aquifer. Evaluate the environmental impacts of the Badush dam on groundwater flow in the surrounding aquifer based on groundwater flow model.	There is a good compatibility between observed piezometric heads and calibrated groundwater heads from the simulation of 10 and 20 years where the dam impacted on the storage of aquifer. During model simulation for long-terms such as 20 years shows that the dam has a negative impact on the foundation of the nearby buildings. The results indicate also that the groundwater flow towards Tigris river before dam construction, but after dam construction, the reservoir becomes a region of net recharge to the aquifer.
Atea et al., (2007) / Basrah, Iraq.	Processing MODFLOW V.5	The numerical mathema -tical model includes 24 rows and 38 columns simulated in an unsteady flow state.	Describe the behavior of groundwater flow at Sandy Dibdiba formation in Safwan region in Basrah city.	The results showed good agreement between measured and calculated elevation values and observed enhancement of water elevation in region wells. They observed that the use of artificial recharge method for rehabilitation of aquifer formation.

Table (2-1) Previous works on groundwater model in Iraq (continued)

Investigators and Year	**Model**	**Model Description**	**Study Objective**	**Conclusion**
Al-Shamma'a et al., (2008) / Al-Razzazah. Iraq.	Mathematical model	Confined / Unconfined aquifer for 3D ground water flow model with 9 columns and 7 rows, was used to develop the model of groundwater.	Explain the behavior of groundwater flow in the upper aquifer and the change in the drawdown.	The groundwater levels will decrease in case the recharge rate stayed without any increase.
Al-Marmuri et al., (2009) / Al-Hawija, Iraq.	Mathematical model (Numerical and Theoretical background)	Apply the theory of superposition at the media, using Darcy's law and Theis Equation for the confined and unconfined aquifers, 3D model with the model domain was 88 rows and 100 columns.	Develop the mathematical model for groundwater motion by applying the theory of superposition at the media, using a theoretical back-ground of Darcy's law and Theis Equation for the confined and unconfined aquifers.	The superposition in heterogeneous hydrogeologyic media revealed a good coincidence between the time and distance-drawdown curves of theoretical (Theis) and numerical solutions for both the confined and unconfined aquifers.
Al-Marmuri, (2010) / Hilla, Iraq.	Mathematical model	A domain of model used 43 rows and 19 columns were simulated unconfined aquifer.	Simulate a groundwater scheme for a specified areas, and describe the important role and features of the main existing hydraulic boundaries.	The maximum allowable groundwater exploitation of the unconfined aquifer is 250 m^3/day which produces 5m drawdown at the centers of the production wells which represent a critical depletion depth.

Table (2-1) Previous works on groundwater model in Iraq (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Al-Aboodi et al., (2010) / Sofwan Al-Zubair, Iraq.	Processing MODFLOW V.5	2D mathematical model contains 24 columns and 74 rows were simulated in steady and unsteady state.	Evaluate, describe and predict groundwater levels.	The results showed that the groundwater levels reduction about 1 m in the central parts of the study area while about 0.5m in the western part. The model appears a good similarity between the simulated and observed heads.
Al-Fatlawi, (2011) / UMM Er-Radhuma, Iraq.	Processing MODFLOW V.7.0.2	Unconfined aquifer, 43 rows, and 43 columns used to simulate transient groundwater flow.	Estimate and predict ground water level.	The model output showed that head loss reaches up to 5.4m which may cause dryness in the upper part of the aquifer in the year 2017 at certain locations, especially, in the west and the northwest side. A good agree between measured and calculated hydraulic heads at the aquifer.
Al-Aboodi et al., (2013) / Missan, Iraq.	MODFLOW program	2D mathematical model was simulated with a domain of 55 columns and 50 rows for the unconfined layer.	Simulate the flow regime of the upper part of quaternary deposits in Al-Teeb area.	A good similarly between observed and calculated head appeared during the calibration process and found a direct relationship between the values of hydraulic conductivity and hydraulic heads. The best value of direct recharge as a percentage from rainfall equal to 10% was remarked.

Table (2-1) Previous works on groundwater model in Iraq (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Ali et al., (2015) / Khanaqin, Iraq.	Processing MODFLOW software (MODFLOW code)	3D groundwater flow model simulated in both steady and transient states, with 13 rows and 17 columns.	Study the groundwater flow system and evaluate the effects of further groundwater exploitation on the groundwater levels.	The calibration process was given a good agreement between the calculated and observed head, where the difference between them varies from (0.1) m to (0.80) m in steady and unsteady state. The model was a sensitive to hydraulic conductivity in steady - state, while in the unsteady-state model was sensitive to the increase and decrease of the specific storage values.
Al-Dabbas et al., (2016) / Salah Din, Iraq.	Processing MODFLOW	Unconfined aquifer of 92 columns and 92 rows was simulated in steady and transient state.	Explain the impact of the climatic change on the groundwater and evaluate rate and direction of movement of groundwater.	The impact of the climatic change on the groundwater was effected the decreasing in the water table in the unconfined aquifer in Samara-Baiji area, where the aquifer was recharged mainly from rain water and received water with a rate less than the rate lost by both evaporation and abstraction wells.

Table (2-2) Previous works on groundwater model in developing countries

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Rao et al., (1999) / Andhra Pradesh India.	Visual MODFLOW software	Two layers were used to simulate steady state flow model (MODFLOW) with 51 rows and 88 columns then linked with mass transport model (MT3D).	Estimate groundwater flow and mass transport, also determine the extent of contaminant migration for last 20 years.	The results that the stream aquifer interaction was responsible for the migration of contaminant. The extent of contaminant migration measured based on TDS concentration and found the contaminant migration extending up to 500-600 m during the last 20 years.
Shamrukh et al., (2001) / Tahta region of the Nile valley aquifer, Egypt.	MODFLOW and MT3D codes for groundwater modeling system (GMS)	Eight layers with 93 rows and 168 columns per each layer were applied as a domain to simulate the 3D ground water flow and contam -inant transport.	Study the effect of the long term of chemical fertilizers on groundwater quality in the aquifer and investigate the contamination of groundwater by nitrogen and phosphorus chemical fertilizers.	The best management practices should be employed to control and reduce the nitrate leaching, the future impact of phosphorus, the potassium fertilizer applications, and the groundwater contamination at deep of 30 m caused by the high rate of chemical fertilizer.
Sokrut, (2001) / Stockholm, Sweden.	ECOFLOW Model = (ECOMAG + MODFLOW +MT3DMS +MODPATH) codes	Aquifer system of unconfined layer system used with (50 m x 50 m) as a model domain to create ECOFLOW model, where Integration the groundwater flow (MODFLOW) and transport (MT3DMS, MODPATH) models with the watershed hydrological model.	Simulate nitrogen concentration in soils and ground water over the whole catchment, and obtain the value of nitrogen concentration in any point of the river network as well.	Integrated ECOFLOW model appeared to be an efficient tool for addressing problems on multiple scales, and problems related to both the groundwater and surface water.

Table (2-2) Previous works on groundwater model in developing countries (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Kim et al., (2002) / Korea.	MODFLOW and MT3D	Aquifer divided to four layers on the basis of geology, with 100 columns and 60 rows in each layer as model domain to build numerical model.	Analyze the leachate flow and pollutant transport around the landfill site and reduce the contamination.	The use radial collector well laterals have low costs, but the efficiency it in pollution reduction is low. As for Installed an interception wall at the circumference of the landfill has high cost and efficient.
Merrick, (2004) / Australia.	MODFLOW and OPTIMAQ software	Developed 3D optimization model with OPTIMAQ linked with MODFLOW software. The model domain contains three layers with 236 rows and 234 columns.	Simulate groundwater flow based on a non-linear programming algorithm. Also to determine the optimal volumes of water, optimal abstraction rates and optimal bore layouts.	The optimal abstraction rates were about 60 percent higher than the natural groundwater flow across each containment line and groundwater discharge will reduce when the pumping at the recommended rate to about 15 percent.
Al-Sibaia, (2005) / Syria.	MODFLOW software	880 cells used to build mathematical model for groundwater flow.	Determine the dangerous areas in terms of high water level and use drainage wells at these areas to lower the ground water level and prevent soil salinity of the lower Euphrates valley basin.	The drainage situation is inadequate and water table continues to rise. They showed that the water table in most of the dangerous area felled to about 1.5 m, and the evaporation volume decreased by 20% and 26.3% respectively.

Table (2-2) Previous works on groundwater model in developing countries (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Nwaneshiudu, (2007) / The U.S. Mexico border.	Visual MODFLOW software	3D numerical ground water flow and transport model were developed by using MODFLOW and MT3D codes which had ten layers with 165 rows and 100 columns a domain of model.	Investigate and characterize the extent of the weakness of the aquifer to potential contamination from land-fills.	The fate and transport model were most sensitive to hydraulic conductivities and flow directions at the sites, and contamination occurred on the U.S. side can effect on groundwater resources on the Mexican side and vice versa, depending on groundwater flow direction, permeability of the geology.
Abu-El-Sha'r et al., (2007) / Azraq, Jordan.	MODFLOW and MT3D	The study model area was divided into 81 columns and 54 rows within aquifer.	Simulate the groundwater flow and solute transport in subsurface systems, and predict the transport of total dissolved solids.	The model was slightly sensitive to the change in horizontal hydraulic conductivity than to the change in recharge values and not sensitive to the specific yield.
Najem, (2008) / Palestine.	MODFLOW and MT3D software	A mathematical model was developed by the model domain of 288 columns and 386 rows with one layer.	Complete development of a mathematical model to simulate the spatial distribution of nitrate in the Eocene aquifer.	The results of MT3D model were given a regression coefficient of 0.97 between the observed and simulated nitrate concentrations. The high influence of decay rate and the mass of nitrate leaching on nitrate concentrations into the aquifer were shown from the result of the model. Also, the cause of pollution from the excessive applications of fertilizers for agriculture and the seepage of untreated wastewater.

Table (2-2) Previous works on groundwater model in developing countries (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Guzha, (2008) / America.	MODFLOW96, TOP MODEL, and TOPNET	Coupled groundwater flow model, and the rainfall runoff model in one state, and coupled MODFLOW with a networked version in another state. Where coupled TOPMODEL to MODFLOW involved development of a routine relating the spatial discretization, while coupled MODFLOW to TOPNET included the development of a feedback scheme where groundwater and surface water interact in the soil zone.	Test the effectiveness of using the couple approach to develop a coupling simulation model that integrates a surface water flow model (TOPMODEL and TOPNET) to (MODFLOW) to simulate flow over large space and time scales in a river basin. Also, assess the influence of groundwater flow dynamics on surface water flow dynamics and vice versa.	The simulation ability of the coupled model is mainly poor as a result of problems in the groundwater model, and it is not able to describe stream flows effectively in the watershed because of the influence of the ground water component of the coupled model. While the simulation obtained using the coupled MODFLOW with TOPNET was fairly good and able to simulate the fluctuation range fairly well.
Saravanan et al., (2010) / Chennai city, India.	MODFLOW and MT3D codes	Three layers are unconfined with 71 rows and 38 columns used as a model domain.	Simulate the groundwater flow and solute concentration and evaluate the current of leachate concentration in ground water.	The pollutant concentration would move towards the southeastern direction from the dumpsite, and the concentrations of the heavy metals in the site within the limits, except chromium.

Table (2-2) Previous works on groundwater model in developing countries (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Rajamanikam et al., (2010) / Amaravathi river Basin of Karur, India.	Visual MODFLOW 2.8.1 version	Two layers within 320 km^2 are divided into 4572 cells with grid size of (350m x200m).	Simulate the groundwater quality for next 15 years under five difference scenarios.	There is no improvement in groundwater quality and the TDS levels are in increasing trend. Also, the visual MODFLOW effective in the study the pollution migration.
Saghravani et al., (2010) / Malaysia.	Visual MODFLOW software combines MT3DMS and MODFLOW	The groundwater flow and contamination simulated as steady and transient state with two layers in aquifer system of 30 rows, and 45 columns.	Study the movement of groundwater and the movement of contamination horizontally and vertically in the aquifer.	The phosphorus concentration in the swamp is the highest, and vertical migration was responsible for the transport of contamination.
Nepal et al., (2011) / Southern India.	Visual MODFLOW software	2D groundwater flow model with single layer was simulated steady and transient conditions. The study area was 75.56 km^2, which divided into series of grid blocks, a grid size of (250 m x 250 m).	Develop a groundwater flow model for a tannery belt to analyze groundwater velocity and assess the aquifer response under different input and output stresses.	The model was sensitive to recharge and specific yield and the groundwater flows toward northwest in the southern part and north and northeast in the northern part.
Andrea et al., (2011) / Sicily, Italy.	Numerical codes (MODFLOW-2000, MT3DMS)	The model area is almost 39 km^2, using a rectangular mesh of (55m × 45m) cells, and total of 263000 nodes, in 16 layers.	Simulate the flow and the head of the aquifer, and find the risk of pollution in the deep carbon.	A strong vertical spreading of the contamination plume, due to the influence of the high conductivity fractured zones.

Table (2-2) Previous works on groundwater model in developing countries (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Ahmad et al., (2012) / Sindh, Pakistan.	Processing MODFLOW (PMWIN) software	3D finite-difference groundwater model MODFLOW and a solute transport model (MT3D) which consists of 3 layers. Each layer includes 41 columns and 39 rows.	Estimate the fate of jet fuel that leak from the above surface storage tanks in the urban site.	The jet fuel plume neither expanded nor moved considerably, and the level of concentration found in the simulated monitoring wells is significant because groundwater is brackish and thus unlikely to be used. No harmful effects are expected.
Ghoraba et al., (2013) / Delta, Egypt.	MODFLOW and MT3DMS	Aquifer system was divided into seven layers and used 75 rows and 88 columns as a model domain.	Investigate and study groundwater quality in the central part of the Nile Delta and solve the problem of contaminants transport with time.	The deterioration of groundwater and ammonium concentrations reached an alarming level.
Cox, (2013) / Gallatin County, Illinois, United States.	MODFLOW and MT3DMS	3D numerical model with the model domain, two layers, 652 rows, and 405 column.	Explain the hydrologic conditions and predict the extent of contamination in the aquifer.	Subsurface movement and surface discharge from the mine have been responsible for the deterioration of water quality in the surrounding area, including the aquifer.
Kori et al., (2013) / Sindh, Pakistan.	MODFLOW and MT3D	Two models were applied, where the first model was 30 columns and 57 rows while the second model was 35 columns and 35 rows.	Evaluate the effectiveness in stabilizing the interface in response to the dual pumping, and determine the optimum strategies of groundwater pumping regime under scavenger tube wells.	The scavenger well is a useful tool to manage agriculture drainage and to supplement irrigation without generating saline water. It found to control saline water and fresh water interface. The scavenger well must operate with the operational factor of 0.55 for the first model and 0.5 for the second model.

Table (2-2) Previous works on groundwater model in developing countries (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Ehtesham et al., (2014) / Iran.	MODFLOW and MT3DMS codes of Processing MODFLOW software	3D was used for single unconfined layer with 37 rows and 45 columns.	Simulate the flow and contamination transport in Mashhad aquifer.	The average amount of nitrate in observation wells was appeared increasing every year and the increment is about 3 mg/l. Also that the model was able to predict the groundwater quality changes within the aquifer.
Beilicci et al., (2014) / Gorj County, Romania.	Processing MODFLOW	Groundwater flow and solute transport modeling were developed to simulate unconfined aquifer under landfill with a model domain that contains 100 columns and 100 rows.	Model groundwater flow and transport processes to determine the extent pollution area of aquifers with time.	The concentrations of pollution were evaluated with time for all points of polluted zones.
Edet et al., (2014) / Niger Delta, Nigeria.	MODFLOW software	Single-layer two-dimensional mathematical model of the aquifer with 207 columns and 252 rows.	Determine the amount of water in the aquifer in Akwa Ibom State, and the recharge rate of the area. Assess the groundwater resources.	The groundwater levels were acceptable and the recharge amounts in aquifer of 235722.26 m^3/d. The inflow of the aquifer system came from infiltration from the rivers. This model used as a basis for groundwater management and simulation of transient groundwater flow.
Surinaidu et al., (2014) / Andhra Pradesh, India.	MODFLOW 2005	58 columns and 68 rows used a model domain.	Estimate the groundwater inflows into mine pits by using numerical ground - water model under steady-state condition.	The model was highly sensitive to hydraulic conductivity and recharge. The direction of groundwater flow was toward mine pits from the aquifer and general groundwater flow direction towards the Godavari river from groundwater aquifer.

Table (2-2) Previous works on groundwater model in developing countries (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Patil et al., (2014) / Mumbai, India.	MODFLOW and MT3DMS packages within Processing MODFLOW software	Confined aquifer with 25 rows and 25 columns to developed three-dimensional numerical model.	Estimate the potential impacts of contaminated ground water on nearby wells and help in selection and design the remedial actions to control, or remove and treat contaminated ground water.	The observed hydraulic head was nearly matching with simulated head and the chloride concentration increasing with time. The groundwater contamination caused by septic tank effluent.
Cobbing, (2014) / Marikina, South Africa.	MODFLOW and MT3D	Two-layer, steady-state numerical groundwater model simulated with the model domain of (200m x 100m) grid block uniform mesh.	Estimate the spreading of potential contaminants within the groundwater system based on a worst case, groundwater inflow rates into the different open pits and the extent of the lowered groundwater levels surrounding the open pits.	The correlation between observed and modeled heads was Y=0.8266X+207.64, and R^2= 0.828. The groundwater flow from the surrounding upper weathered and underlay fractured aquifers to the open pits due to the head differences between the ambient groundwater levels and the pit depth.
Hassan et al., (2015) / South Western Desert, Egypt.	Visual MODFLOW	Four layers with 100 rows and 100 columns as model domain used to create a groundwater flow model by MODFLOW code. Then the non-reactive transport model MT3DMS applied.	Evaluate and manage the groundwater aquifer in Nubian Sandstone aquifer, and simulate the ground water heads and quality changes for next 10, 25 or 50 years.	The groundwater table started to decline. TDS increased throughout ten years but after 25 years would not be changed and became constant.

Table (2-2) Previous works on groundwater model in developing countries (continued)

Investigators and Year	Model	Model Description	Study Objective	Conclusion
Tziatzios et al., (2015) / Greece.	Surface hydrology model (UTHBAL), MODFLOW, and MT3DMS	Surface hydrology model first used and coupled with MODFLOW to simulate groundwater flow that integrated with MT3DMS to simulate the nitrate contamination. Single layer unconfined aquifer used with 12500 rectangular grids.	Simulate groundwater flow and nitrate contamination.	The most contaminated areas are located in the south and east part of Karla aquifer's area.
Rashid et al., (2015) / Arkansas, United States.	MODFLOW program	Unconfined layer used with 294 rows and 147 columns.	Simulate the part of the Mississippi river Valley alluvial aquifer in the Cache, and determine the change in head and the maximum optimal pumping of the irrigation wells.	The number of constraints has no significant effect on the optimal results, and the number of shutdown wells increased by 14-188 % in the case of the maximum pumping constraint specified as 200 % of the pumping rate.

2.3 Radioactive Pollution

Radioactive pollution is one of the most serious types of pollution because it threatens the lives of living organisms directly. The scientist Henry 1896 defines the radioactivity as the disintegration of the nucleus of material with lower values known as radioisotope. Radioactive contamination occurs either naturally or artificially. The natural source is cosmic or earth. The industrial sources occurred as a result of nuclear explosions, the leakage of nuclear reactors from scientific research centers and medical and power stations, or as a result of the burial of nuclear waste in the underground (Pepper et al., 2011).

The radiation emitted from radioactive materials are alpha, beta, and gamma. The danger of radioactive materials is not limited to leakage only, but continues to influence the future generations, for difficulty of disintegration in nature, where numerous of radioactive materials need hundreds of years to cancel the influence. Radioactive contaminants spread easily in air, soil and water. It reaches the lungs through respiration, then into the cells and tissues of the body as well as through the skin due to crack or wound. The most cases of radioactive pollution damage is the damage of the genetic material (DNA), causing mutations leading to the formation of cancerous malignant cells, disrupting the genetic code carried by molecules (DNA) and leading to disturbances in genetic traits that appear in birth defects and certain diseases. It happened in the dropping of nukes on Hiroshima and Nagasaki in Japan 53 years ago during World War II in 1945, and the Chernobyl nuclear reactor accident in the Soviet Union in 1986 (Assaf et al., 2007).

The environment of Iraq was exposed to radioactive uranium pollution as a result of wars, particularly the 2003 war. Nuclear Research Center at Al-Tuwaitha was exposed to a bombing, looting and vandalism later, leading to the leakage of radioactive materials. Containers carrying signs of radioactivity, and a number of radioactive traces were found in farms, villages and the houses surrounding areas at Al-Tuwaitha, south of Baghdad (Rasheed, 2013).

Al-Waeli et al., (2013), explained that Iraq's environment was exposed to the radioactive contamination, and central and south regions are more polluted than other areas of Iraq. The concentration of uranium in Al-Tuwaitha area evaluated about 3.45 ppm.

Al-Obaidy et al., (2013), estimated the radiological risk which resulted from destruction of nuclear reactor in Al-Tuwaitha area, Iraq. They found that the concentration levels of U series, Sr-90, Cs-137, and Co-60 were higher than the environmental levels through analyzed collection of soil samples.

Zapoon et al., (2013), defined the radioactive pollution in Al-Tuwaitha, Iraq, by using GIS techniques. The radiation level was higher compared with nuclear association 2011, and the maximum level was in the Russian 5MW reactor. They found the absorbed rate level was higher than the environment levels by 9500 times.

2.3.1 Cesium 137

Cs-137 is a radioisotope and chemically unstable which is created as one of the popular fission outputs by the nuclear fission of U-235 and other fissionable isotopes in nuclear reactors, nuclear weapons and product of the nuclear fission of much heavier elements (Okumura, 2011); as in the Goiânia accident of 1987 (Oberhofer et al, 1988); the Acerinox accident of 1998 (LaForge, 1999); and in 2003, in Iraq. Cs-137 has a half-life of about 30.17 years (Unterweger et al, 1992), and isotope mass is 136.907 g, where one gram of Cs-137 has an activity of 3.215 Terra Becquerel. Principle rays emissions of Cs-137 are Beta, Gamma (g) / X-Rays, Alpha (a), and Neutron (n).

Cs is a soft, shiny, gold-colored metal. It reacts with oxygen, bound with chlorides to form a powder and liquefies at room temperature. Its melting point is 28.4°C and boiling point is 678.5°C (Pais and Jones, 1997).

Cs-137 is used in practical applications to calibrate medical radiation detection equipment and radiate treatment devices for curing cancer. It is also used in industrial mensuration device (Okumura, 2011).

It causes observable effects on health on a long-term, including increased cancer risk depending on the route, magnitude and duration of exposure. It considers one of the contaminants of main worries due to their ease of entry into biological systems. The exposure to amounts of Cs-137 can lead acute radiation sickness and cancer (LaForge, 1999). Cs-137 is an isotope that attracts the attention of many researchers and scholars all over the world due to its chemical nature. Some of these studies are related to the transport of Cs in soils and groundwater.

Lee et al., (1990), studied the migration characteristics of Cs-137 in the packed column and compared the results with two mathematical models, the bulk reaction model and mass transfer model. The results obtained from the comparison showed that the mass transfer model with the assumption of intraparticle diffusion simulated the migration behavior of Cs-137 more adequately. They found that hydrodynamic dispersion coefficient was 0.0011 cm^2/g and distribution coefficient was 11.3 cc/g.

Mason et al., (1999), studied transporting Cs-137 and Sr-90 in Los Alamos, New Mexico, DP Canyon Los mousses city which is subjected to contamination by radioactive which released from the Plutonium

Processing Facility. They found that the radioactivity associated with Cs-137 decreased linearly if soils particle size increased, and distribution coefficient of Cs-137 is greater than Sr-90 coefficient. It showed that Cs-137 and Sr-90 originating from the same source, will distribute with different transport mechanisms.

Bucur et al., (2000), estimated the parameters that control migration of radionuclides (Cs-137) in geological medium and groundwater. It was found that the diffusion coefficient for Cs-137 in clay soil was greater than loess soils about 9.89×10^{-9} cm^2/s, and distribution coefficient was 120 ml/g. This is because the clay content affects the absorption of the radioactive material.

Dmitri, (2014), assessed groundwater contamination with radioactive materials, including Cs-137 as a result of Chernobyl accident. It was found that a high concentration of Cs as a result of the leak, and showed that the movement of Cs in soil and groundwater was slowly and absorption coefficient of 100-700 *L/kg*.

Zaboon et al., (2014), evaluated Cs-137 concentration levels in Al-Tuwaitha Nuclear site by using GIS technique. They showed that distribution of Cs-137 concentration in soil samples was variable and higher than normal environmental concentration levels about 77 Bq/g.

Shihab, (2014), investigated and assessed the transport Cs-137 in loam clay soils leached with the convection-dispersion model. It was found that the distribution coefficient for Cs-137 was 20 to 295 ml/g and retardation factor was 821 and 118, while the dispersion coefficient was 2 and 2.8.

2.4 Summary

Most of the local studies that were carried out by using groundwater models (MODFLOW) related to study the properties of hydraulic and environmental impacts on the water level of the aquifer. Also, MODFLOW model was used to determine the sources feeding for the aquifer and the importance of artificial feeding in improving the formation of the aquifer. Some researchers found a direct relationship between hydraulic conductivity and hydraulic head of the aquifer, as in Table (2-1).

As for the problems of contaminant migration within the aquifer by using transport model (MT3D or MT3DMS), most studies were conducted outside the country, as in Table(2-2). Transport models showed that the contact between surface water and groundwater are responsible for contaminant migration. The change of hydraulic conductivity for the aquifer effects on the contaminant transport in addition to the effect of the velocity and direction of groundwater flow. As it was proved by groundwater models, the use of the effective pumping wells reduces pollution in groundwater over time.

Available information about pollution migration problems in groundwater are rather limited in Iraq, especially for Al-Tuwaitha area. In this study, we chose Nuclear Research Center at Al-Tuwaitha area as a case study to identify the hydraulic properties and flow pattern of groundwater. In addition to study and estimate the Cs-137 contaminant migration within the aquifer.

As a conclusion, groundwater models are considered important tool in addressing problems of contaminated groundwater and finding effective ways to treat pollution or decrease its level with the lowest cost and time.

Chapter Three
Groundwater Flow and Transport Modeling

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Groundwater Flow and Transport Modeling

3.1 General

Any model is a theory, law and hypothesis or perfect construction, which gives a simple explanation of a complex system and better understanding of the processes that occur in this system. It may represent a simplified state of the real-world system, which nearly simulates the excitation response relations for that system (Bear and Verruijt, 1987).

Groundwater models have represented an approximation of a subsurface water system (Kumar, 2015). It is considered one of the successful tools to solve many problems related to groundwater flow and contaminants (Mercer and Faust, 1980).

3.2 Types of Groundwater Modeling

Models of groundwater are classified into eight main groups according to Spitz and Moreno (Spitz and Moreno, 1996):-

1-Analytical Models

In general, this type is more effective than the other types, and is widely used for applications of two-dimensional issues of steady-state flow in the homogeneous medium and by using the Laplace's equation. It is used to solve many of flow equations by using differential equations. The solution is carried out by complex mathematical analysis.

2- Porous Media Models

It depends on hydraulic properties that are used in the laboratory. The study area is represented through the model by a special scale that has the same physical features and materials in the area to be studied. It is used as a method to clarify for students (Peterson et al., 1978).

3- Hele Show Model (Viscous Fluid Models)

The model is used to monitor the fluid viscous movement, using the laws of physics. The permeability and storage can be determined by the model.

4- Membranc Models

These models are used by engineers in the laboratories before the existence of the computer. It consists of mechanical machines and a tool for measuring the shape accuracy rate by using special equations to describe the steady state flow in the homogeneous medium for groundwater.

5- Electrical Analog Models

They are based on symmetry between electric flow and groundwater flow. It has a voltage opposite to the change in the head to the groundwater system. They were used before the use of mathematical models (Gupta, 1979).

6- Empirical Models

They are also called (lumped parameter models) and based on the use of physical and chemical laws. They are divided into two types. The first explains the processes or the independent technologies which includes a description of Darcy's law and other statues. The second explains the input of groundwater matter, which involves the implementation of a physics laws series (Kresic, 2006).

7- Mass Balance Models

They are called (black-box models) and (single-cell models). These models depend on the amount of estimated increasing or decreasing in the level of water from the underground water system during the period within a typical specification. These types of models are simpler than mathematical models of groundwater which are used to determine the average of concentration.

8- Numerical Models

These models rely on dividing the study area into a number of cells and uses the computer in solving the flow of groundwater equations. These models have the ability to solve simple and complex issues with all types of the border (boundary type). They are divided into finite difference models and finite element models. This study is based on a numerical model with finite difference approach.

3.3 Model Development

Generally, the process of models follows 9 steps (Bear et al., 1992). Figure (3-1) presents a typical model application process.

1- Find the aim of the model.

It is essential identified the aim of the modeling at the onset in order to avoid the problems related with time, and process other steps with small effort.

2- Develop a conceptual model.

A conceptual model is a representation of the groundwater flow system and simplifying the field problem and organize the associated field data so that the system can be analyzed more readily. The nature of the conceptual model will determine the dimensions of the numerical model and the design of the grid.

3- Choose the governing equations and computer code.

The code is the computer program that contains an algorithm to solve the mathematical model numerically. Both the governing equation and the code should be verified. Verification of the governing equation demonstrates that it accurately describes the physical processes occurring in porous media. Verification of the code ensures that the computer program accurately solves the equations that constitute the mathematical model.

4- Model design-by generating a grid and entering preliminary hydrologic parameters necessary for the input files.

5- Calibration-by adequate simulation of field measurements such as head and contaminant concentrations in the study area.

6- Find the effect of uncertainty in the calibrated model.

7- Model verification.

The purpose of model verification is to establish greater confidence in the model by using the set of calibrated parameter values and stresses to reproduce a second set of field data.

8- Prediction to evaluate the reply of the system to future events.

9- Showing the modeling design and results.

Clear presentation of model design and results is essential for effective communication of the modeling effort.

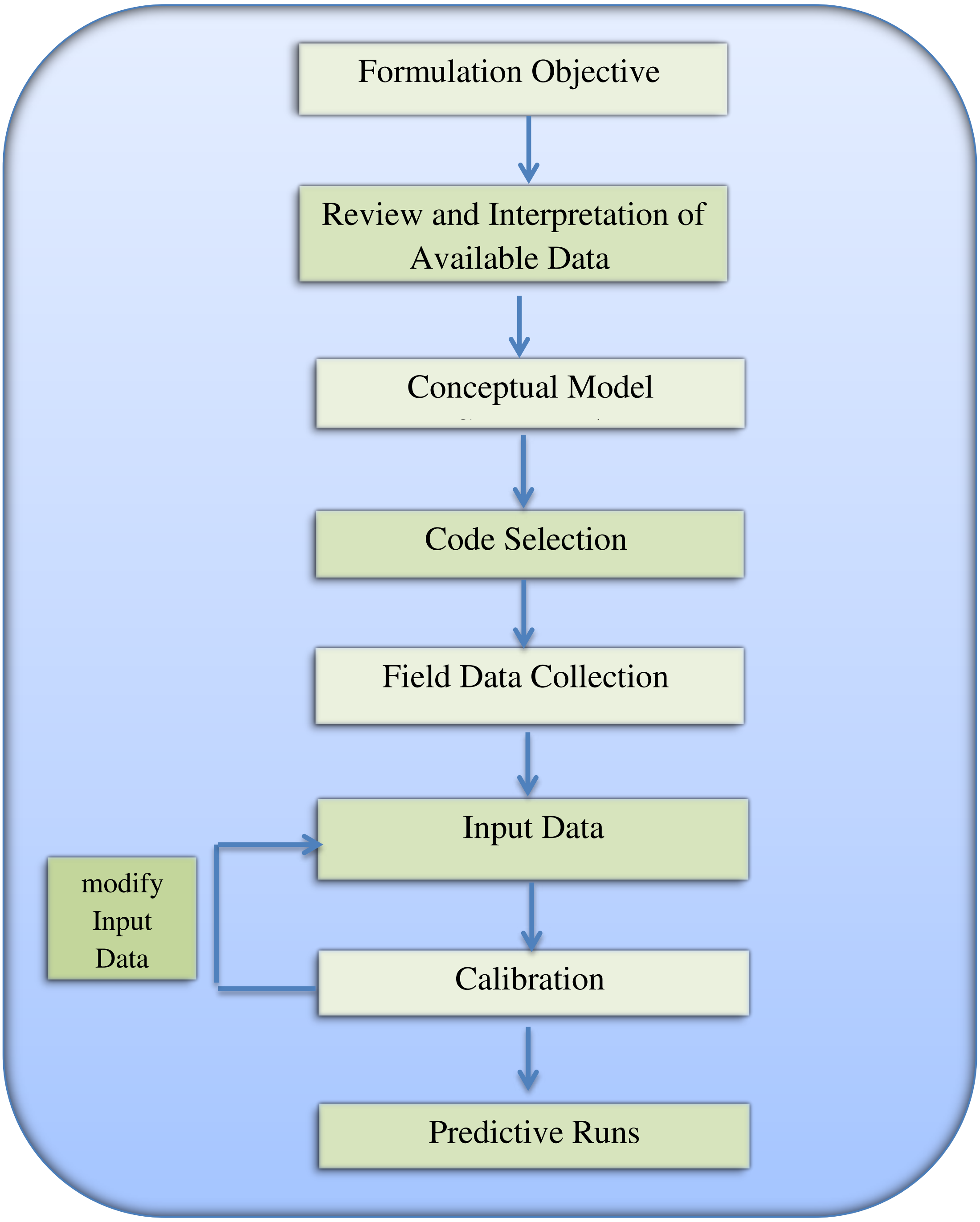


Fig. (3-1) The modifying of model process(Bear et al., 1992)

3.4 Mathematical Foundations

Water movement and contamination migration through surface water and groundwater are predicted by computer modeling and simulation. Monitoring of groundwater and tracking of water movement and contaminant are complex processes. Therefore, the simulation of groundwater is important. The modeling and simulation are completed by mathematical equations based on the simplifying assumption (Kumar, 2002).

The equations that represent the processes of groundwater flow and transport can be solved by using several types of models. Mathematical models can be solved analytically or numerically (Anderson and Woessner, 2002). Analytical models give accurate solutions to equations that represent the very simple flow or transport conditions, while numerical models give approximate solutions (Rajamanickam and Nagan, 2010).

3.4.1 Governing Flow Equations

The process of groundwater flow is based on Darcy's law and the conservation of mass (Rushton, 2004). The conservation mass law states that all water going into the system should equal the water leaving the same system. Inflow through cell face $x\ z$ is equal to $(q_y)\ in$ as in Figure (3-2), and outflow is equal to (q_y)out. The varying in flow rate toward the y axis is:

$$\frac{\partial q_y}{\partial y}(\Delta x \Delta y \Delta z)$$

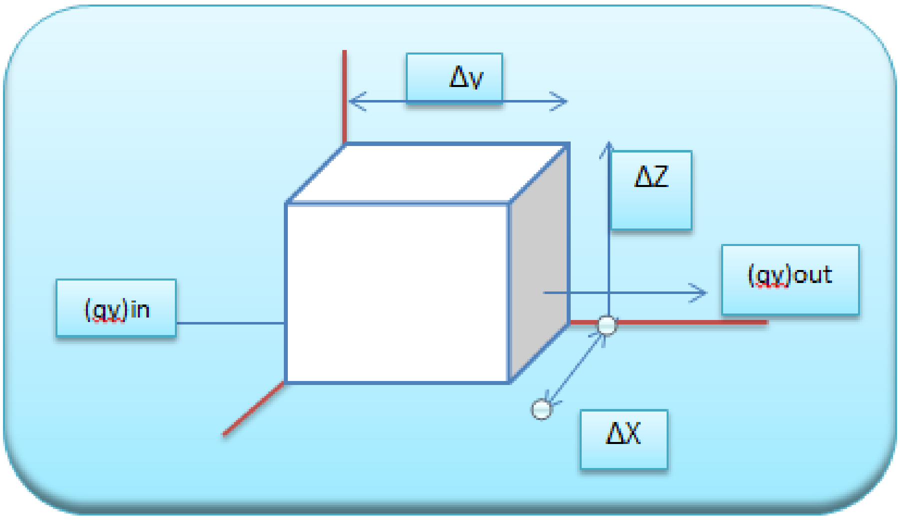


Fig. (3-2) Elemental volume

In terms of flow rates along the x, y and z-axes, the varying in storage is the same varying in flow rate.

$$(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z})\Delta x \Delta y \Delta z = \text{change in storage} \tag{3-1}$$

Where :-

❖ $\frac{\partial q}{\partial}(x, y, z)$ are values of varying in-flow rate toward x, y, z axises.

By adding the term W, the equation became:

$$(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} - W)\Delta x \Delta y \Delta z = \text{change in storage} \tag{3-2}$$

Where :-

❖ W is the flux of volumetric per unit volume describing sources / sinks of water (T^{-1}).

A change in storage is defined by the term specific yield, Ss, and the specific yield is $S_S = -\frac{\Delta V}{\Delta h \Delta x \Delta y \Delta z}$ (3-3)

The volume changes with time

$$\frac{\Delta V}{\Delta t} = -S_S \frac{\Delta h}{\Delta t} \Delta x \Delta y \Delta z \qquad (3\text{-}4)$$

From Equation (3-4) sub in Equation(3- 2)

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = -S_S \frac{\partial h}{\partial t} + W \qquad (3\text{-}5)$$

From Darcy law (Todd and Mays, 2005):

$$q_x = -k_x \frac{\partial h}{\partial x}, \qquad q_y = -k_y \frac{\partial h}{\partial y}, \qquad q_z = -k_z \frac{\partial h}{\partial z}$$

Where: -

- $q(x, y, z)$ is Darcy speed (*L/T*) along x, y, z axises,
- k is the value of hydraulic conductivity (L/T), and
- h is the hydraulic head (L).

Sub in Equation (3-5)

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = S_S \frac{\partial h}{\partial t} - W \qquad (3\text{-}6)$$

Where:-

- S_S is a specific storage of the porous material (L^{-1}),
- t is the time (T).

No change in storage, and for isotropic and homogeneous soils, Equation (3-6) became:-

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad (3\text{-}7)$$

Assuming that all of the aquifers are confined (the saturated thickness does not change with time).

In unconfined aquifers, *h* (saturated thickness) changed the Equation (3-7) converts to Equation (3- 8).

$$\frac{\partial}{\partial x}\left(k_x h \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y h \frac{\partial h}{\partial y}\right) = S_S \frac{\partial h}{\partial t} - W \qquad (3\text{-}8)$$

Where:-

- $T = K * h$; is the transmissivity (L^2/T), sub in Equation (3-8):

$$\frac{\partial}{\partial x}\left(Tx \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Ty \frac{\partial h}{\partial y}\right) = S_S \frac{\partial h}{\partial t} - W \qquad (3\text{-}9)$$

3.4.1.1 Solutions to the Governing Flow Equations

The equations that govern groundwater systems can solve analytically or numerically (Anderson and Woessner, 2002).

Analytical methods give exact solutions by solving the differential equations using the classical mathematical approaches by simplifying assumptions, such as assumptions of homogeneity. Numerical methods include more complexities of the actual field situations and by the availability of computer made solving the numerical models easier compared with analytical methods (Todd and Mays, 2005). The numerical methods are used in this study.

3.4.1.2 Numerical Method

It is a powerful tool to solve the groundwater problems. The partial differential equations are approximated numerically by a computer to generate a set of algebraic equations, which are then solved to reach a solution (Rushton, 2004). There are five methods in numerical solution are applied in groundwater modeling (Batu, 2005): "the integrated finite differences (Narasimhan and Witherspoon, 1976), the finite differences, and the finite elements (Wang and Anderson, 1995), the analytic elements (Strack and Moreno, 1996), and the boundary integral equation method (Liggett, 1987)".

3.4.1.3 Discretization Convention

The aquifer system in the block centered is replaced by a discretized domain that includes an array of nodes and linked cells. Figure (3-3) explains the spatial discretization of an aquifer system with cells, by describing rows, columns, and layers. The hypothetical system is discretized into seven rows, ten columns, and four layers. An i, j, k indexing system is used to refer the cells (McDonald and Harbaugh, 1988).

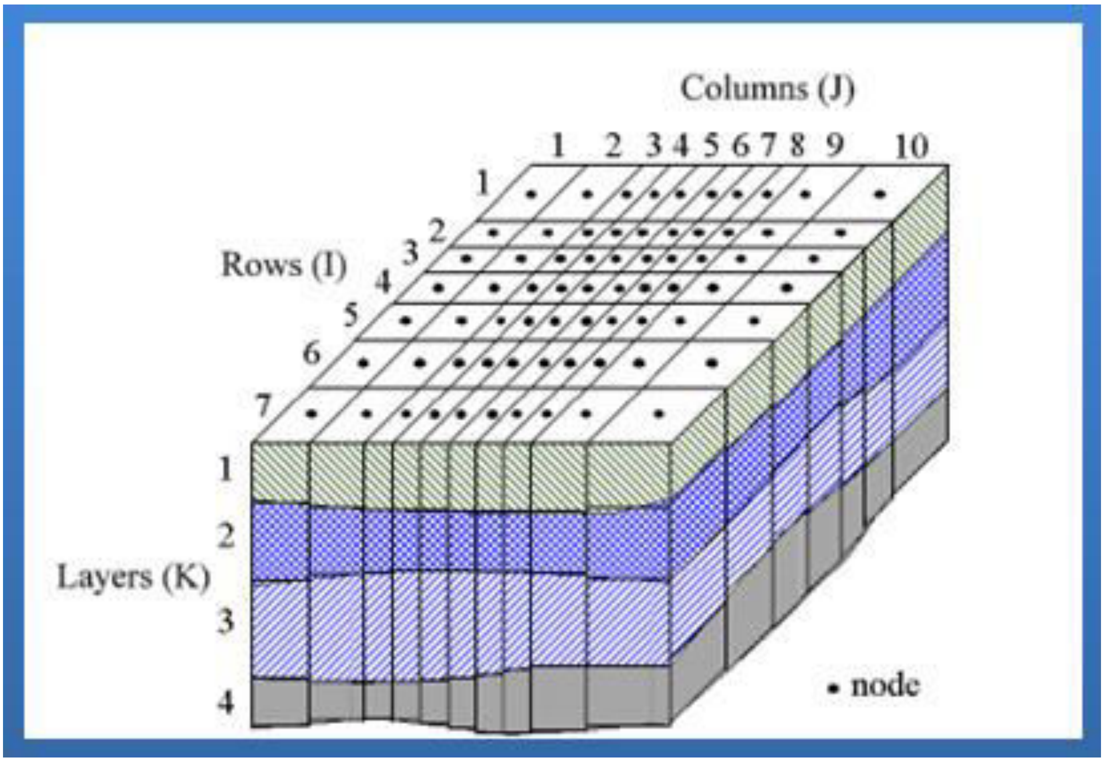


Fig. (3–3) Discretized hypothetical aquifer system

3.4.1.4 Finite Difference Method

The equation of groundwater flow is developed by using the continuity equation in finite difference method, the continuity equation representing the balance of flow for a cell (Kresic, 2006) is:

$$\sum Q_i = SS\frac{\Delta h}{\Delta t}\Delta V \qquad (3\text{-}10)$$

Where :-

- Qi is the flow rate for the cell (L^3T^{-1}),
- SS is the water volume which can be syringed per unit volume of aquifer material per unit change in head (L^{-1}),
- ΔV is the cell volume (L^3).

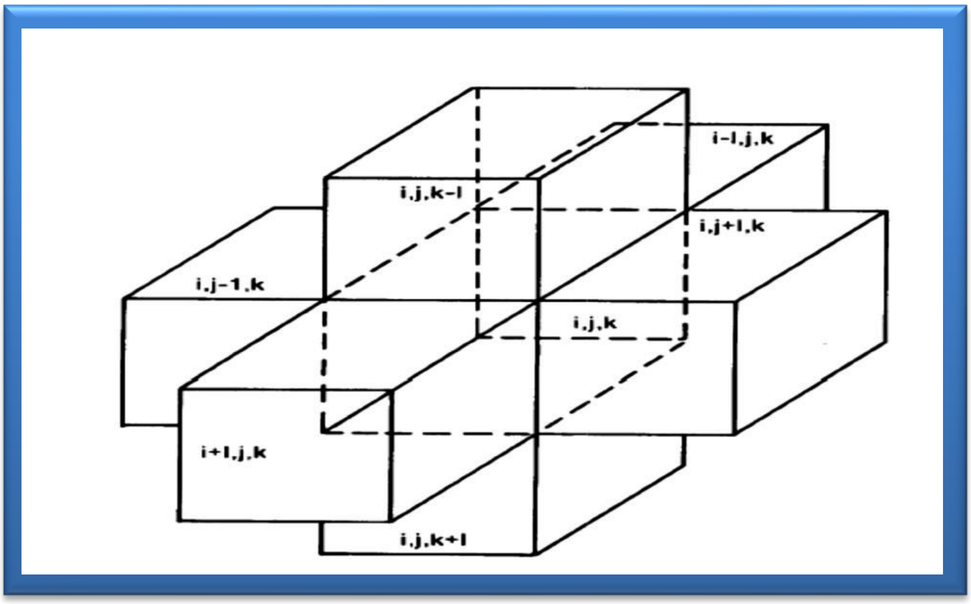


Fig. (3-4) Indices for the six cells surrounding cell i,j,k (McDonald and Harbaugh, 1988)

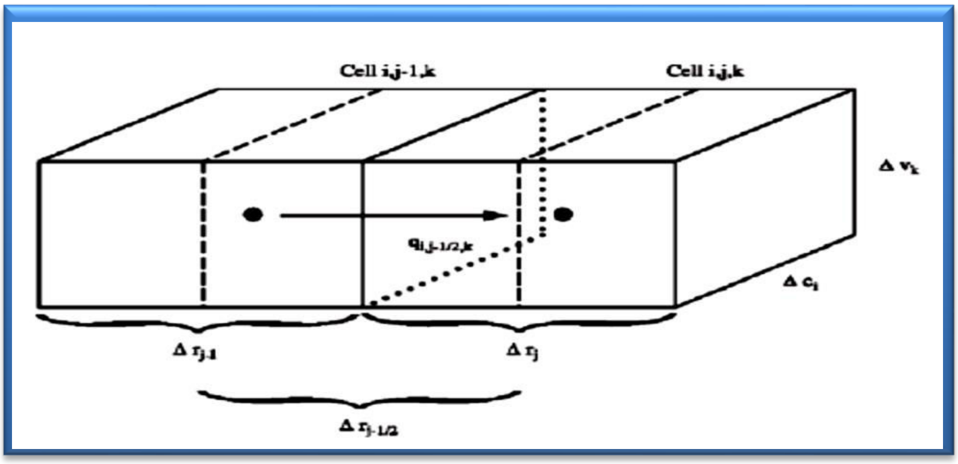


Fig. (3–5) Flow into cell i, j, k from cell $i, j-1, k$

McDonald and Harbaugh, 1988)

The flow into cell i, j, k in the row direction from cell $i, j-1, k$, Figure (3-5), is given by Darcy's law as:

$$q_{i,j-1/2,k} = KR_{i,j-1/2,k}\Delta c_i \Delta v_k \frac{(h_{i,j-1,k} - h_{i,j,k})}{\Delta r_{j-1/2}} \qquad (3\text{-}11)$$

Where:-

- $h_{i,j,k}$ and $h_{i,j-1,k}$ are the head at node i,j,k and $i,j-1,k$, respectively,
- $q_{i,j-1/2,k}$ is the rate of volumetric flow at the face between cells i,j,k and $i,j-1,k$ (L^3T^{-1}),
- $KR_{i,j-1/2,k}$ is the hydraulic conductivity along the row at the nodes i,j,k and $i,j-1,k$ (LT^{-1}),
- $\Delta ci \Delta vk$ is the area of the cell,
- $\Delta r_{j-1/2}$ is the space between nodes i,j,k and $i,j-1,k$ (L).

Since :

$$CR_{i,j-1/2,k} = \frac{kR_{i,j-\frac{1}{2},k}\Delta c_i \Delta v_k}{\Delta r_{j-1/2}} \qquad (3\text{-}12)$$

The out of flow term for the cell i,j,k is:

$$\sum_{n=1}^{N} a_{i,j,k,n} = P_{i,j,k}h_{i,j,k} + Q_{i,j,k} \qquad (3\text{-}13)$$

Where:-

- $a_{i,j,k,n}$ is the flow from any external source into the cell i,j,k (L^3T^{-1}),
- $P_{i,j,k}$ and $Q_{i,j,k}$ are constants.

By applying Equation (3-10) for the cell *i, j, k*, that taking the flows from the six cells, change in storage, and the out of flow rate, The equation became :

$$q_{i,j-1/2,k} + q_{i,j+1/2,k} + q_{i-1/2,j,k} + q_{i+1/2,j,k} + q_{i,j,k-1/2} + q_{i,j,k+1/2} + P_{i,j,k}h_{i,j,k} + Q_{i,j,k} = SS_{i,j,k}(\Delta r_j \Delta c_i \Delta v_k)\frac{\Delta h_{i,j,k}}{\Delta t} \qquad (3\text{-}14)$$

Equation (3-14) is converted to the finite-difference for cell i,j,k as

$$CR_{i,j-1/2\,,k}\left(h_{i,j-1,k}-h_{i,j,k}\right)+CR_{i,j+1/2,k}\left(h_{i,j+1,k}-h_{i,j,k}\right)+ CC_{i-1/2,j,k}\left(h_{i-1,j,k}-h_{i,j,k}\right)+CC_{i+1/2,j,k}\left(h_{i+1,j,k}-h_{i,j,k}\right)+ CV_{i,j,k-1/2}\left(h_{i,j,k-1}-h_{i,j,k}\right)+CV_{i,j,k-1/2}\left(h_{i,j,k+1}-h_{i,j,k}\right)+P_{i,j,k}h_{i,j,k}+ Q_{i,j,k}=SS_{i,j,k}(\Delta r_j\Delta c_i\Delta v_k)\frac{\Delta h_{i,j,k}}{\Delta t} \qquad (3\text{-}15)$$

The storage term at the right-hand side of Equation (3-15), is set to zero for steady-state (Harbaugh, 2005).

3.4.2 Govern Equation of Contaminant

The equation that representing transport of contaminants in groundwater (Javandel, 1984) is:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(V_iC)+\frac{q_x}{n}C_s+\sum_{k-1}^{N}R_c \qquad (3\text{-}16)$$

Where:-

- C is the contaminant concentration in groundwater,
- t is the time (t),
- V_i is the seepage velocity,
- q_x is the volumetric water flux per unit volume of the aquifer,
- C_s is the sources or sinks concentration,
- D_{ij} is the coefficient of hydrodynamic dispersion,
- n is the porous medium porosity,
- R_c is the term of chemical reaction.

3.4.2.1 Contaminant Transport Governing Processes

The processes that govern the transport of contaminants in groundwater are dispersion, advection and retardation. The dispersion and density/

viscosity factors can increase the contaminant movement while retardation factor can decrease the rate of movement (Ahmad et al., 2013).

1- Advective Transport

The advection factor is one of the contaminants transport mechanisms in groundwater that depended on the rate and the direction groundwater flow. The average linear velocity of groundwater flow (Zheng and Wang, 1999) is:

$$V_x = \frac{K}{n_e}\frac{dh}{dl} \tag{3-17}$$

Where:-

- n_e is an effective porosity,
- dh/dl is the hydraulic gradient,
- V_x is the average linear velocity (L/T).

By using a mass balance approach, the advective transport equation is.

$$q_m = q\ c \tag{3-18}$$

The variation in mass along a section of groundwater flow.

$$\frac{dM}{dt} = qA(C_1 - C_2) \tag{3-19}$$

Where:-

- q is The scalar velocity.

One-dimensional advective transport equation is:

$$-q\frac{\partial C}{\partial l} = n_e\frac{\partial C}{\partial t} \tag{3-20}$$

Derive Equation(3-20) for three dimensions (Charles, 2002):

$$-\frac{\partial}{\partial x}(V_x C)-\frac{\partial}{\partial y}\left(V_y C\right)-\frac{\partial}{\partial z}(V_z C)+\frac{q_s}{n}C_s=\frac{\partial C}{\partial t} \qquad (3\text{-}21)$$

2- Dispersive Transport

It is spreading of contaminants by mechanical dispersion that results from actual velocity deviations on a microscale from groundwater average velocity and molecular diffusion (Zheng and Wang, 1999).

Mechanical dispersion is described by Fick’s law, and it is a function of the average linear flow velocity. We cannot separate transport by diffusion and mechanical dispersion during groundwater flow, therefore, dispersion coefficient (Bear, 1979), is:

$$D=\alpha_i V_i+D^* \qquad (3\text{-}22)$$

Where:-

- a_i is a dynamic dispersivity in the i direction,
- V_i is the average linear velocity of groundwater flow,
- D^* is diffusion coefficient.

The transport equation for solutes that describes processes of advection and dispersion is:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(V_i C)+\frac{q_s}{n}C_s \qquad (3\text{-}23)$$

Where:-

- C is concentration,
- C_s is concentration at source/sink,
- V_i is the average linear flow velocity,
- q_s is source/sink term.

3- Retardation Processes

In groundwater systems, many processes act to transform, retard and attenuate the solutes by biochemical, geochemical and chemical reactions. The retardation factor (Zheng, 1990) is:

$$R = 1 + \frac{\rho_d}{n_e} K_d \tag{3-24}$$

Where:-

- ρ_d is bulk density of the sediment/soil (g/cm^3);
- K_d is partition coefficient (L/kg).

The governing equation is affected by the retardation factor:

$$R\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}(D_{ij}\frac{\partial C}{\partial x_j}) - \frac{\partial}{\partial x_i}(V_i C) + \frac{q_s}{n} C_s \tag{3-25}$$

3.5 Processing MODFLOW

"Processing MODFLOW for windows (PMWIN)" is used to simulate groundwater flow and pollution. At the first, it was prepared as a processor for the flow of groundwater model then began with various codes to complete simulation system. The extent of the code developed to prepare the windows-depended on transport model PMPATH, MT3D, MT3DMS, MOC3D and PEST and UCODE.

It was designed with the user-interface of graphical and other useful tools. The user-interface of graphical allows to simulate and create models with ease. It handles models with more than 900 stress periods, 70 layers and 200,000 cells in all the layer. The output of simulation included hydraulic heads, and drawdowns (Chian and Kinzelbach, 1998).

3.6 Model Input Codes

3.6.1 MODFLOW Code

The code is chosen for the numerical 3D finite-difference modeling work. It was developed by the U.S. Geological survey. The MODFLOW first code was developed between1981 and 1983. In 1988, MODFLOW 88 was released to explain and evaluate the groundwater flow behavior (Chian, 2006). MODFLOW was designed to facilitate change and did not cover solving equations except groundwater flow equation. Then it was developed to MODFLOW2000, where it included multiple types of equation. After that MODFLOW 2005 was released (Banta et al., 2000).

The finite-difference is used to solve the equation of groundwater flow in MODFLOW where the model domain is divided into a number of equal-sized cells-usually by assigning the number of rows and columns. Hydraulic properties are assumed to be uniform within each cell and an equation is developed for each cell based on the surrounding cells. Steady-state and transient-flow conditions that can simulate in MODFLOW. MODFLOW has become the worldwide standard groundwater flow.

3.6.2 PMPATH Code

It is used to represent flow lines and paths lines of groundwater. It is linked with the groundwater models and outputs of the simulation from MODFLOW. The semi-analytical particle tracking scheme (Lu, 1994) is used to determine the paths of groundwater. It gives a difference on screen graphical options involving head contours and velocity vectors (Chiang, 2005).

3.6.3 MT3D Code

"Modular three-dimensional" transport model is used to simulate dispersion, advection and chemical reactions in groundwater systems. It allows user to create and calibrate a flow model independently. It takes the calculated hydraulic heads and different flow conditions saved by MODFLOW model. The transport model simulates the changes in the contaminants concentration in groundwater (Zheng and Wang, 1999).

3.7 Steady State Model Calibration

The model is calibrated by matching computed heads from the model with the field measured values of heads within less error. The calibration model has adjustable input so that the model can adequately simulate field measurements such as head and contaminant concentration in the study area. Hydrologic parameters are altered systematically either by trial and error until reaching on agreed match or minimum error rate between the observed value and a modeled value (Reilly and Harbaugh, 2004).

Chapter Four

METHODOLOGY

of The Study

CHAPTER FOUR

Methodology of the Study

4.1 Site Description

The Nuclear Research Center is located at Al-Tuwaitha site about 18 kilometers (km) south of the southern edge of Baghdad governorate between (44°27'-44°35') Longitude and (33°10'-33°15') Latitude, and covers about 10 square kilometers (km^2) as shown in Figure (4-1). It is located south of the confluence point of the river Tigris and Diyala. Estimated distance of Al - Tuwaitha is around one kilometers east of The Tigris river and 3.5 kilometers south of The Diyala river.

Al-Tuwaitha is located in lower Mesopotamian plain, Figure (4-2); that is covered with Quaternary-age alluvial deposits that are as much as 50 m thick. The deposits are composed of alternating layers of clay, silt, sand, and occasional gravel. It is characterized by a flat floor surface, surrounded by earthen dikes and ranging from 30-32m above mean sea level and the topography factor has no significant impact on water level and groundwater movement (Copland and Cochran, 2013). The groundwater level which Al-Tuwaitha area is located within, is 30 m.a.s.l. (Ali, 2012) and the hydrogeologic cross-section that is constructed using the lithologic descriptions for drilling locations, as shown in Figure (4-3).

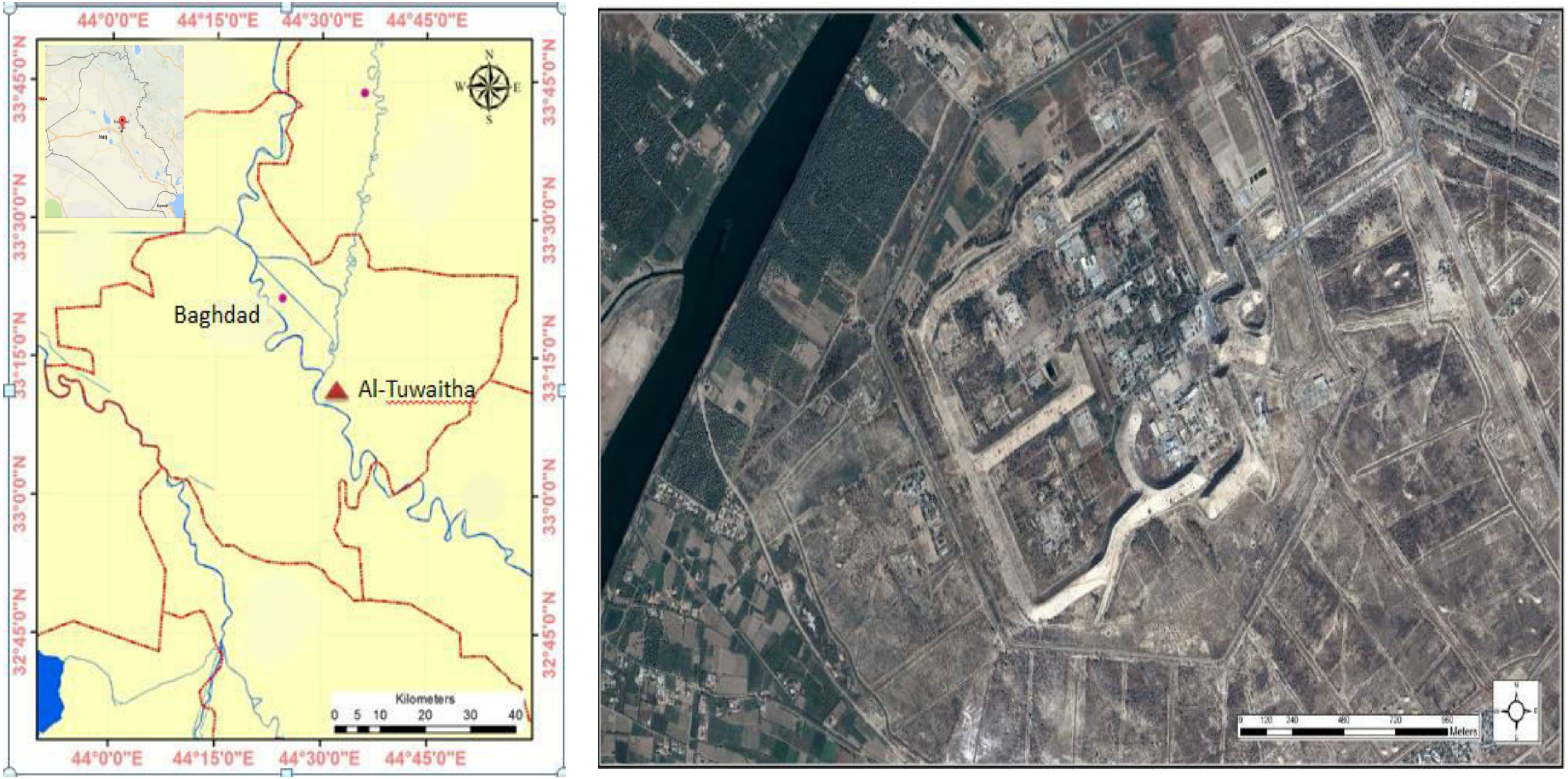


Fig. (4-1) Location of Nuclear Research Center at Al-Tuwaitha site (Al-Daffaie, 2014)

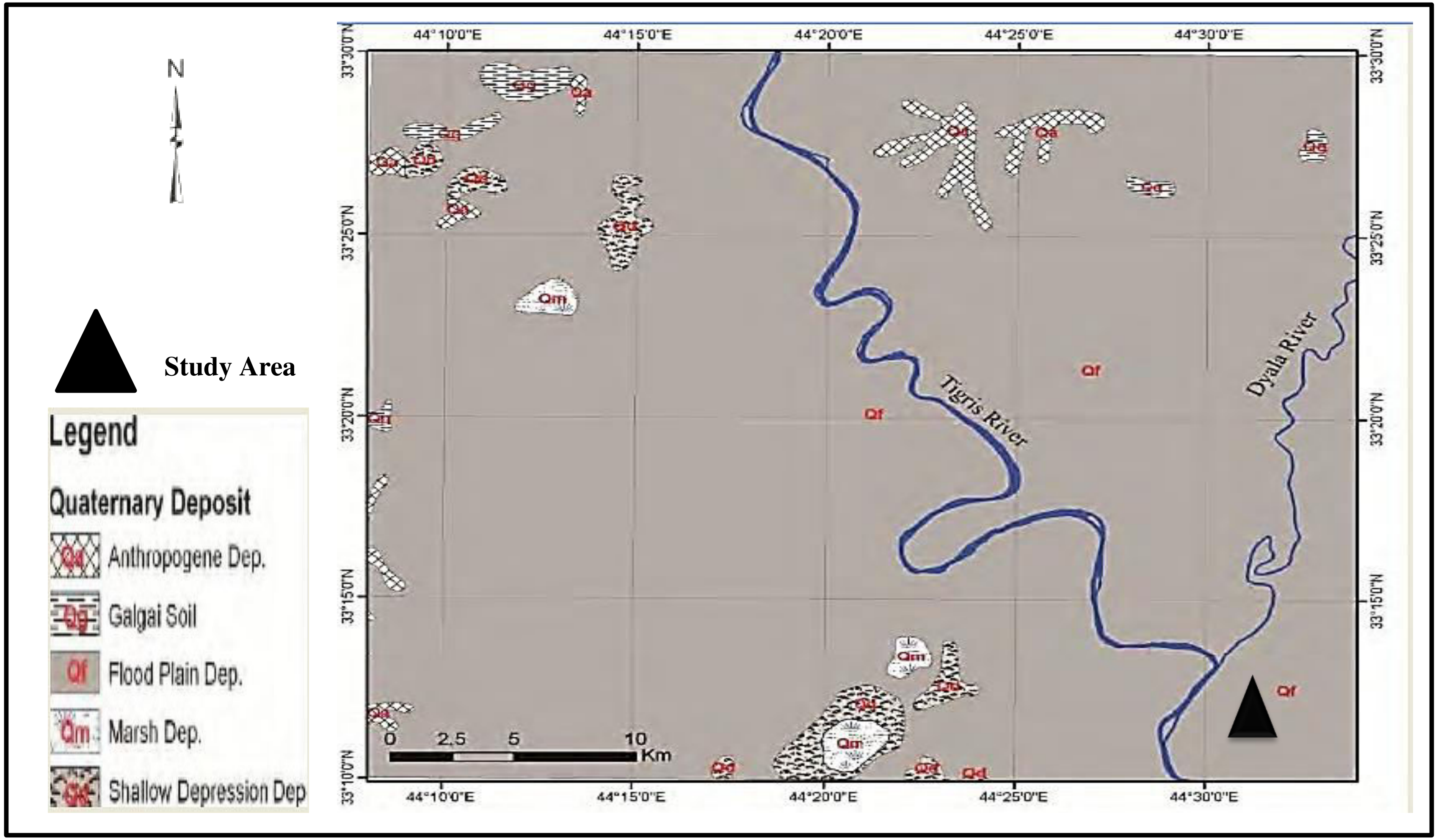


Fig. (4-2) Geological map of Baghdad area (Hamza and Yacoub, 1982)

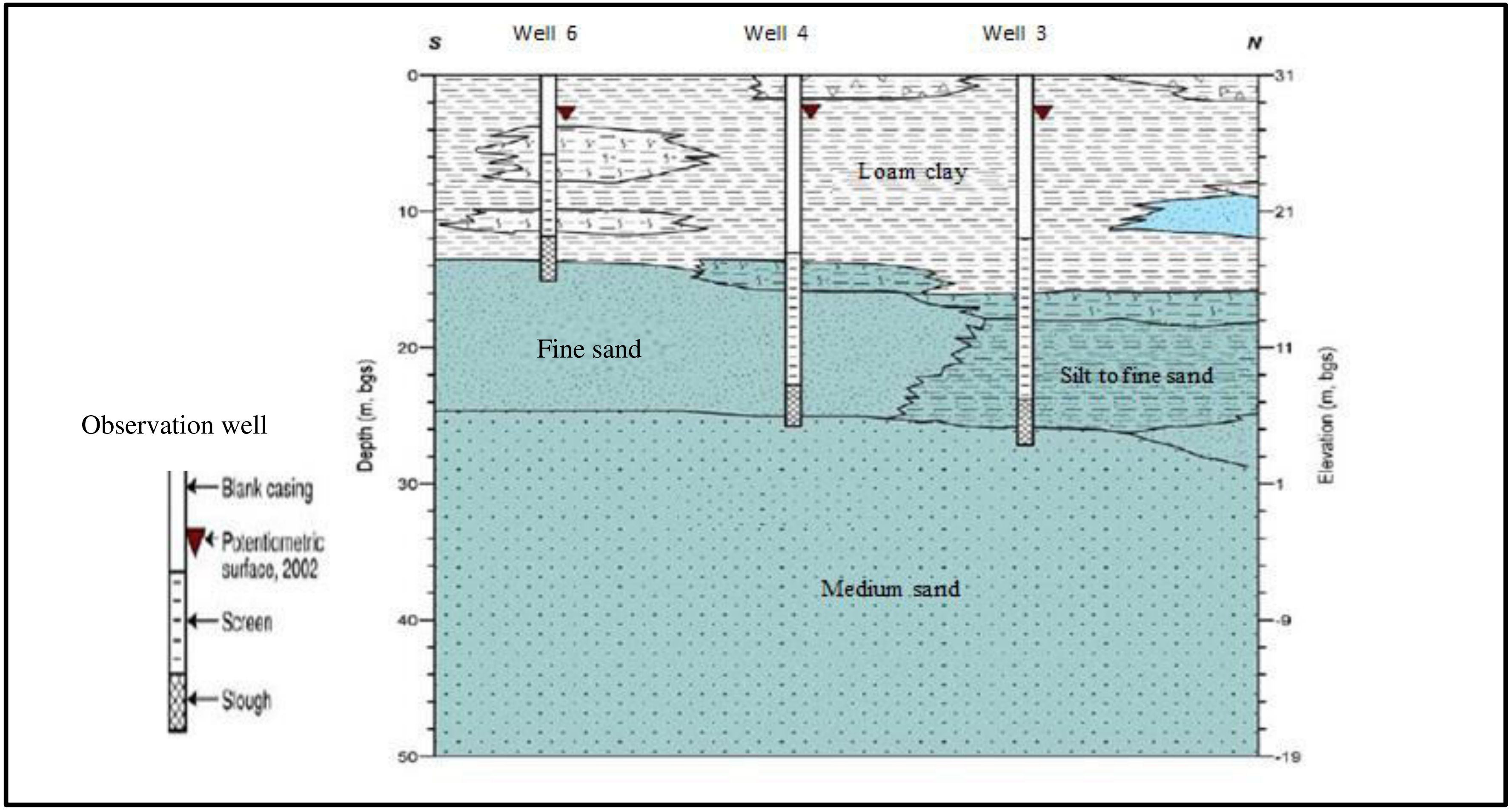


Fig. (4-3) Hydrogeologic cross section for the some drilling locations Al-Tuwaitha constructed using lithologic descriptions (Copland and Cochran, 2013)

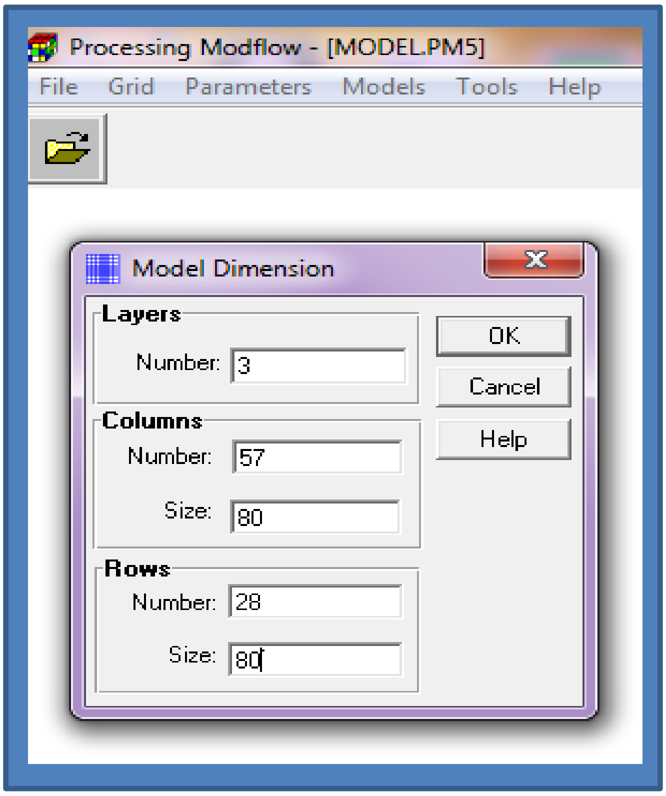
4.2 Groundwater Modeling

three models for solving the mathematical models numerically were used by using the finite difference method with Processing MODFLOW interface. The first and second models (MODFLOW and PMPATH) have been implemented in the solution of groundwater movement problems. While the third model MT3D was applied for the determination of contaminant transporting movement and distribution, it communicates with MODFLOW model through data files. This should link known ground water movement to determine the distribution and movement of a contaminant in groundwater.

4.2.1 Groundwater Flow Model (MODFLOW)

4.2.1.1 Model Domain

Groundwater flow model was simulated as a three-dimensional steady-state. The model area has three layers based on the geology of study area. Each layer has 57 columns and 28 rows with grids sizes 80m x 80m as shown in Figure (4-4). The total number of cells is 1596 cells which included active, inactive and constant cells by assigning values of 1, 0 and -1, respectively by using the INBOUND array in MODFLOW. Model area (grid) occupies an approximately 10214 m^2.



Layers
Number: 3

Columns
Number: 57
Size: 80

Rows
Number: 28
Size: 80

Fig. (4-4) The dialog box of model dimension

MODFLOW was needed to define the INBOUND for limiting the problem and achieving unique solutions for the partial differential equations (Wang and Anderson, 1995). The boundaries of the model give a positive and negative values for active and fixed-head cell, respectively. The cells that represent the Tigris river are defined as a constant head boundary and the adjacent cells for the Tigris river from the northwest are considered inactive cells, while other cells are defined as variable head boundaries, as in Figure (4-5). The river head specified for constant boundary condition was 27.6 m.a.s.l. this head represents minimum head condition in 2002 (Copland and Cochran, 2013) and it is used for model calibration.

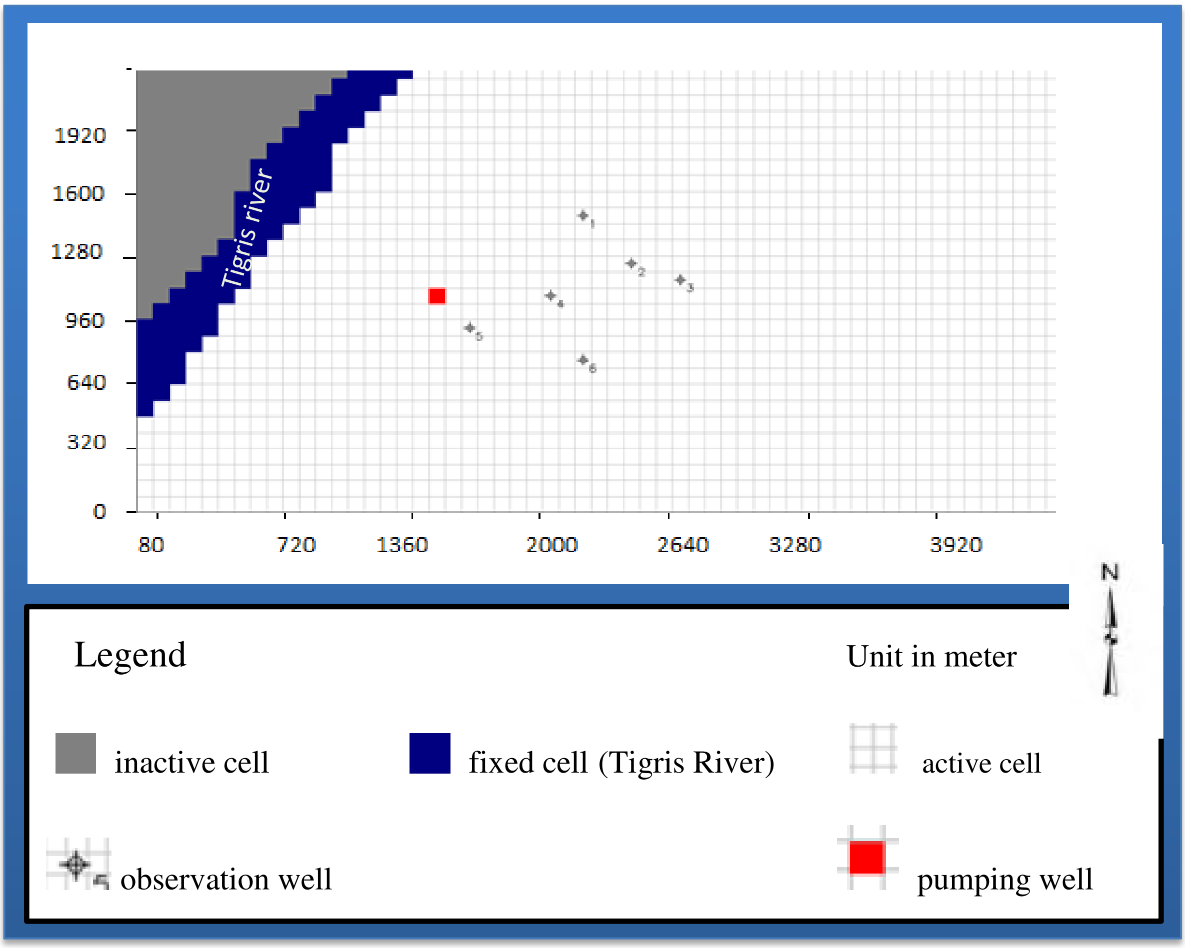


Fig. (4-5) Plane view of the model

4.2.1.2 <u>The Aquifer System Characteristics</u>

The aquifer system has been subdivided into three layers in a vertical direction according to the geology of region (Copland and Cochran, 2013). The thickness of the layers was specified by defining the layer elevation top and bottom. The upper layer (loam clay) was about 16 m thick, middle layer (silt to fine sand) was 14, and the lower layer (medium sand) was about 20 m thick (Al-Daffaie, 2014).

Hydraulic characteristics were varied for the aquifer of the city of Baghdad as a result of the variations of the lithological units composing the aquifer. The horizontal hydraulic conductivity values for Al-Tuwaitha aquifer between (0.09 - 8 m/day) (Al-Jiboury, 2009). The values were adjusted through the steady calibration of the flow model. The k_V was assumed to be 0.1of k_H (Todd and Mays, 2005). The numerical models that used to represent groundwater flow are based on the type of layer, where Table (4-1) gives the layer properties for flow model.

Table (4-1) The layers properties

Layer No.	**Soil Type**	**Horizontal Hydraulic Conductivity m/day**	**Layer Type**	**Elevation m.a.s.l**	
				The Layer Top	The Layer Bottom
1	Loam / Clay	0.001-0.09	Unconfined	31	15
2	Silt / Fine sand	0.09—0.9	Confined / Unconfined, Transmissivity varies	15	1
3	Medium sand	1-12	Confined / Unconfined, Transmissivity varies	1	-19
Reference	(Al-Daffaie, 2014)	(Osterbaan and Nijland, 1986) and (Heath, 1983)	(Ali, 2012)	(Al-Daffaie, 2014)	

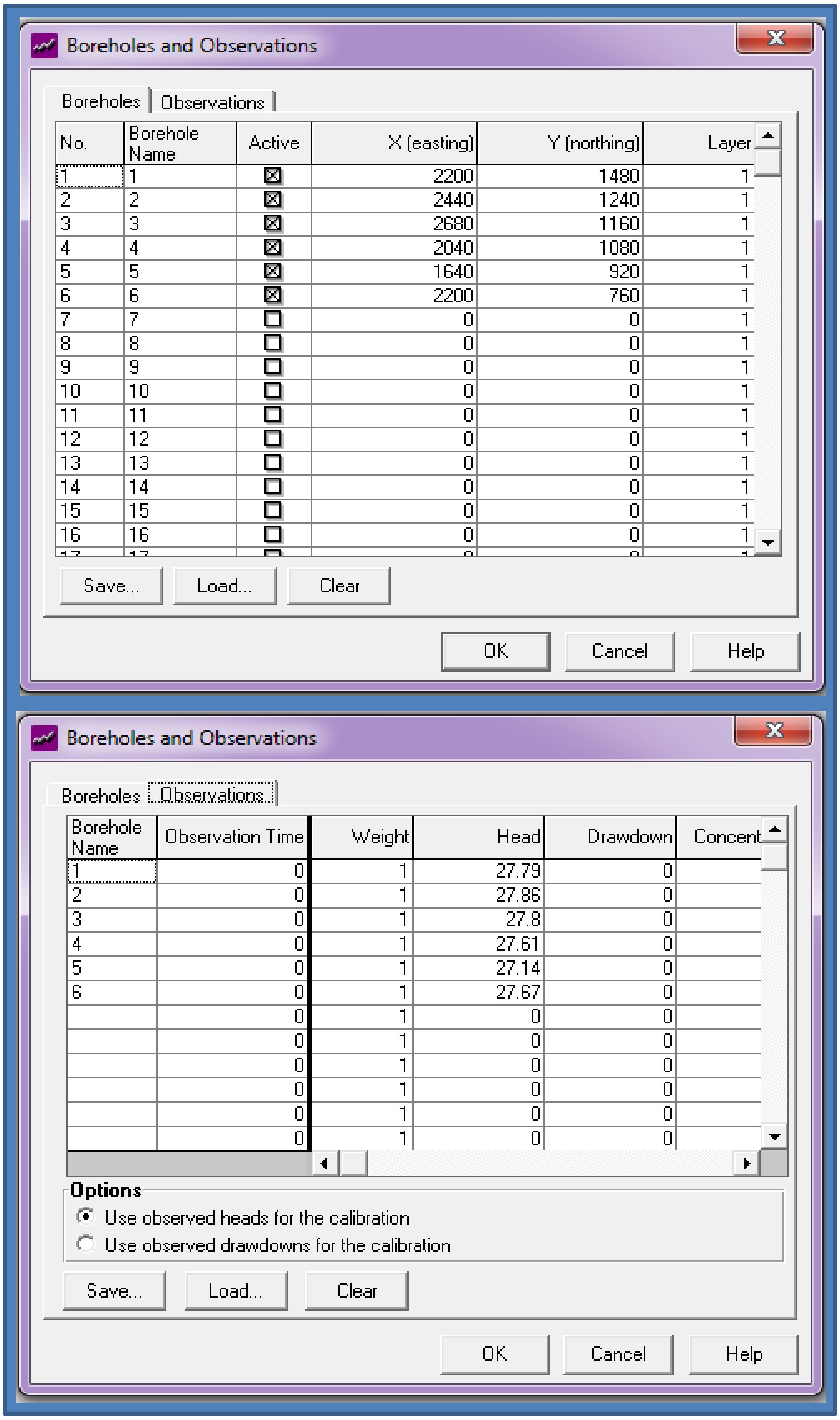
4.2.1.3 Observation Wells and Pumping Well

Water levels of six observation wells were used to simulate the aquifer for the study area, data were taken from the water levels of wells previously studied (Copland and Cochran, 2013) as in Table (4-2). The values of hydraulic head of observation wells were logged in the model as in Figure (4-6). The water levels of wells were used in the calibration process and compared with the result of the MODFLOW simulations.

In this study, the pumping out well was suggested for treatment. It is used to reduce or limit spreading of contamination in the aquifer. The pumping rate was specified about 518 m^3/day, and this value was used after calibration process and chose the optimal location and rate for it.

Table (4-2) Water elevation of observation wells
(Copland and Cochran, 2013)

Observation Well	Ground Surface Elevation (m)	Water Table (m.a.s.l.)
W1	31.81	27.79
W2	31.57	27.86
W3	32.02	27.80
W4	31.56	27.61
W5	31.14	27.14
W6	31.88	27.67



No.	Borehole Name	Active	X (easting)	Y (northing)	Layer
1	1	☒	2200	1480	1
2	2	☒	2440	1240	1
3	3	☒	2680	1160	1
4	4	☒	2040	1080	1
5	5	☒	1640	920	1
6	6	☒	2200	760	1
7	7	☐	0	0	1
8	8	☐	0	0	1
9	9	☐	0	0	1
10	10	☐	0	0	1
11	11	☐	0	0	1
12	12	☐	0	0	1
13	13	☐	0	0	1
14	14	☐	0	0	1
15	15	☐	0	0	1
16	16	☐	0	0	1

Borehole Name	Observation Time	Weight	Head	Drawdown	Concent
1	0	1	27.79	0	
2	0	1	27.86	0	
3	0	1	27.8	0	
4	0	1	27.61	0	
5	0	1	27.14	0	
6	0	1	27.67	0	
	0	1	0	0	
	0	1	0	0	
	0	1	0	0	
	0	1	0	0	
	0	1	0	0	
	0	1	0	0	

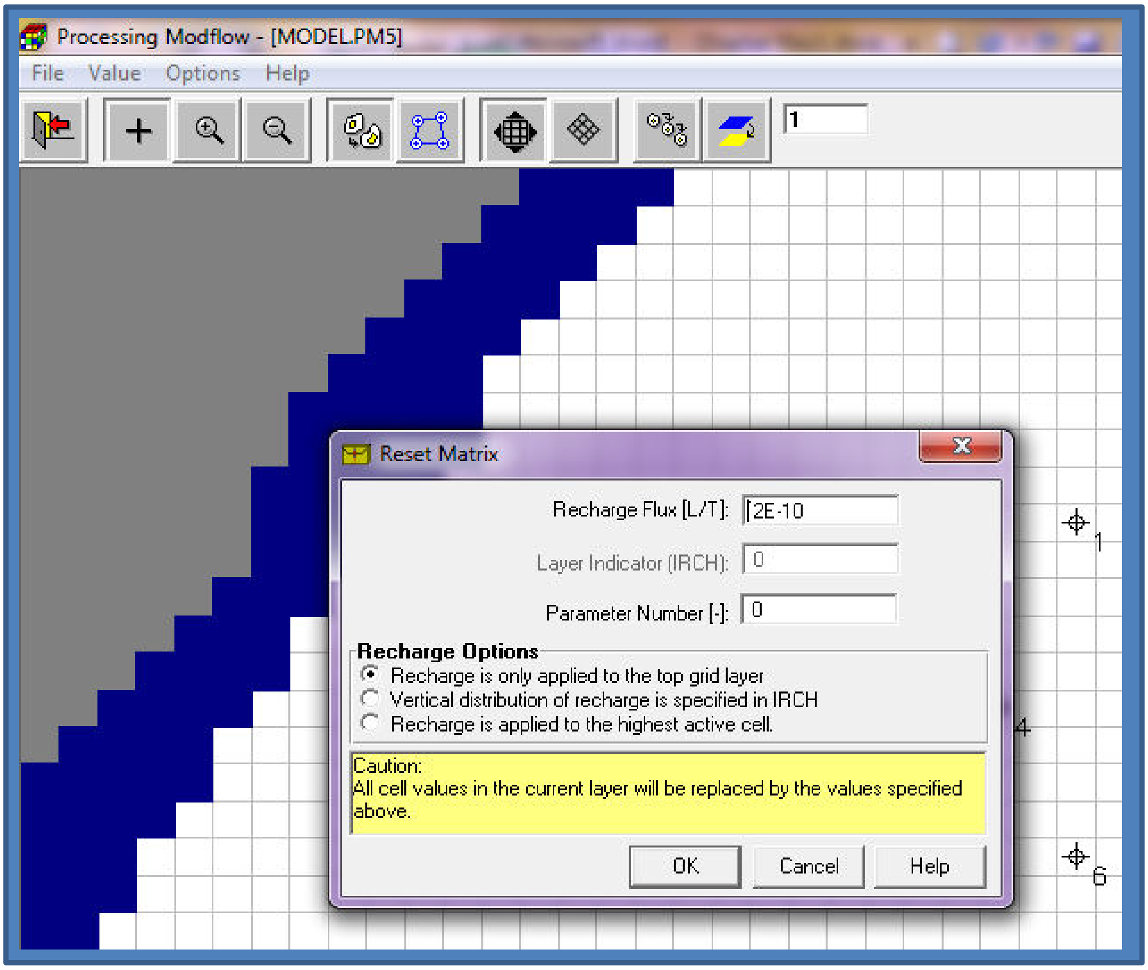
Options

● Use observed heads for the calibration
○ Use observed drawdowns for the calibration

Fig. (4-6) The boreholes and observations dialog box

4.2.1.4 Recharge Rate

Recharge package is one of the most critical components in a hydrological study. It is prepared to simulate the distribution recharge to the groundwater system. It has been defined by specifying the data to all vertical column of the cells. For this study, the recharge is applied to a top grid layer and the input parameter is assumed to be constant during the time simulation. The main source of recharge in Al-Tuwaitha area is considered the rainfall. The value of recharge rate was taken as 1.7 x 10^{-5} m/day (Bashoo, 2005) and the parameter used is illustrated in Figure (4-7) and depended on this value as input parameter to simulate groundwater flow in Nuclear Research Center at Al-Tuwaitha site.



Recharge Flux [L/T]: 2E-10

Layer Indicator (IRCH): 0

Parameter Number [-]: 0

Recharge Options

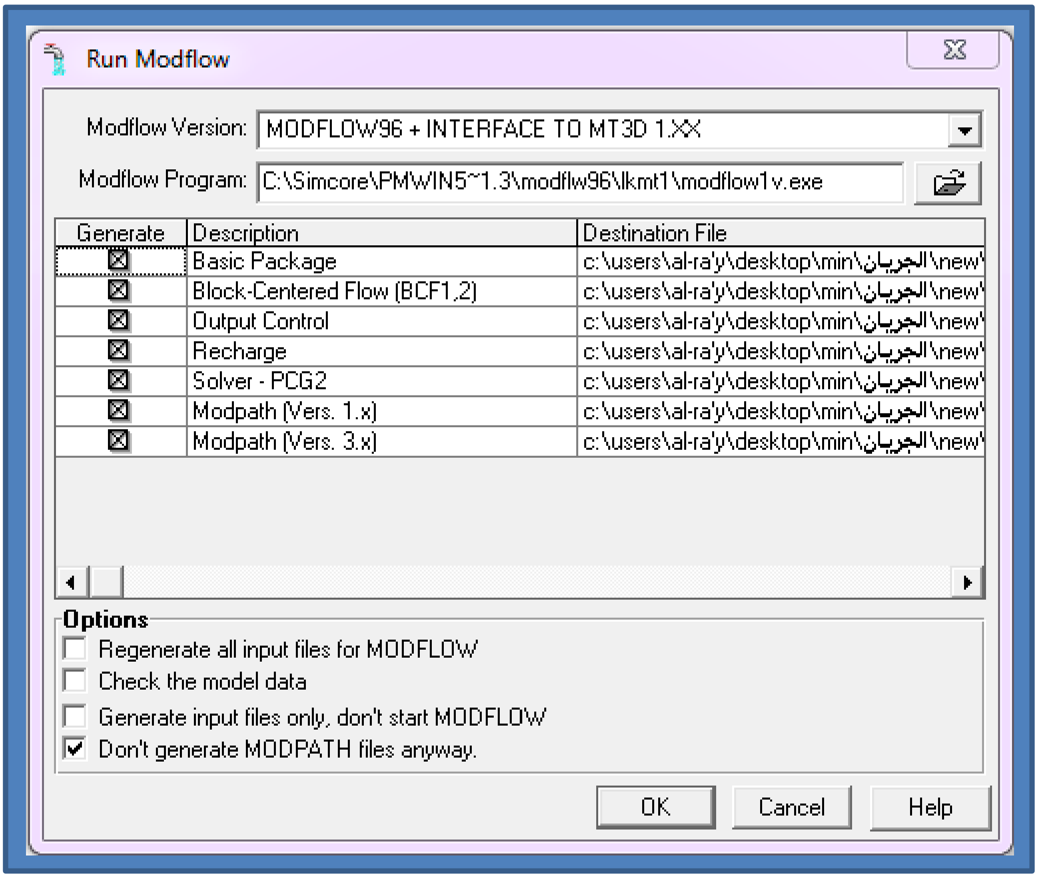
- ● Recharge is only applied to the top grid layer
- ○ Vertical distribution of recharge is specified in IRCH
- ○ Recharge is applied to the highest active cell.

Caution:
All cell values in the current layer will be replaced by the values specified above.

Fig. (4-7) Parameter value of the recharge package

4.2.1.5 Steady State Flow Model Run and Calibration

After entering parameters values and confirming the homogeneity of units for all parameters, the model becomes ready to run in steady state and calibration as illustrated in Figure (4-8).



Modflow Version: MODFLOW96 + INTERFACE TO MT3D 1.XX

Modflow Program: C:\Simcore\PMWIN5~1.3\modflw96\lkmt1\modflow1v.exe

Generate	Description	Destination File
☒	Basic Package	c:\users\al-ra'y\desktop\min\الجريان\new
☒	Block-Centered Flow (BCF1,2)	c:\users\al-ra'y\desktop\min\الجريان\new
☒	Output Control	c:\users\al-ra'y\desktop\min\الجريان\new
☒	Recharge	c:\users\al-ra'y\desktop\min\الجريان\new
☒	Solver - PCG2	c:\users\al-ra'y\desktop\min\الجريان\new
☒	Modpath (Vers. 1.x)	c:\users\al-ra'y\desktop\min\الجريان\new
☒	Modpath (Vers. 3.x)	c:\users\al-ra'y\desktop\min\الجريان\new

Options

☐ Regenerate all input files for MODFLOW
☐ Check the model data
☐ Generate input files only, don't start MODFLOW
☑ Don't generate MODPATH files anyway.

Fig. (4-8) The dialog box of MODFLOW run

Model's calibration is necessary to show that the simulation of groundwater behavior conducted satisfactorily (McMahonet, 2001). The boundary conditions and input parameters are modifying in the calibration model until the results of the model match the field observations within a pre-established range of error. To match observed values, one input parameter was adjusted while holding the other constant, until the best match between observed and calculated values was found. The objective of calibration can also be carried out by automated parameter estimation or manual adjustment by trial and error procedure (Kresic, 2006).

The steady state flow model was calibrated using six heads well data at different locations as in Figure (4-5). It was calibrated by adjusting the hydraulic conductivity with using the manual trial and error method. The calibration took 70 runs to determine suitable hydraulic conductivity for reaching to the minimum error between the calculated and observed heads. After model calibration process for groundwater flow model, the model was run in two scenarios:

Scenario 1:

Case 1: In this case, the flow model was run by specifying the value of constant head of the Tigris river of 28.7 m.a.s.l. this head represents average head condition in 2002 (Ministry of Water Resources, 2013) to show the effect of rising water in the Tigris river from 27.6 to 28.7 on water level in wells and aquifer.

Case 2: The flow model was run with the highest water level of the Tigris river of 29.8 m.a.s.l in 2002 (Ministry of Water Resources, 2013).

Scenario 2:

The model was run with using pumping well and the water level in the Tigris river was 28.7 m.a.s.l.

4.2.1.6 Steady-State Model Verification

To ascertain that the calibrated process was accurate, the model predicted hydraulic heads were checked against observed head values from six observation wells. The model calibration error can be represented by using mean error (ME) in Equation (4-1), mean absolute error (MAE) in

Equation (4-2) and root mean square error (RMSE) in Equation (4-3), (Anderson and Woessner, 2002).

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_c - h_o) \qquad (4\text{-}1)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|(h_c - h_o)_i| \qquad (4\text{-}2)$$

$$RMSE = \left|\frac{1}{n}\sum_{i=1}^{n}(h_c - h_o)^2{}_i\right|^{0.5} \qquad (4\text{-}3)$$

Where:

h_c is calculated hydraulic head;

h_o is observed hydraulic head; and

n is the number of observations head.

4.2.2 Contaminant Transport Model (MT3D)

Hydrodynamic dispersion, advection and chemical reactions are processes that cause the transport of solute in porous media. The method of characteristics (MOC) is used to simulate the advection transport. The coefficient of molecular diffusion and dispersivity are used to describe the hydrodynamic dispersion for the solute in a porous medium (Zheng, 1990).

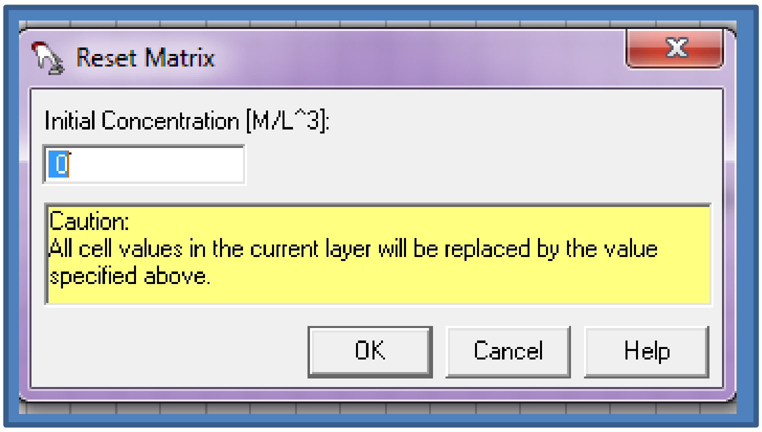
After a steady state run and the calibration of groundwater flow model, MODFLOW becomes ready to simulate transport model. The MT3D model was linked with MODFLOW model. The MT3D model was based on the results of groundwater flow model, where the heads obtained from the steady state simulation in scenario 2 which was run with the average of the river water surface elevation. This study modeled the transport through advection and dispersion.

4.2.2.1 Model Domain

Both the transport and flow model have the same domain and grids. Also, MT3D model needs a boundary condition for all model cells, where it gives -1,1, and 0 for a constant, an active concentration, and an inactive concentration cell, respectively. The boundary conditions of MODFLOW model was converted to MT3D conditions. In this study, the cells of transport model were given as active concentration cells.

4.2.2.2 Initial Concentration

MT3D model needs initial concentration to simulate the transport model for each model cell as an initial hydraulic head in MODFLOW model (Chiang and Kinzelbach, 1998), where the initial concentration is assumed to be zero in this study, and illustrated in Figure (4-9).



Initial Concentration [M/L^3]: 0

Caution:
All cell values in the current layer will be replaced by the value specified above.

Fig. (4-9) The initial concentration dialog box

4.2.2.3 Input Parameter

In addition to the parameters used in MODFLOW and the hydraulic heads which resulted from the simulation of groundwater flow, MT3D was used other parameters such as effective porosity, diffusion and dispersivity.

4.2.2.3.1 Effective Porosity

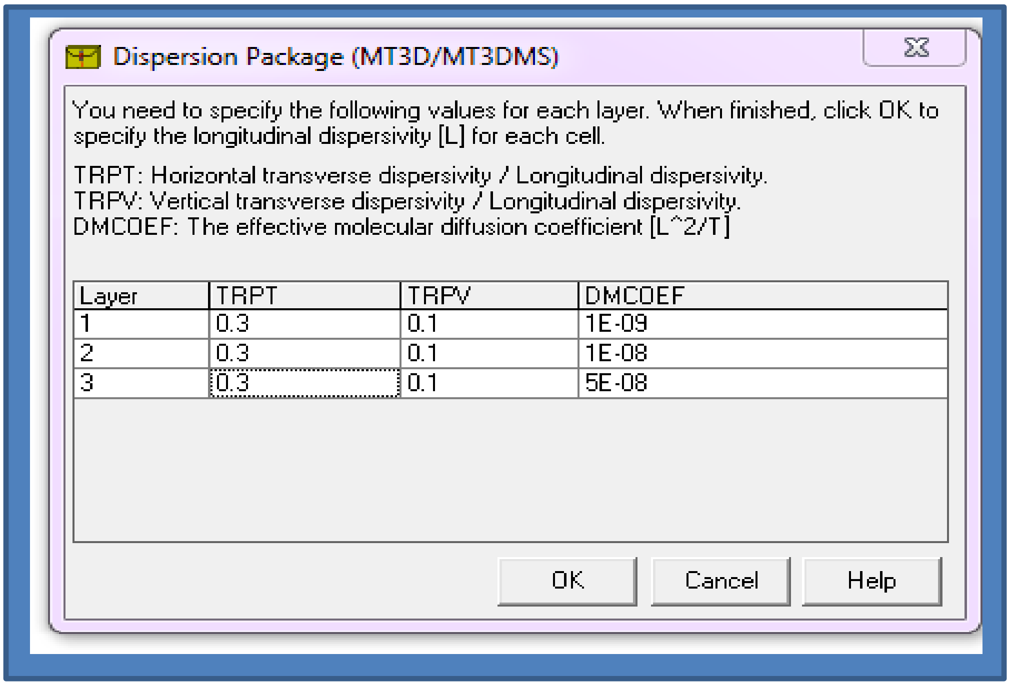
The effective porosity for three layers is usually smaller than porosity, (Kresic, 2006). Table (4-3) gives the extent of effective porosity values for the types of soils which was based upon it in this study.

Table (4-3) Range of effective porosity of soil texture (Todd, 1999)

Soil Texture	**Effective Porosity**	
	Min	Max
Loam / Clay	0.01	0.18
Silt /Fine Sand	0.20	0.33
Medium Sand	0.16	0.46

4.2.2.3.2 Dispersion

The input parameters that controlled dispersion were longitudinal dispersivity (α_L), transverse dispersivity (α_T) and vertical dispersivities (α_V). Longitudinal dispersivity value was assumed equal to 3 m (www.geo-slope.com). (Gelhar, 1986) provided standard ratios to determine transverse and longitudinal dispersivity with α_T/α_L equal 0.1. The values of parameters that controlled dispersion factor were illustrated in Figure (4-10).


Dispersion Package (MT3D/MT3DMS)

You need to specify the following values for each layer. When finished, click OK to specify the longitudinal dispersivity [L] for each cell.

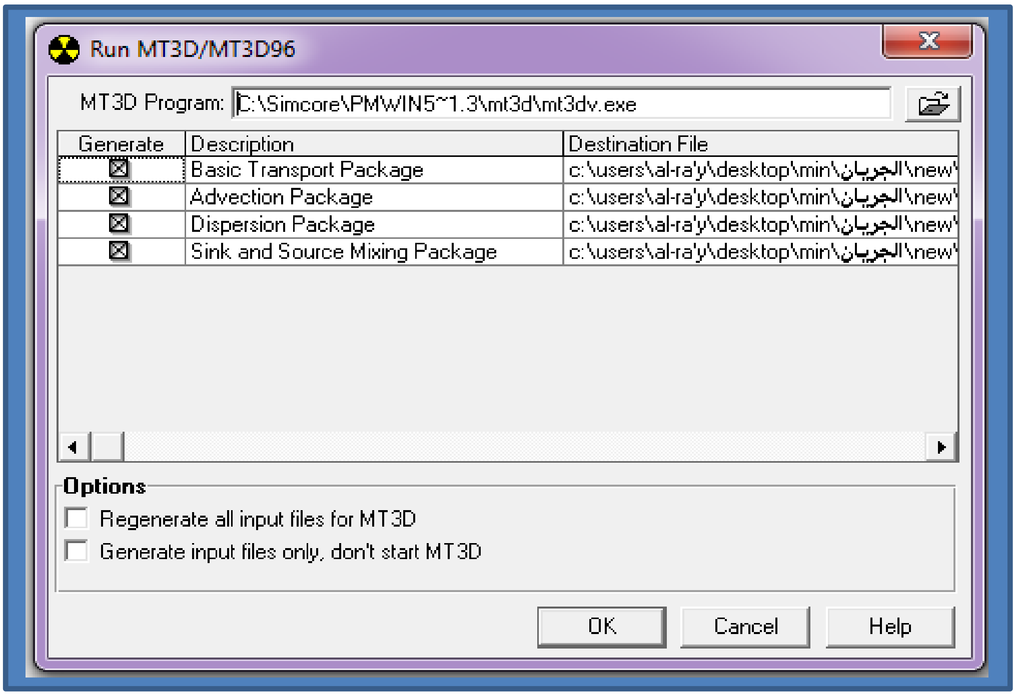
TRPT: Horizontal transverse dispersivity / Longitudinal dispersivity.
TRPV: Vertical transverse dispersivity / Longitudinal dispersivity.
DMCOEF: The effective molecular diffusion coefficient [L^2/T]

Layer	TRPT	TRPV	DMCOEF
1	0.3	0.1	1E-09
2	0.3	0.1	1E-08
3	0.3	0.1	5E-08

Fig. (4-10) The parameters of dispersion package (MT3D) box

4.2.2.4 Steady State Solute Transport Model

The model was run with (Cs-137) concentrations of groundwater to prove and restrict the flow model, Figure (4-11).


Run MT3D/MT3D96

MT3D Program: C:\Simcore\PMWIN5~1.3\mt3d\mt3dv.exe

Generate	Description	Destination File
☒	Basic Transport Package	c:\users\al-ra'y\desktop\min\الجريان\new\
☒	Advection Package	c:\users\al-ra'y\desktop\min\الجريان\new\
☒	Dispersion Package	c:\users\al-ra'y\desktop\min\الجريان\new\
☒	Sink and Source Mixing Package	c:\users\al-ra'y\desktop\min\الجريان\new\

Options

☐ Regenerate all input files for MT3D
☐ Generate input files only, don't start MT3D

Fig. (4-11) The run MT3D/MT3D96 dialog box

According to the studies conducted on Al-Tuwaitha area, it is shown that there is a presence of pollution in Al-Tuwaitha with radioactive materials which are considered a hazardous waste. So, it is important to keep track of the movement of pollutants in the aquifer. However, one site in this study is regarded as a possible contaminant as shown in Figure (4-12). A Cs-137 concentration of 76.9 Bq/g, measured by (Zaboon et al., 2014) using GIS technique was applied uniformly to the area contaminant. MT3D model was run for 20 years for the imposition of that contamination which occurred in 2009. The steps which follow in performing the groundwater flow and contaminant transport models simulation shown in Figure (4-13).

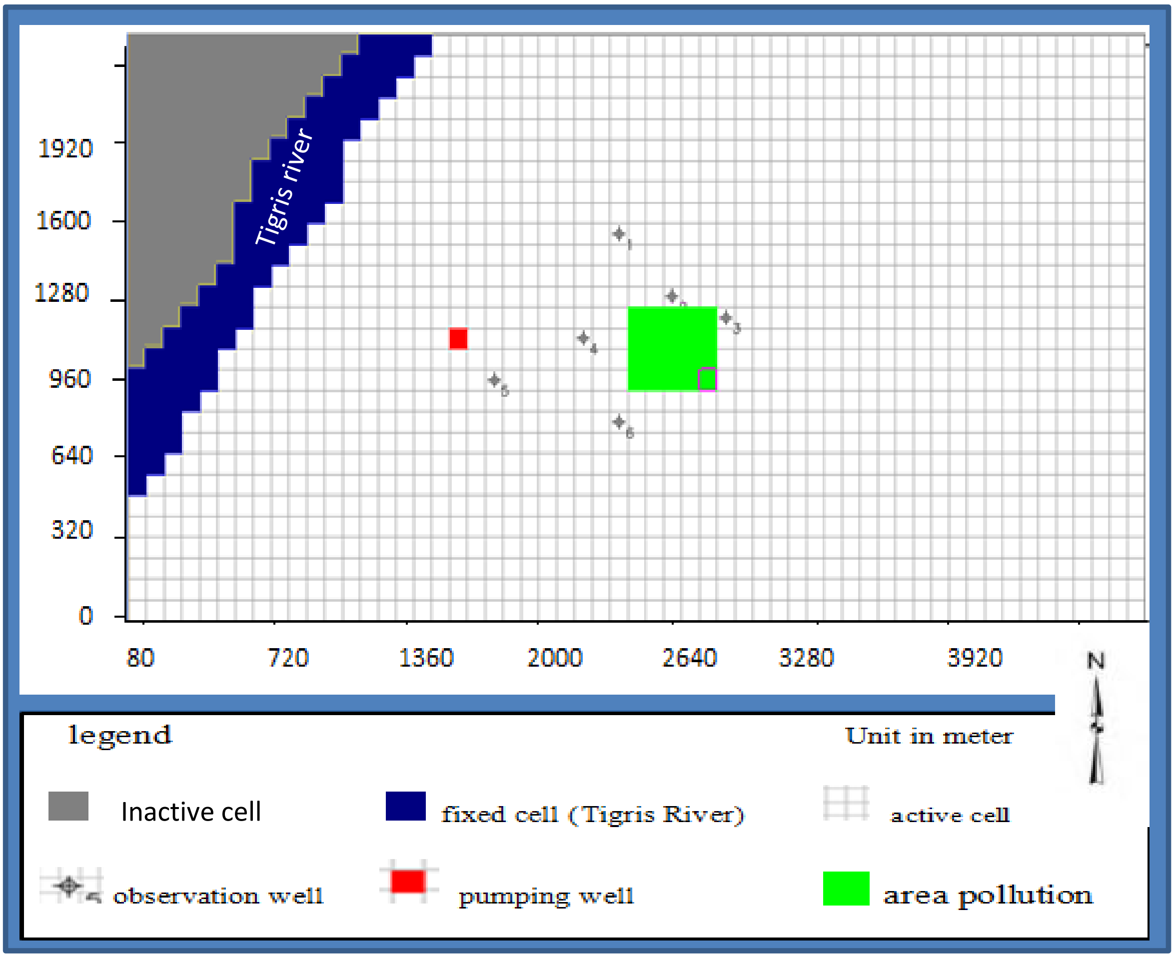


Fig. (4-12) Area pollution of model

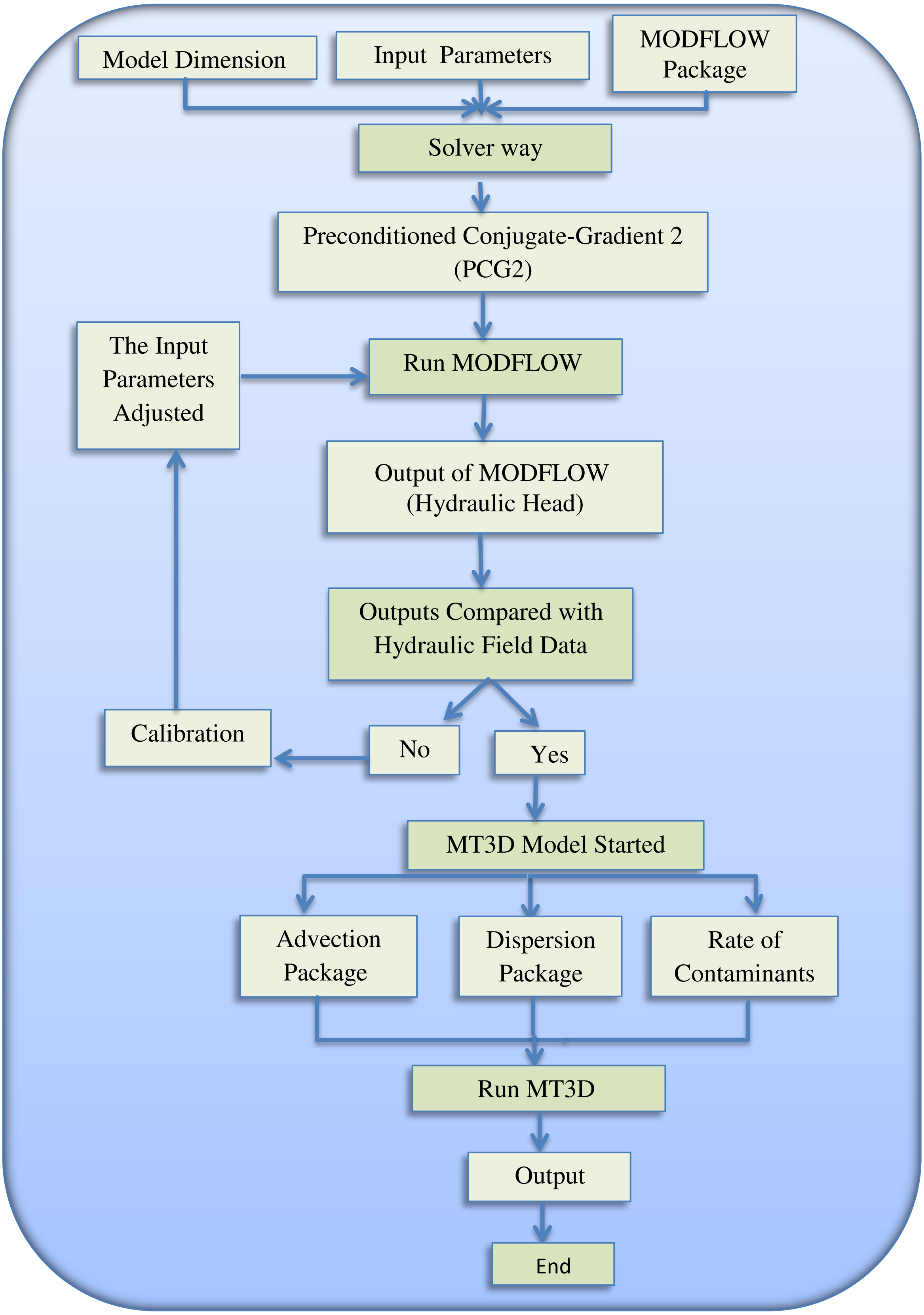


Fig. (4-13) Logical steps that follow in performing the groundwater flow and contaminant transport models simulation

Chapter Five

Results and Discussion

CHAPTER FIVE

Results and Discussion

5.1 General

The groundwater flow model was run at a steady-state after entering the data. Then the calibration model process and three scenarios to study groundwater flow and transport model were started. In this study, the using of pumping well was proposed to collect groundwater contaminate flow and treat it prior to discharge to the Tigris river. Then, the transport model was run based on the results of groundwater flow model to estimate the distribution of contaminant concentration within the aquifer system.

5.2 Modeling the Steady-State Flow

The flow model calibration showed relatively agreed match between the simulated and observed heads for the six observed wells. It was conducted by changing of hydraulic conductivity of aquifer layers. It was shown that the calibrated model is sensitive to change of hydraulic conductivity, especially the change of horizontal hydraulic conductivity.

5.2.1 Hydraulic Head Simulation

The model was operated with the initial conditions and hydraulic conductivities which were adjusted during the calibration of the model using manual calibration. The final calibration process gave a good match between the simulated and observed heads and it was noted that the hydraulic head of wells is sensitive to the change in the hydraulic conductivity of layers. Table (5-1) shows agree match between the calculated and observed heads.

Table (5-1) The values of calculated and observed heads (m) in Nuclear Research Center at Al-Tuwaitha site

Well No.	Obs. Head m.a.s.l	Sim. Head m.a.s.l
1	27.79	27.73
2	27.86	27.75
3	27.80	27.77
4	27.61	27.73
5	27.14	27.7
6	27.67	27.74

The values of statistical evolution for calculated and observed heads are presented in Table (5-2) which was estimated by Equations (4-1), (4-2), and (4-3).

Table (5-2) Statistical evaluations of errors

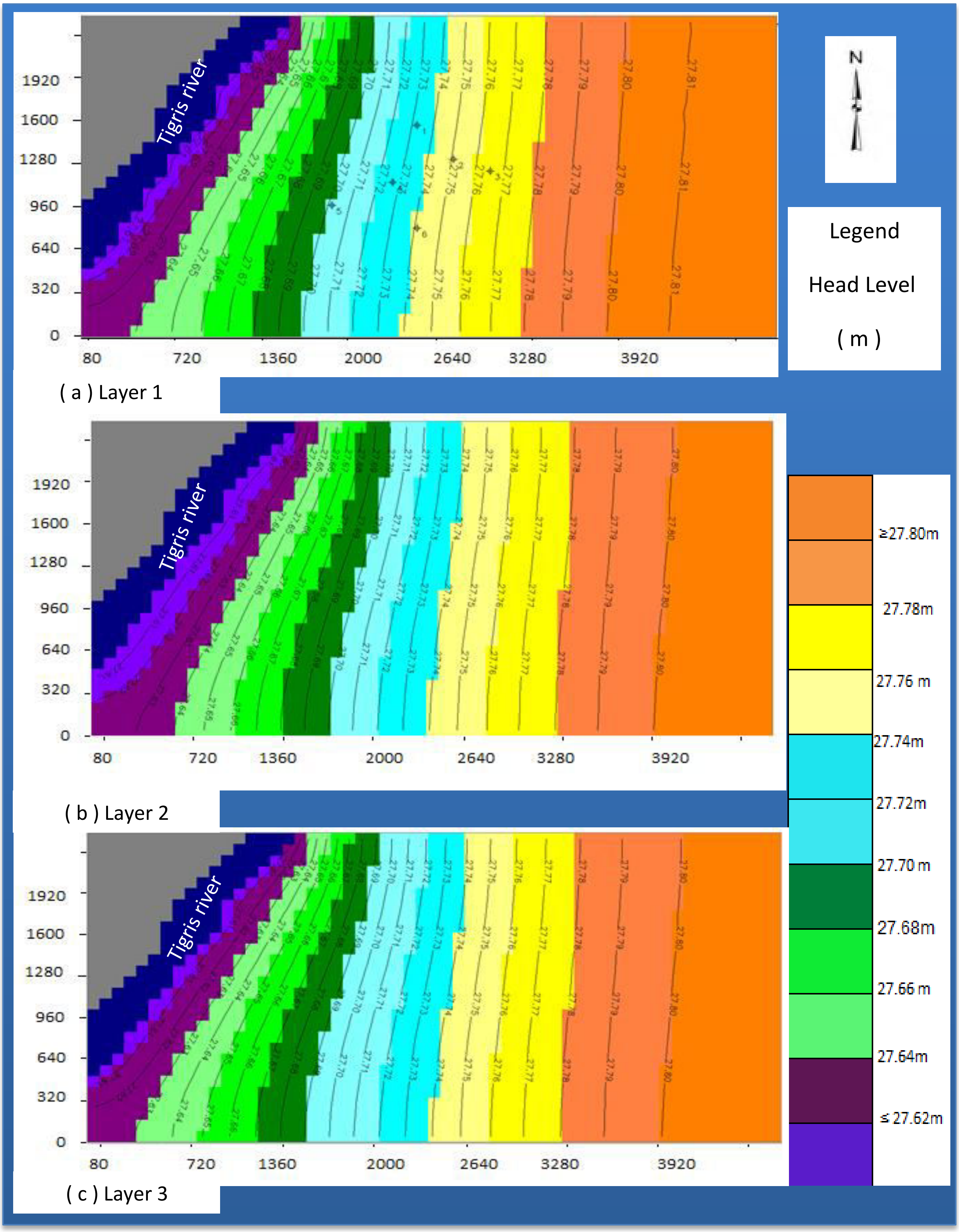
Statistical Measure	Values (m)
Mean Error	0.092
Mean Absolute Error	0.16
Root Mean Square Error	0.24

The best statistical measure was ME because its value was very close to 0 which indicates that, on an average, the calculated heads were slightly greater than the corresponding observed heads.

The values of ME, MAE, and RMSE were 0.092, 0.16 and 0.24 m, respectively. Since it is impossible to obtain an exact match for calculated and observed heads, therefore the model can be accepted with an acceptable error ratio. The accuracy of calibration model based on the input data implies that there is always a percentage of error associated with groundwater models because of the lack of enough data and the capability of numerical methods to describe natural processes (Gaganis and Smith, 2006).

5.2.2 Equipotential Lines of Groundwater Flow (Hydraulic Heads)

The groundwater contour lines (equipotential lines) explain the change in hydraulic gradient at the surface of the earth and the elevation of the water table. It has a high value in the eastern part of the aquifer of 27.82 m, while the smallest value of the area neighboring the river of 27.61m. The groundwater will move toward the river which the grade from the eastern part to western. The hydraulic grade of aquifer system is 5.25 x 10^{-5}, because approximately distance was 4000m. Figure (5-1) shows the equipotential lines of groundwater flow in the first, second, and third layer.



(a) Layer 1

(b) Layer 2

(c) Layer 3

Fig. (5-1) Calculated hydraulic heads in the steady-state simulation when the river water surface elevation 27.6 m.a.s.l.

5.2.3 Flow Lines of Groundwater Flow

In general, the movement of groundwater flow is relatively slow and depends mainly on the topography and soil type of the region (Rethati, 2004). Since the ground surface of Al-Tuwaitha is flat which ranges between 30 - 32 m.a.s.l, (Al-Daffaie, 2014), so the topography factor has less impact in this study. It has been noticed that when the groundwater flow was drawn by PMPATH model, the groundwater movement was slow, especially in the first layer identity type of loam clay but it was higher in the third layer. The ground water flow velocities in the first, second and third layers were 9.77 x 10^{-6}, 3.6 x 10^{-4}, and 0.0015 m/day, respectively as referred (Harter, 2003) that the groundwater velocity was less than 3 3.5x10^{-6} m/day. Figure (5-2a)-(5-2c) shows groundwater flow from the aquifer system towards the river.

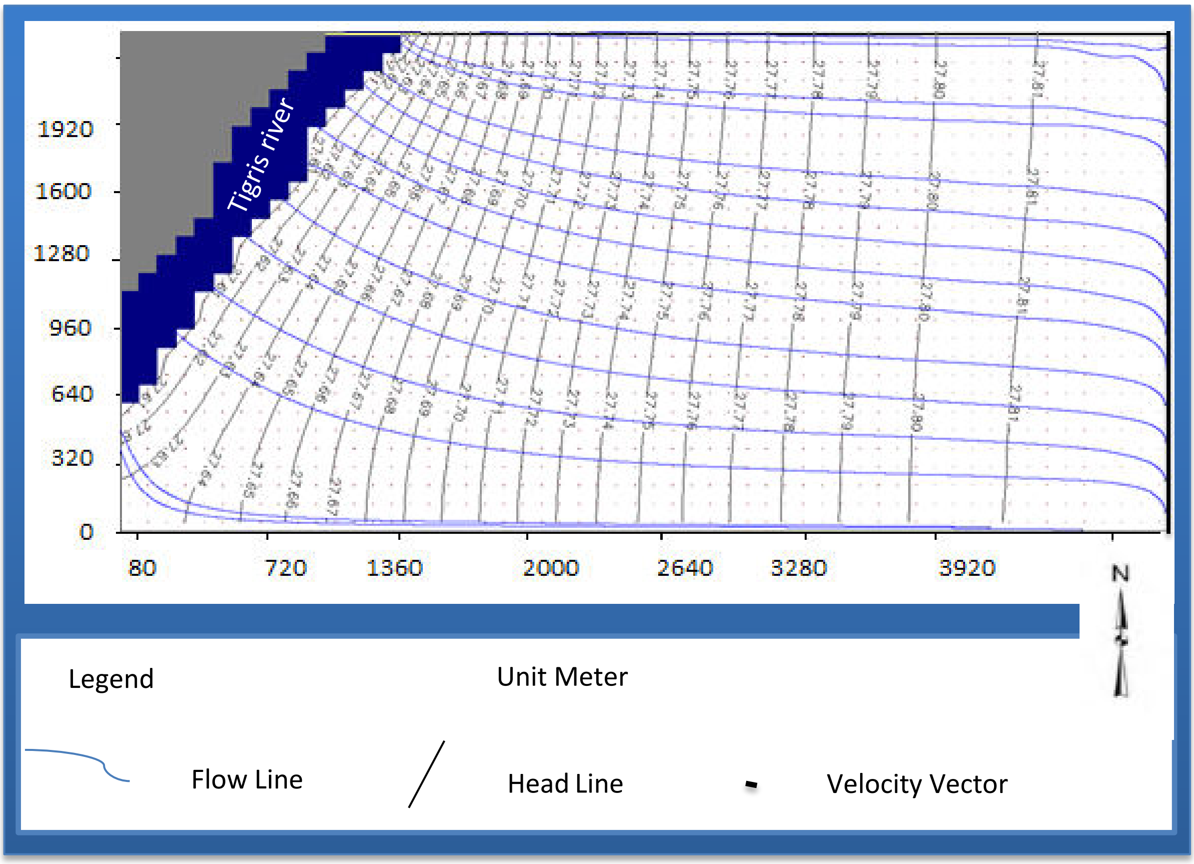


Fig. (5-2a) The flow net of groundwater direction in the first layer

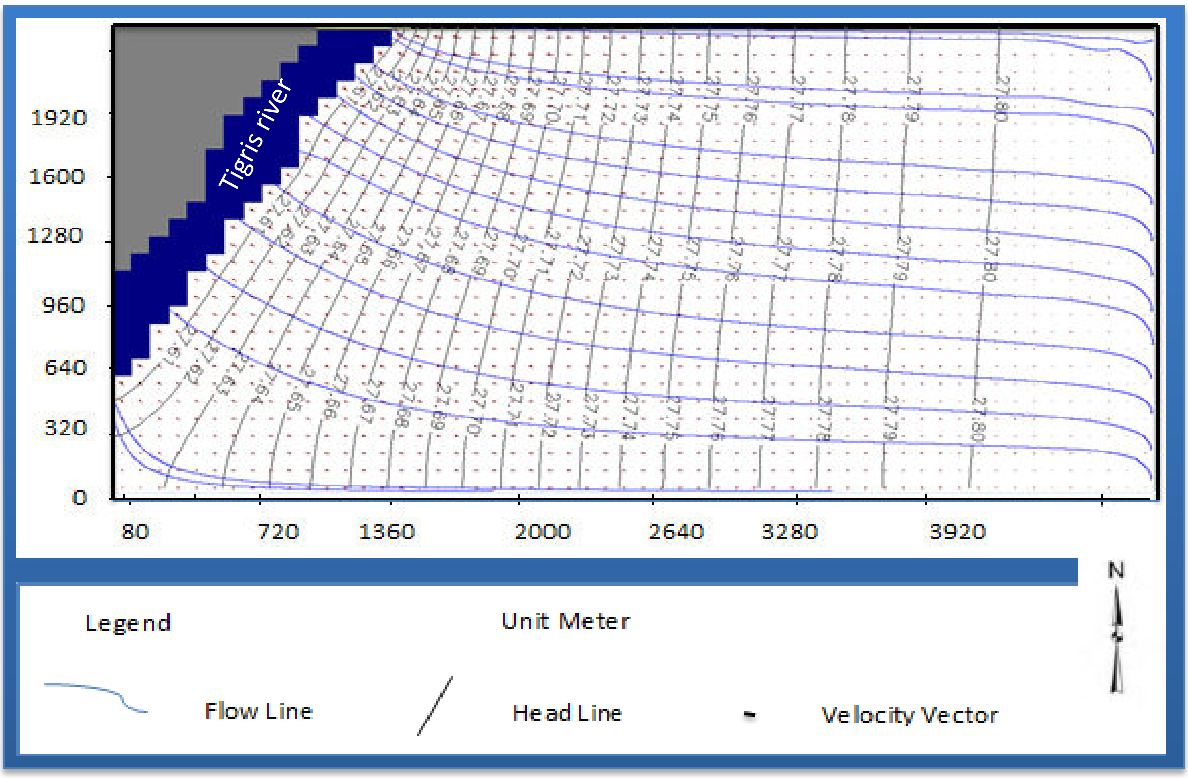


Fig. (5-2b) The flow net of groundwater direction in the second layer

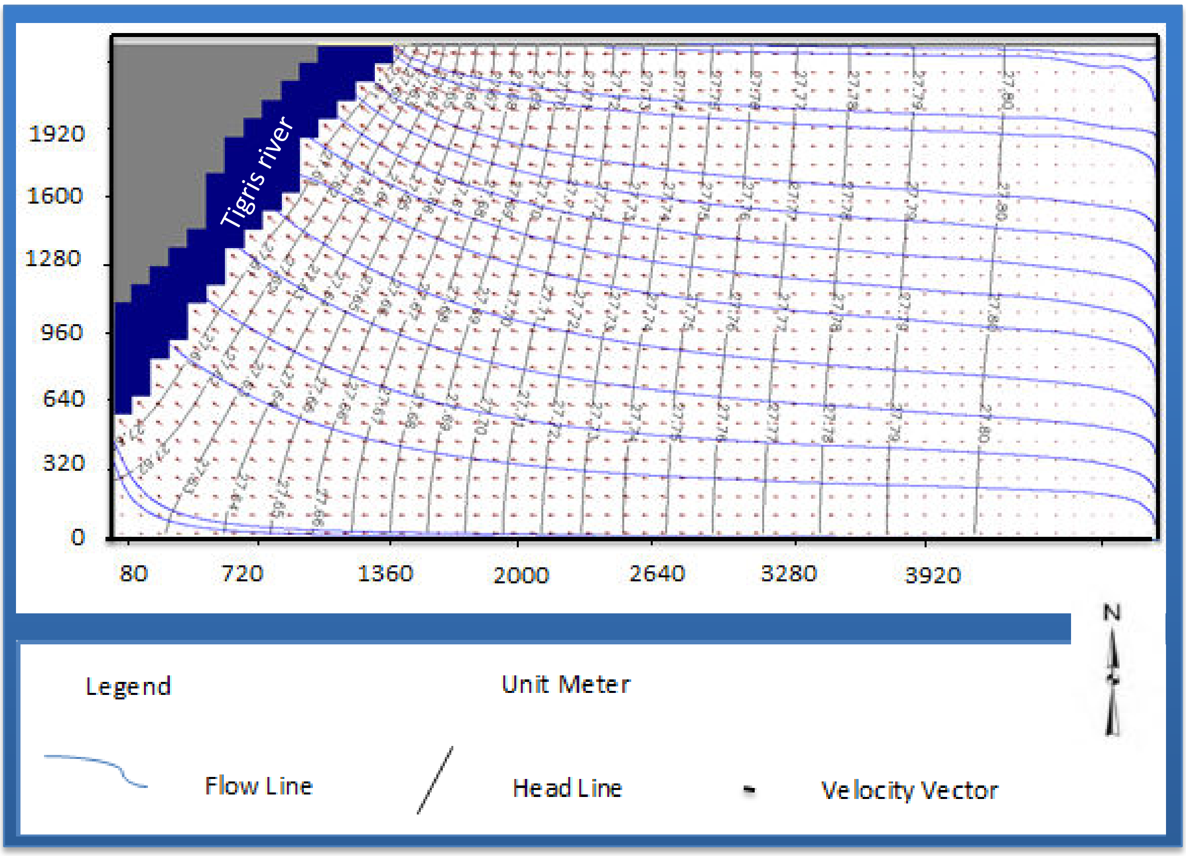


Fig. (5-2c) The flow net of groundwater direction in the third layer

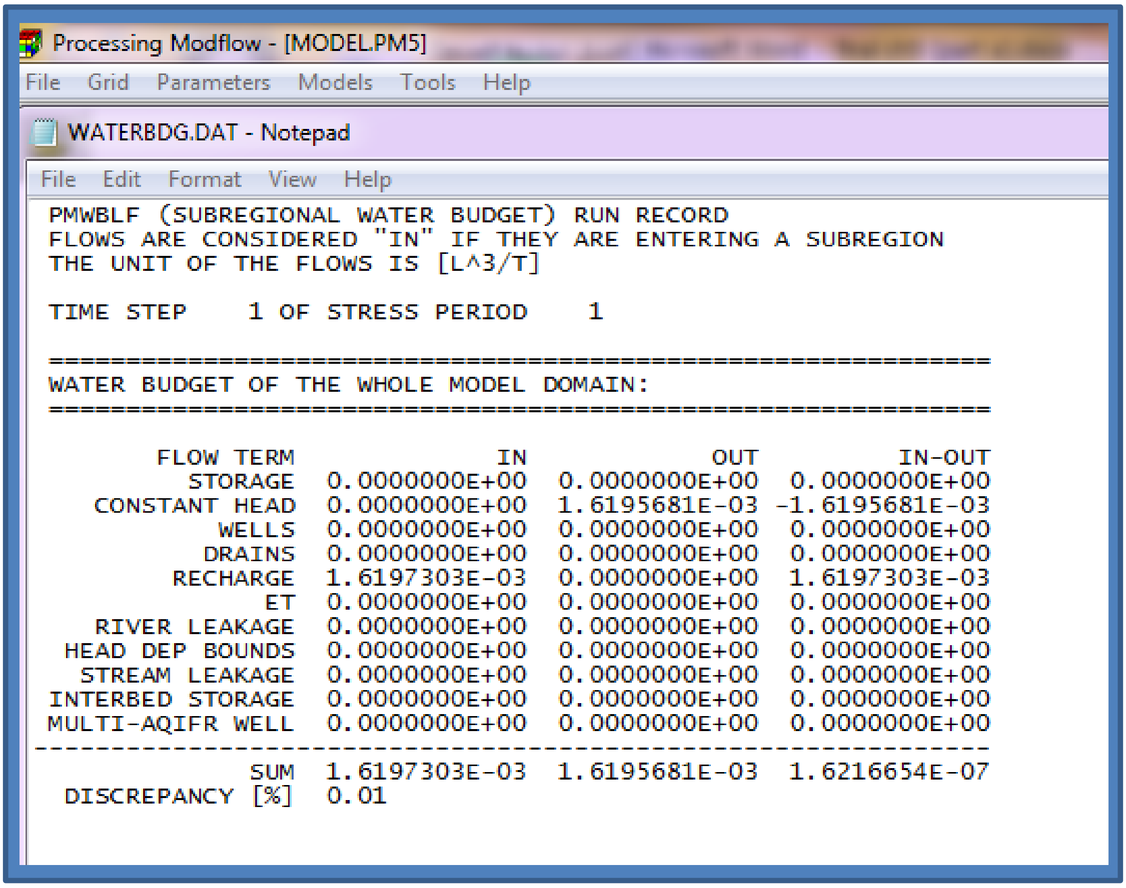
5.2.4 Analysis of Groundwater Flow in the Steady State

When the model is operated in the steady- state conditions, it is assumed that there is no change in recharge, that means the recharge will be constant. In addition to that, the change in the water level of the Tigris river also remains constant during simulated period.

After the final calibration, the model indicates a good match between the calculated and observed heads. In addition, the water volume which flows inside and out of the aquifer system is very matching as in Figure (5-3) and Table (5-3). The variation between the water entering and getting out of the aquifer is 0.014 m^3/day and the percent discrepancy is 0.01 %. It was found from calibration processes that the model was more sensitive to change in recharge rate and hydraulic conductivity.

Table (5-3) The model water budget m^3/s

Flow Te.	IN	OUT	ΔS
Storage	0	0	0
Constant Head	0	1.6195681×10^{-3}	$-1.6195681 \times 10^{-3}$
Recharge	1.6197303×10^{-3}	0	1.6197303×10^{-3}
Sum	1.6197303×10^{-3}	1.6195681×10^{-3}	1.6216654×10^{-7}
Discrepancy %	0.01		



```
PMWBLF (SUBREGIONAL WATER BUDGET) RUN RECORD
FLOWS ARE CONSIDERED "IN" IF THEY ARE ENTERING A SUBREGION
THE UNIT OF THE FLOWS IS [L^3/T]

TIME STEP     1 OF STRESS PERIOD     1

==============================================================
WATER BUDGET OF THE WHOLE MODEL DOMAIN:
==============================================================

       FLOW TERM            IN             OUT          IN-OUT
         STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
   CONSTANT HEAD  0.0000000E+00  1.6195681E-03 -1.6195681E-03
           WELLS  0.0000000E+00  0.0000000E+00  0.0000000E+00
          DRAINS  0.0000000E+00  0.0000000E+00  0.0000000E+00
        RECHARGE  1.6197303E-03  0.0000000E+00  1.6197303E-03
              ET  0.0000000E+00  0.0000000E+00  0.0000000E+00
   RIVER LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
  HEAD DEP BOUNDS  0.0000000E+00  0.0000000E+00  0.0000000E+00
  STREAM LEAKAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
INTERBED STORAGE  0.0000000E+00  0.0000000E+00  0.0000000E+00
MULTI-AQIFR WELL  0.0000000E+00  0.0000000E+00  0.0000000E+00
---------------------------------------------------------------
             SUM  1.6197303E-03  1.6195681E-03  1.6216654E-07
  DISCREPANCY [%]  0.01
```

Fig. (5-3) Volumetric budget of the model

A change of 10% in the recharge rate value leads to ± 0.016 m in the head of observed wells. Also, the change in horizontal hydraulic conductivity (K_h) caused a changed in the hydraulic head, especially in the third layer, while the change in K_h in the first and the second layer lead to a little variation, as shown in Table (5-4). The impact of the change in the vertical hydraulic conductivity is almost existent.

Table (5-4) Values of hydraulic head change for observed wells

Values of K_h change	**10%**	**50%**
First or second layer	/	± 1%
Third layer	± 1%	± 5%

The direction of groundwater flow in the aquifer system is toward the Tigris river and the velocity of flow increase, as the flow is approaches the river as it is clear in the third layer in Figure (5-2). The water table level in the eastern part of the aquifer system is higher than the water surface level of the Tigris river, therefore the direction of water table slopes from east to west.

5. 3 The Results of Study

Two scenarios were tested in order to check the influence of variation in water surface elevation of the Tigris river and pumping well proposed on the hydraulic head in the aquifer system. The case 1 and case 2 of scenario 1 were specified 28.7 m.a.s.l and 29.8 m.a.s.l, identified as the average value of water elevation of the Tigris river and the maximum value of the Tigris river from 2002-2010, respectively (Ministry of Water Resources, 2014). Pumping well is proposed in scenario 2.

5.3.1 Scenario 1

The case 1 and case 2 of scenario 1 were run with an average and maximum water surface elevation values of the Tigris river of 28.7 and 29.8 m.a.s.l, respectively, to predict the impact of the Tigris river on groundwater aquifer and on the hydraulic head of observation wells.

The increase of water elevation of the Tigris river creates an increase in the calculated head values of the groundwater levels as compared with the values head in the observation wells, as in Table (5-5).

Figure (5-4) and Figure (5-5) show the equipotential lines of ground water for case 1 and 2, respectively. Despite the imposed increase in water level of the Tigris river in case 1 and 2, the direction of groundwater flow remains the same towards the Tigris river. Figure (5-6a)-(5-6c) and Figure

(5-7a)-(5-7c) show the direction of flow lines towards the Tigris river as indicated below.

Table (5-5) The values of calculated steady-state and observed heads (m) in Nuclear Research Center at Al-Tuwaitha site

Well no.	**Obs. Head m.a.s.l**	**Cal. Head in cas 1 m.a.s.l**	**Cal. Head in case 2 m.a.s.l**
1	27.79	28.83	29.93
2	27.86	28.85	29.95
3	27.80	28.87	29.97
4	27.61	28.83	29.93
5	27.14	28.80	29.90
6	27.67	28.84	29.94

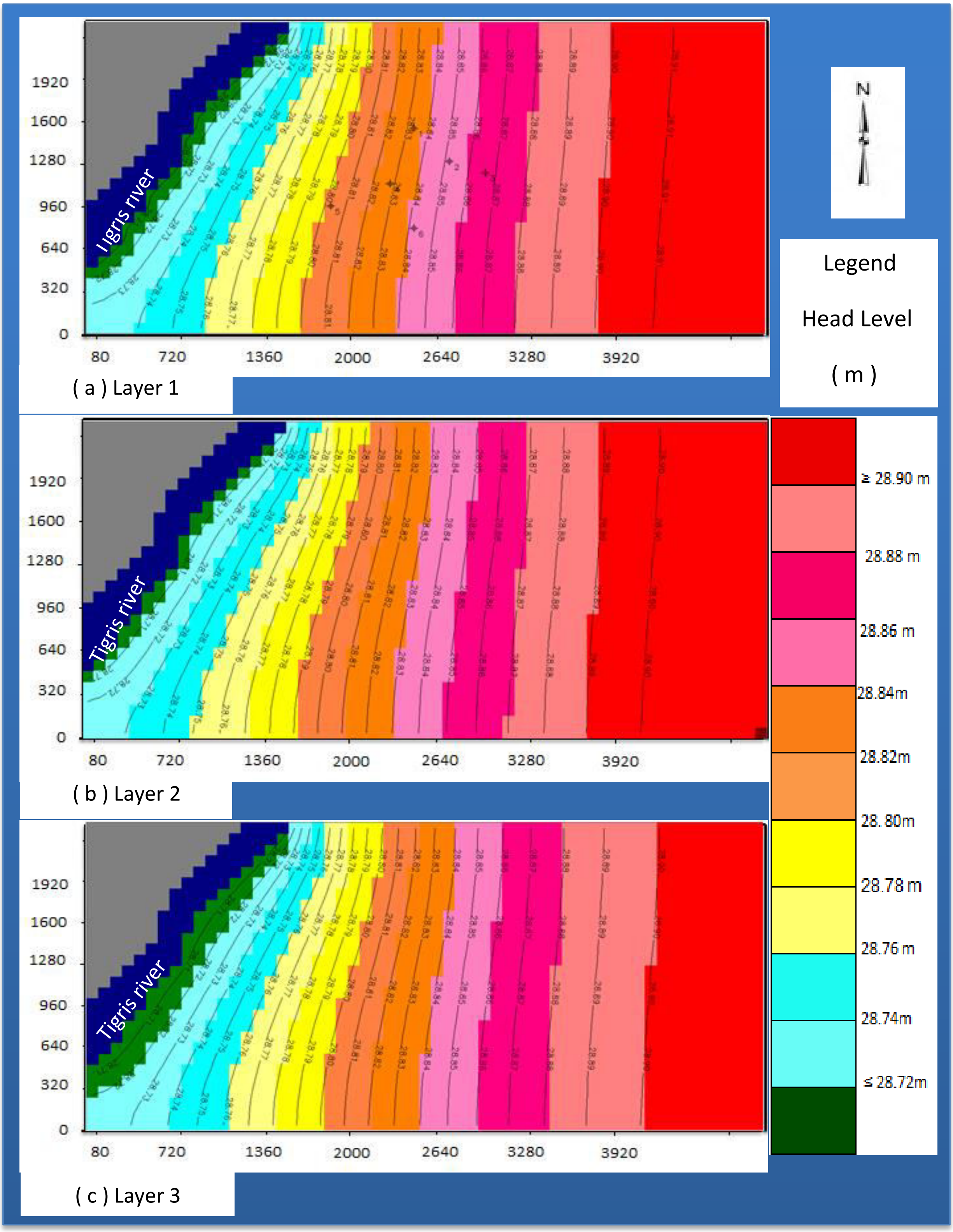
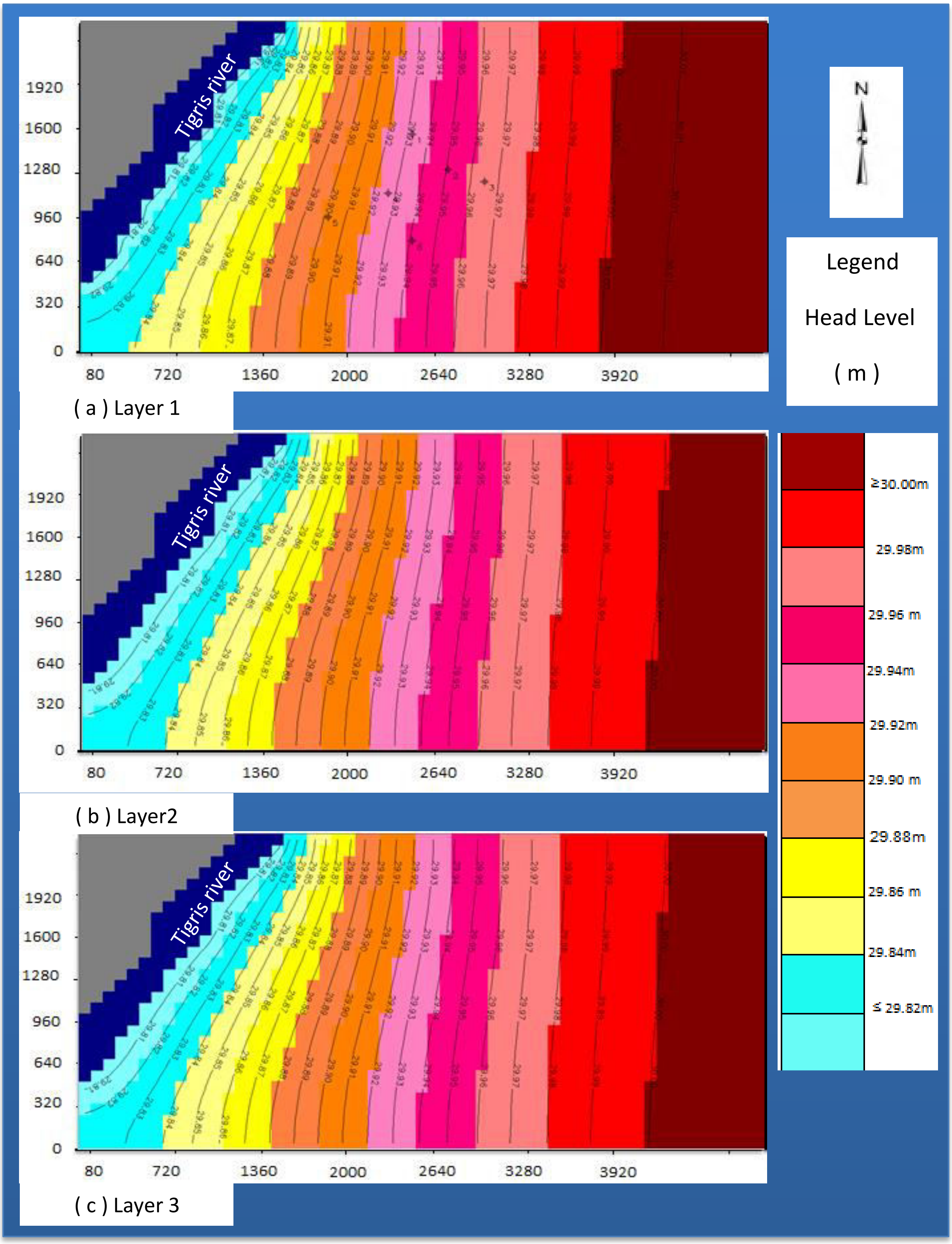


Fig. (5-4) Calculated hydraulic heads in the steady-state simulation when the river water surface elevation 28.7m.a.s.l.



(a) Layer 1

(b) Layer2

(c) Layer 3

Fig. (5-5) Calculated hydraulic heads in the steady-state simulation when the river water surface elevation 29.8 m.a.s.l.

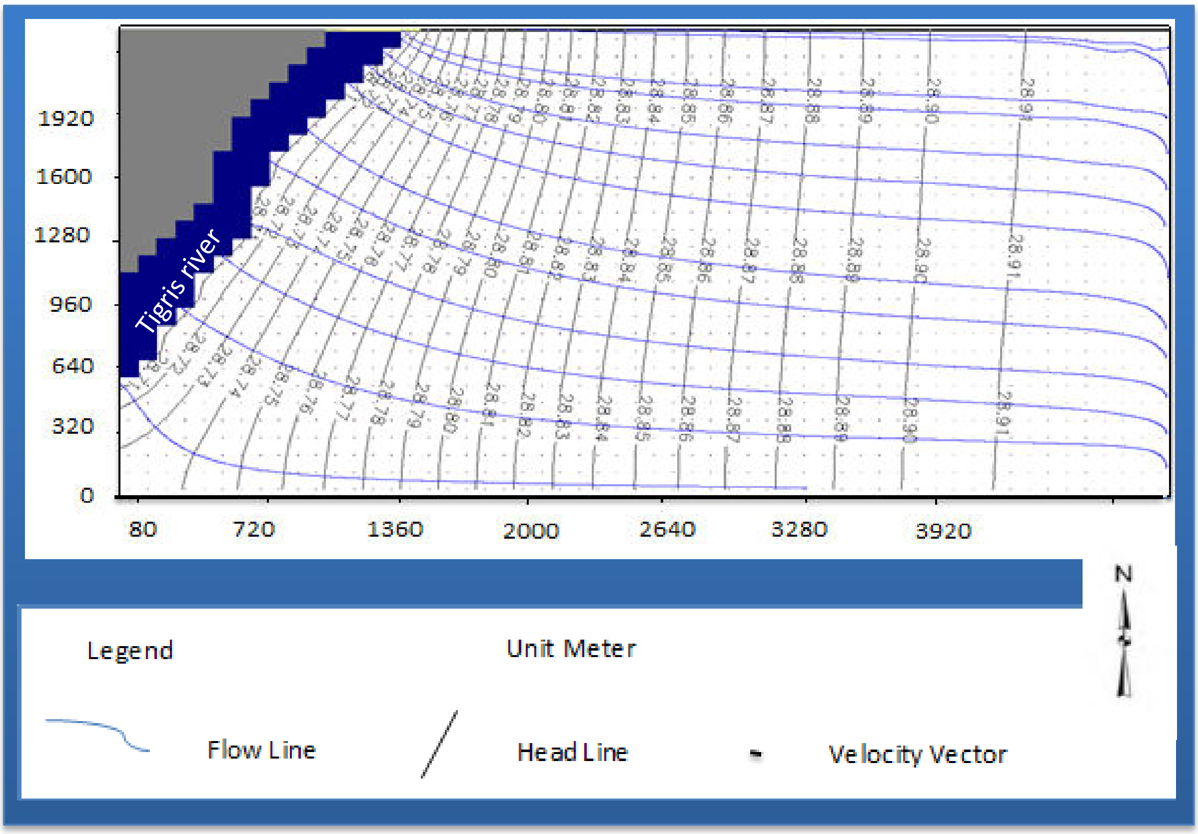


Fig. (5-6a) The flow net of groundwater direction in the first layer

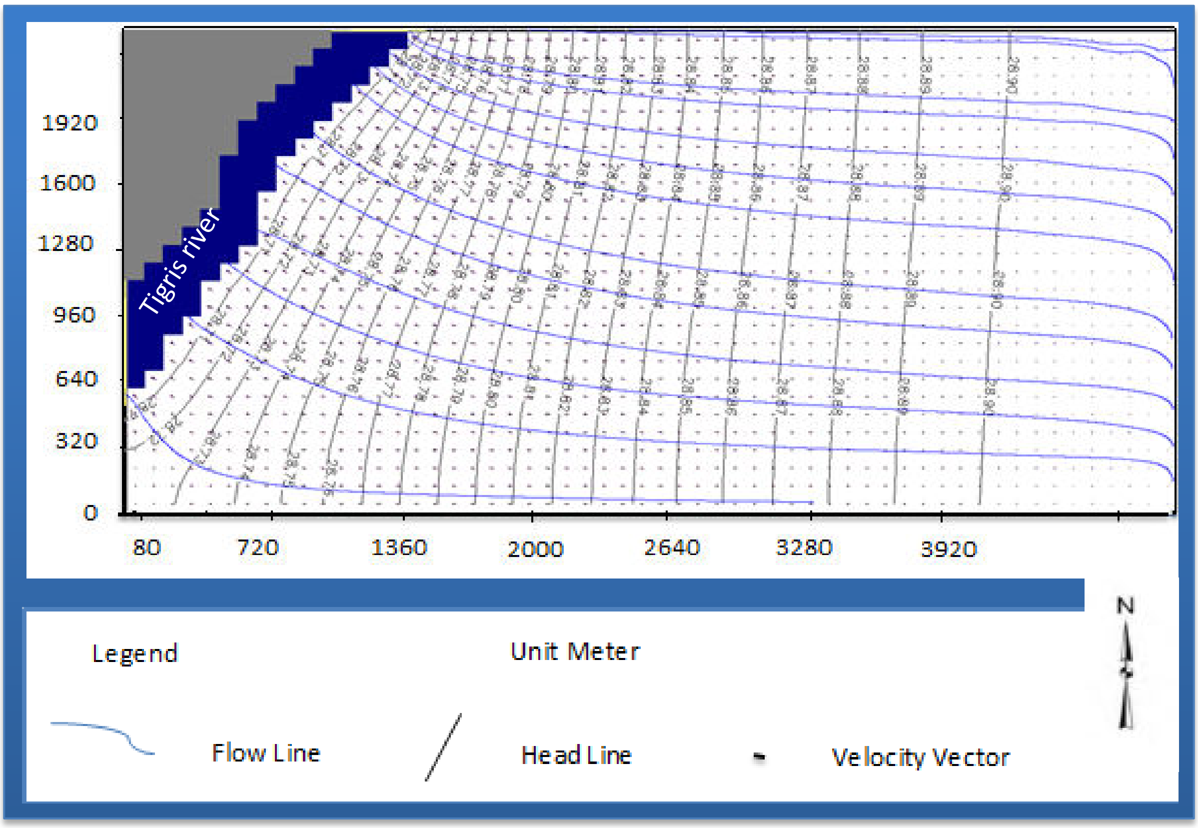


Fig. (5-6b) The flow net of groundwater direction in the second layer

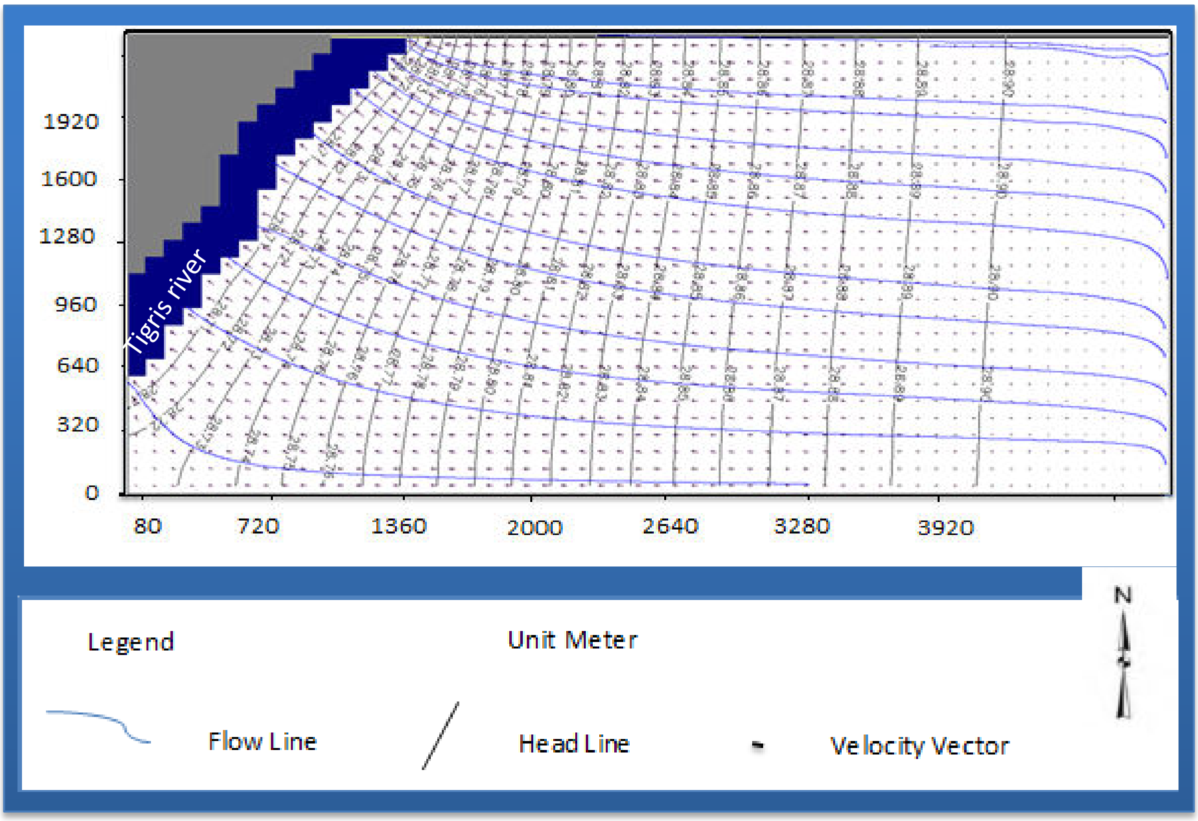


Fig. (5-6c) The flow net of groundwater direction in the third layer

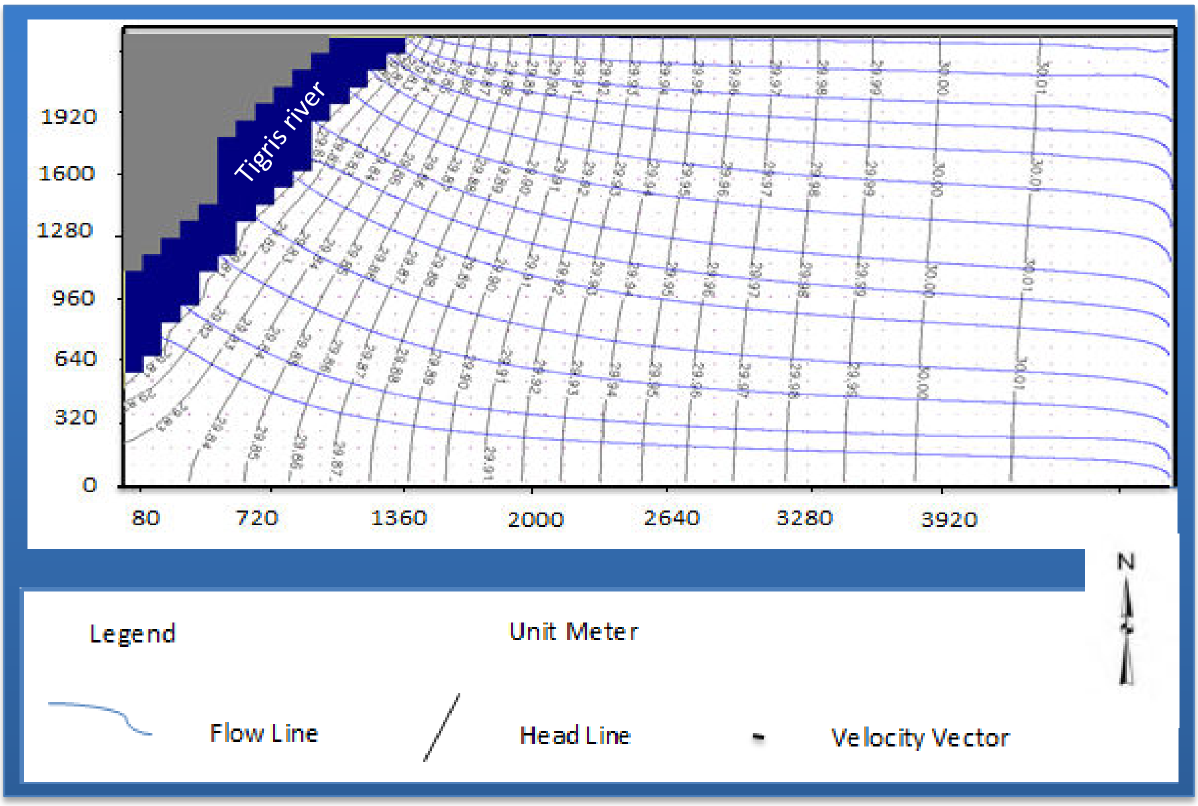


Fig. (5-7a) The flow net of groundwater direction in the first layer

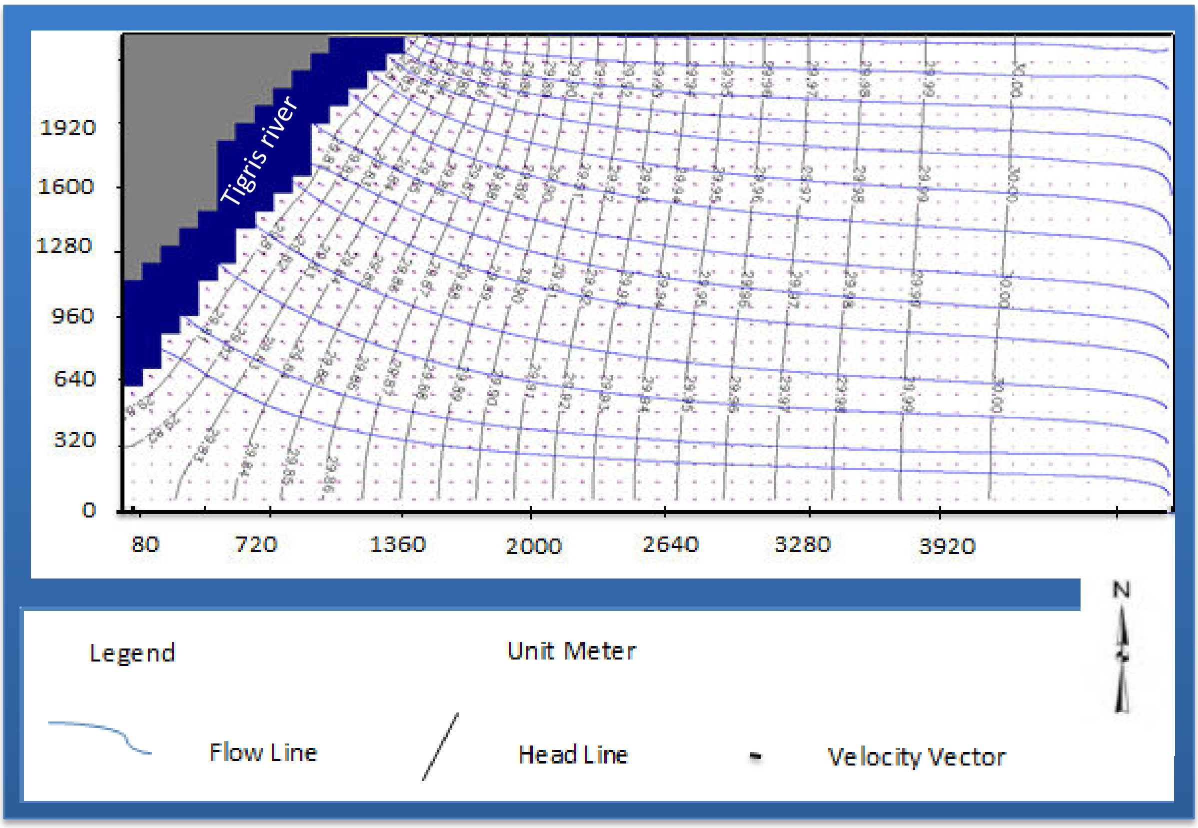


Fig. (5-7b) The flow net of groundwater direction in the second layer

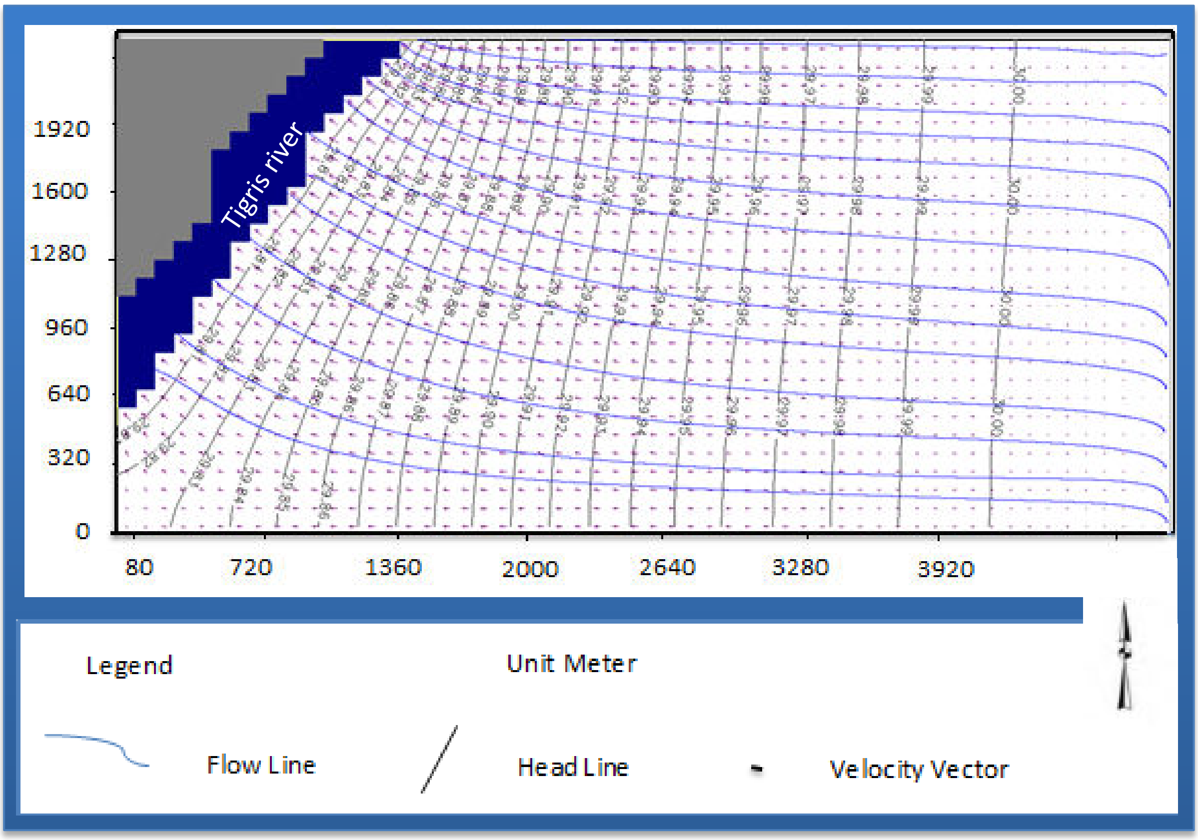


Fig. (5-7c) The flow net of groundwater direction in the third layer

5.3.2 Scenario 2

The model in this scenario was run assuming an average of water surface elevation of the Tigris river of 28.7 m.a.s.l and the activating the pumping well rate. The site of pumping well was chosen to intercept the flow path identified it in case 1 of scenario 1. This should be helpful to evaluate the effect of the well on the flow path and the level water table. Since the contaminated area is located near the Tigris river, therefore the well will reduce the contaminated water movement toward the river.

The use of pumping well leads to reduce the water level in the observed wells when compared with the results of case 1 of scenario 1, as in Table (5-6).

Table (5-6) The values of calculated and observed heads (m) in Nuclear Research Center at Al-Tuwaitha site

Well no.	Obs. Head m.a.s.l	Cal. Head in Case1 of Scenario 1 m.a.s.l	Cal. Head in Scenario 2 m.a.s.l
1	27.79	28.83	28.55
2	27.86	28.85	28.56
3	27.80	28.87	28.57
4	27.61	28.83	28.50
5	27.14	28.80	28.40
6	27.67	28.84	28.53

The distribution of the equipotential lines is varying in this scenario, where the highest equipotential line of 28.62 m after it was 28.92 m, while the least equipotential line 28.26 m for the area around the pumping well after it was 28.72 for area neighboring to the Tigris river, as in Figure (5-8).

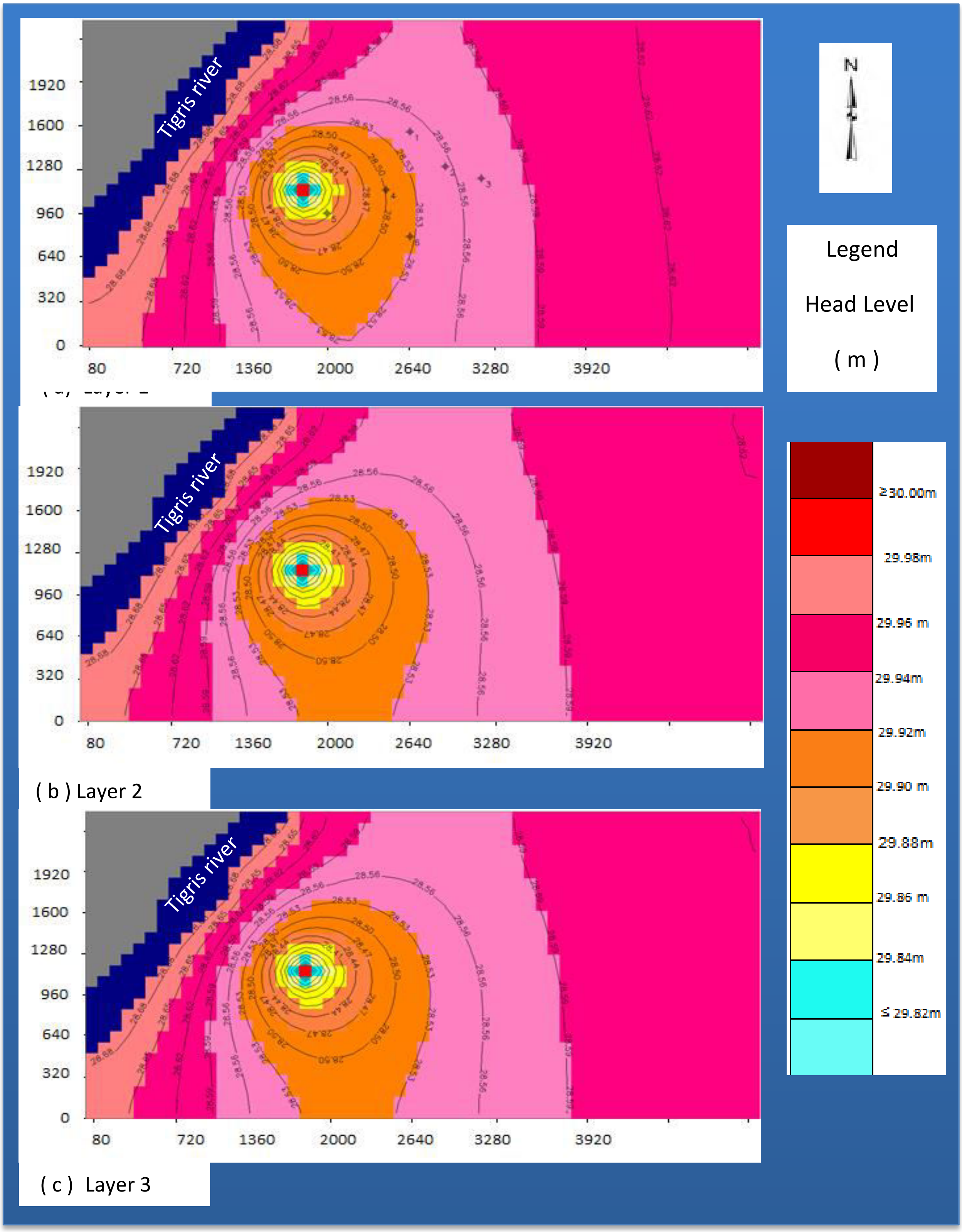


Fig.(5-8) Calculated hydraulic heads in the steady-state simulation assuming pumping rate of 518 m^3/day

The groundwater flow direction becomes toward the pumping well as shown in Figure (5-9a)-(5-9c), especially the area around the well. So the movement of contaminant will follow the groundwater movement and it will be toward the pumping well and this is noted from the output of this scenario. The pumping well proposed to limit the movement of water contaminant toward the Tigris river and thereby reduces the movement of contamination deposited to aquifer from the surface for Al-Tuwaitha area near the Tigris river. The scenario results were used in the transport of contaminant model to evaluate the contamination distribution in the aquifer system.

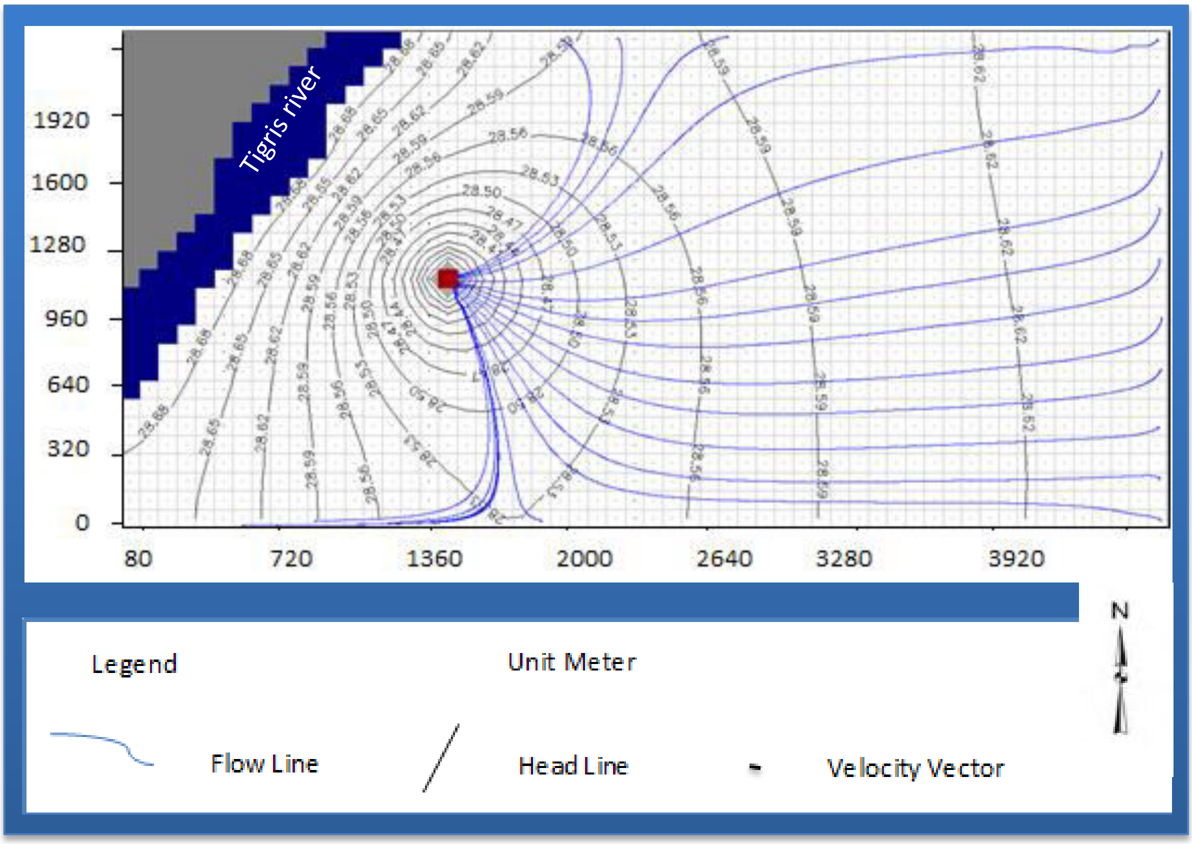


Fig. (5-9a) The flow net of groundwater direction in the first layer

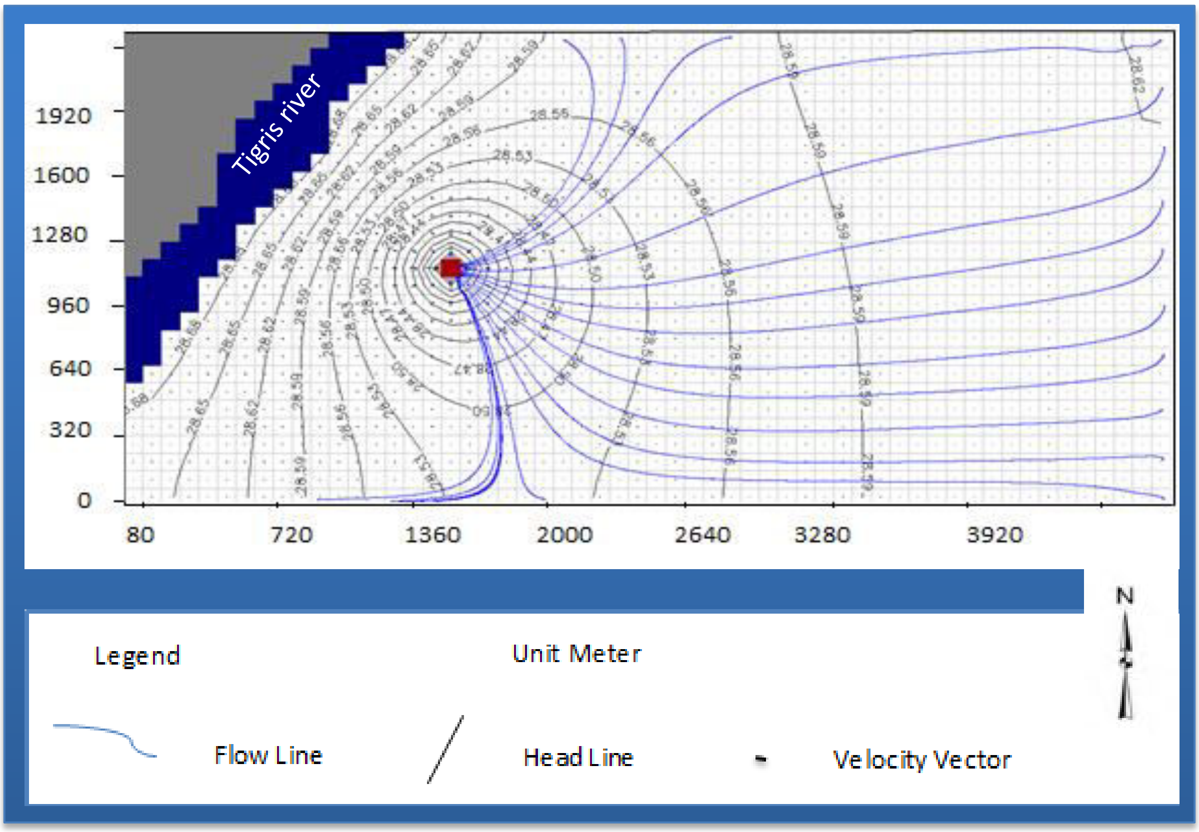


Fig. (5-9b) The flow net of groundwater direction in the second layer

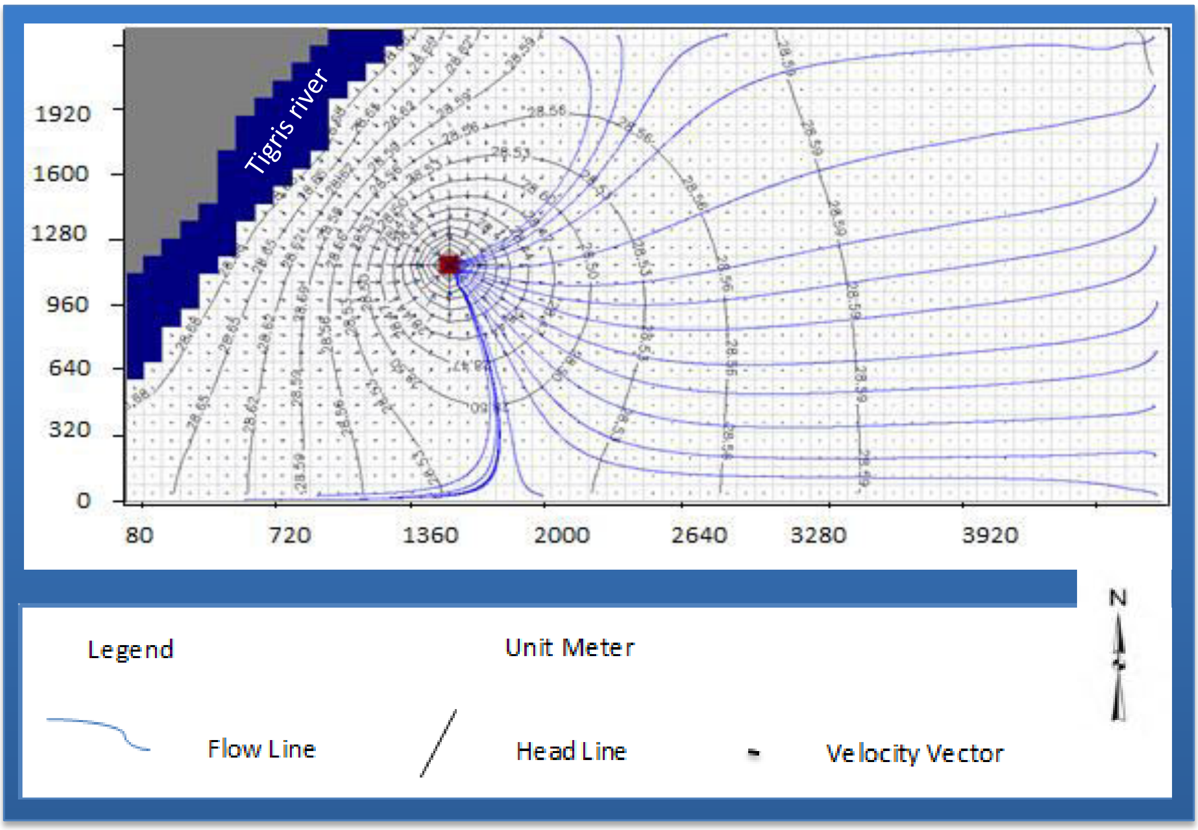


Fig. (5-9c) The flow net of groundwater direction in the third layer

5.4 Steady State Transport Model

The transport model MT3D was run under advection, dispersion conditions and the choice of the Cs concentration which is one of the radioactive pollutions in the soil of (Nuclear Research Center) Al-Tuwaitha area that has a long life. In this model it was assumed that Cs-137 concentration considered from the standard limit of the radioactive pollution (Zaboon, 2013) and applied to polluted area as in Figure (4-13). Cs-137 pollution model was simulated for 10, and 20 years to investigate the extent of migration of Cs-137 concentration in the aquifer system. Cs-137 transport model simulation shows that it does not leak into the second and third layers after one year of simulation. Increasing simulation time leading to increase pollutant movement in vertical and horizontal direction toward the Tigris river as in Figure (5-10a)-(5-10b) and Figure (5-11a)-(5-11b). Figure (5-12) shows that there was increasing in Cs-137 concentrations in wells.

The results indicated that there was a slow migration of contamination which takes about 20 years to reach the well. Therefore, it can be considered that the suggested pumping well in this study was effective to reduce the contaminant migration towards the river. It was also observed that Cs-137 contaminant migration in horizontal direction is small because of flow groundwater seepage velocity, where the advection is the main factor that controls the movement of contamination in the aquifer system. The dispersion has low influence because the longitudinal dispersion and diffusion coefficients are small for the aquifer and Cs-137 contaminant.

The model was calibrated by changing longitudinal dispersion and diffusion coefficients. A difference in the distribution of contaminant in the aquifer system was not observed, but the highest change was observed through a change in the horizontal hydraulic conductivity of the layers

When the top layer is a sand layer, the spread of contamination will be very high and the possibility of its leakage to the Tigris river is higher. It specified 3m as a value of the longitudinal dispersion coefficient, and ($2x10^{-9}$ – $5x10^{-8}$) m^2/s as a value of the diffusion coefficient for layers of aquifer system, while it specified 2 $x10^{-6}$, 7 $x10^{-5}$, and 3 x 10^{-4} m/s as a value of horizontal hydraulic conductivity for the first, second, and third layer, respectively. These values are used in this study.

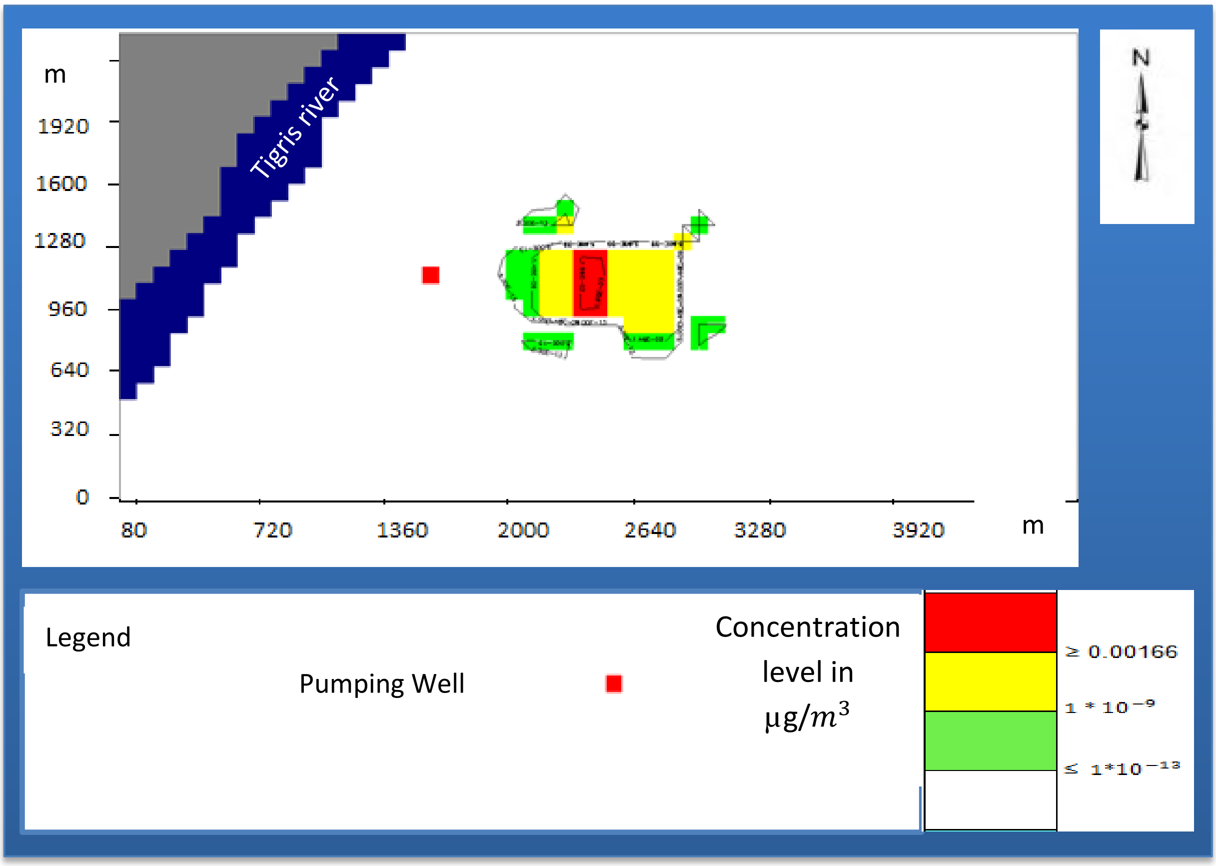


Fig. (5-10a) The Cs-137 concentration distribution in the groundwater second layer after 10 years

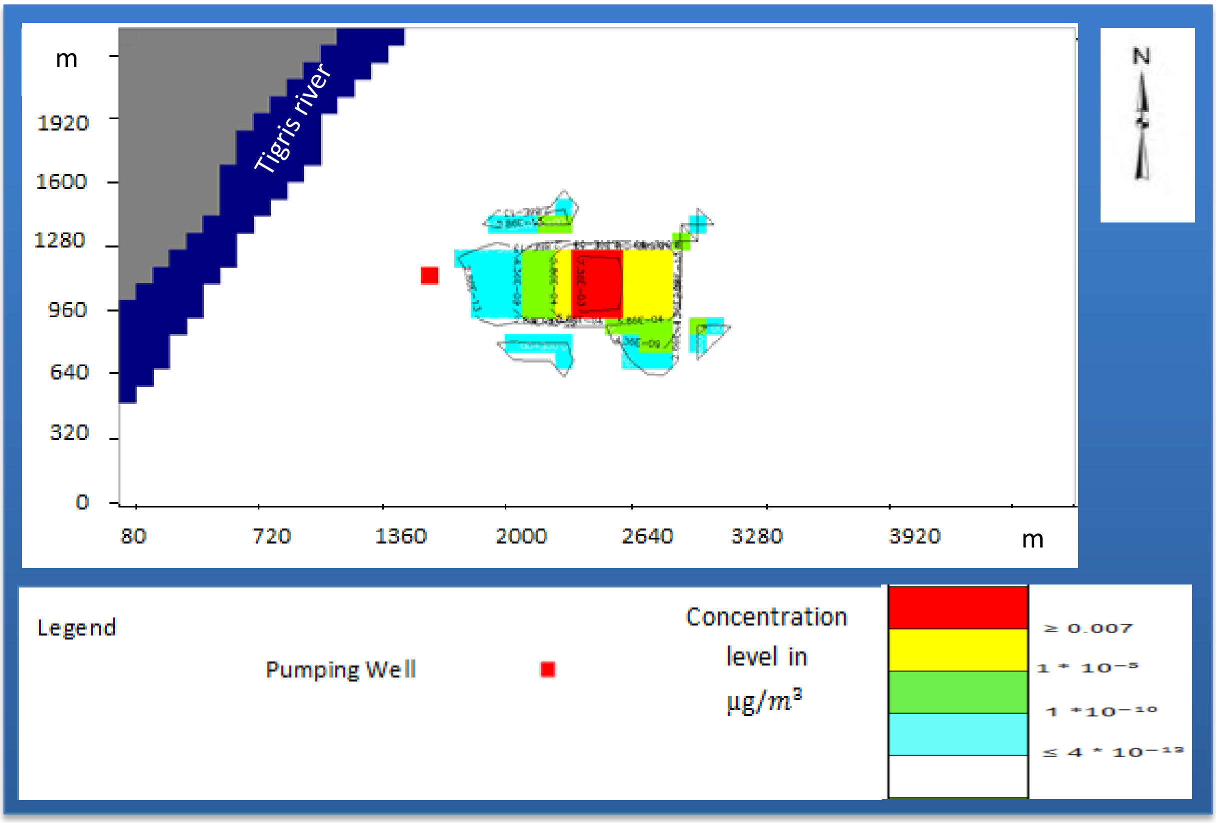


Fig. (5-10b) The Cs-137 concentration distribution in the groundwater of second layer after 20 years

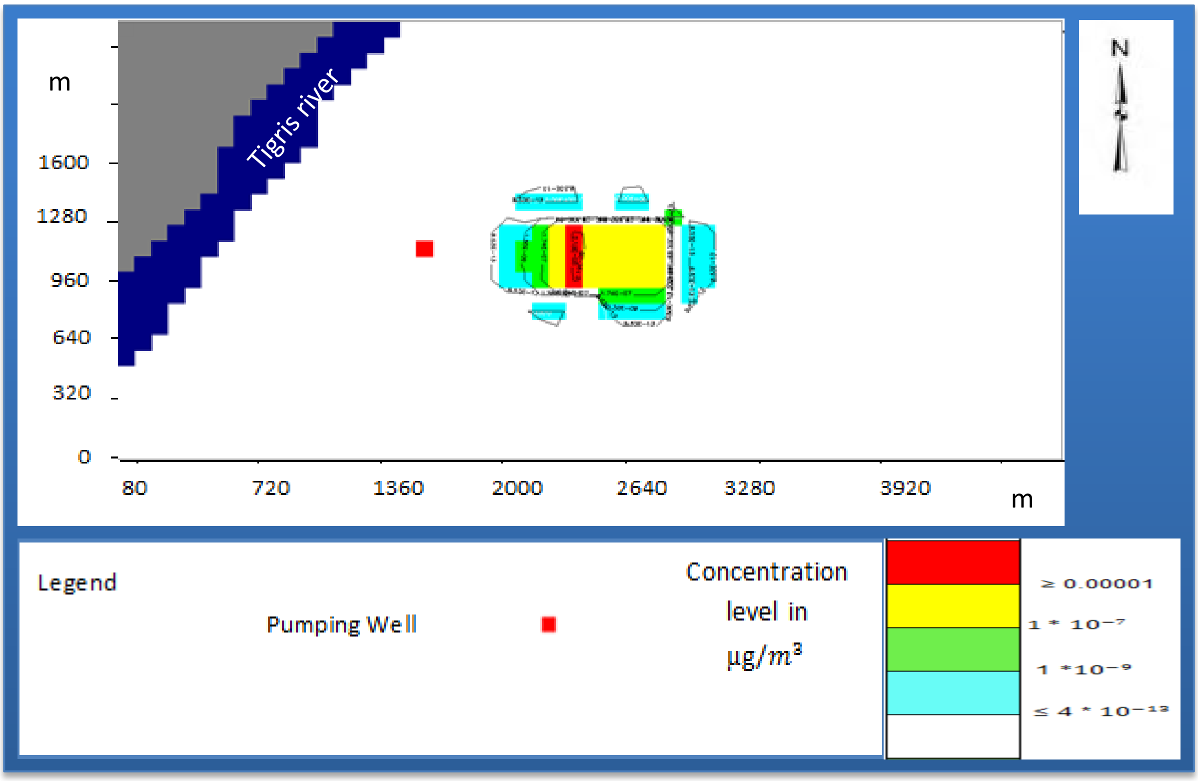


Fig. (5-11a) The Cs-137 concentration distribution in the groundwater of third layer after 10 years

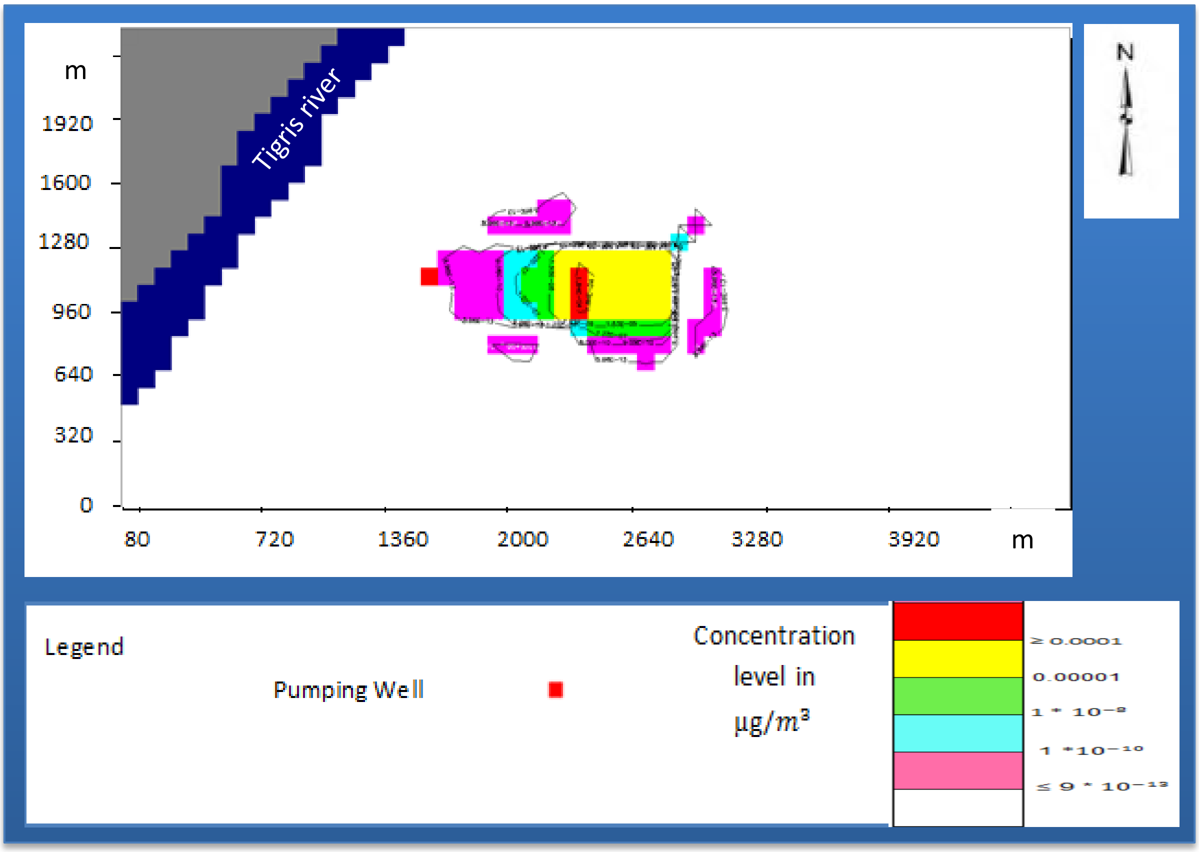
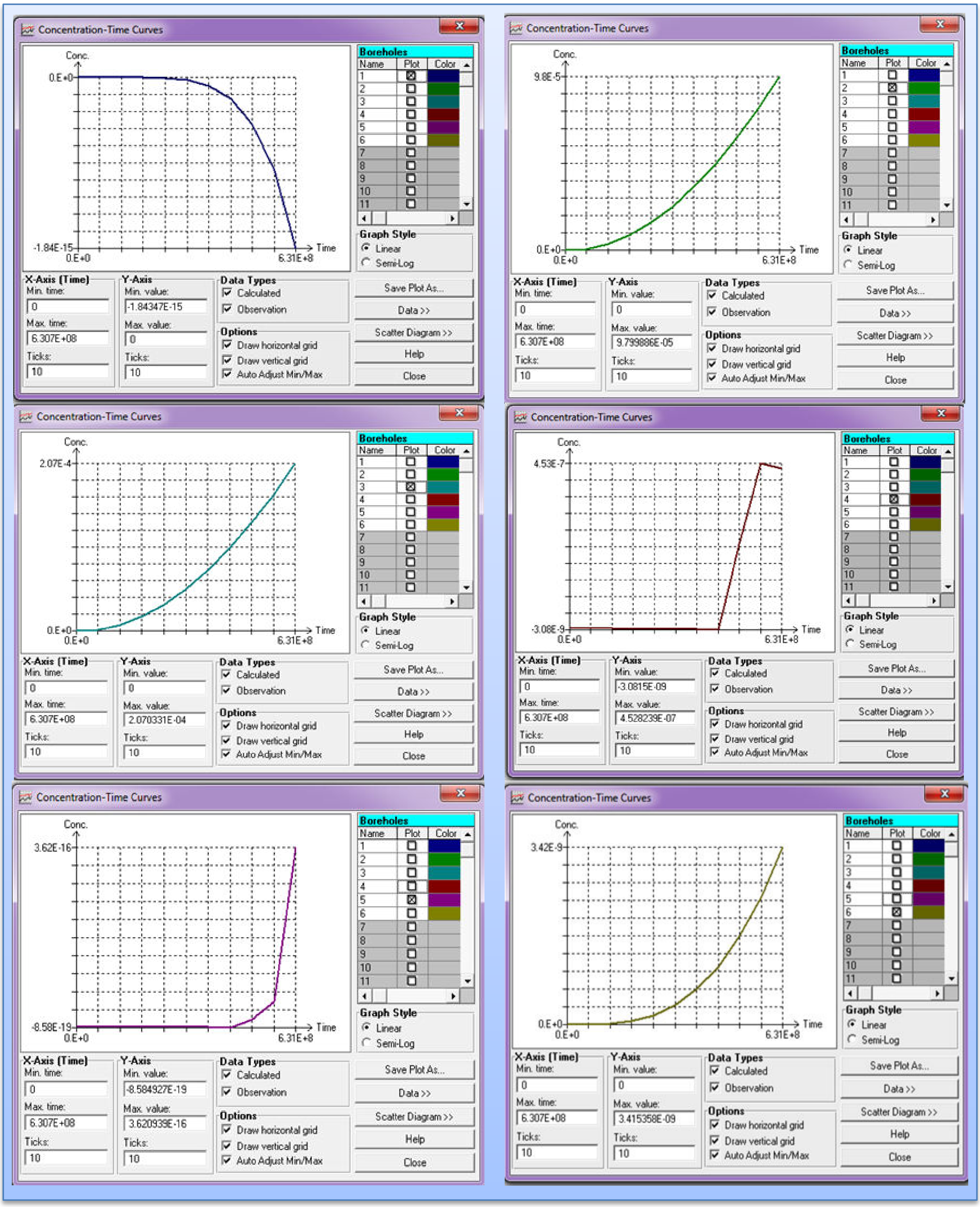


Fig (5-11b) The Cs-137 concentration distribution in the groundwater of third layer after 20 years



Concentration-Time Curves

Boreholes: 1 ☒, 2 ☐, 3 ☐, 4 ☐, 5 ☐, 6 ☐, 7 ☐, 8 ☐, 9 ☐, 10 ☐, 11 ☐
Graph Style: ● Linear ○ Semi-Log
X-Axis (Time): Min. time: 0; Max. time: 6.307E+08; Ticks: 10
Y-Axis: Min. value: -1.84347E-15; Max. value: 0; Ticks: 10
Data Types: ☑ Calculated ☑ Observation
Options: ☑ Draw horizontal grid ☑ Draw vertical grid ☑ Auto Adjust Min/Max

Concentration-Time Curves

Boreholes: 1 ☐, 2 ☒, 3 ☐, 4 ☐, 5 ☐, 6 ☐, 7 ☐, 8 ☐, 9 ☐, 10 ☐, 11 ☐
Graph Style: ● Linear ○ Semi-Log
X-Axis (Time): Min. time: 0; Max. time: 6.307E+08; Ticks: 10
Y-Axis: Min. value: 0; Max. value: 9.799886E-05; Ticks: 10
Data Types: ☑ Calculated ☑ Observation
Options: ☑ Draw horizontal grid ☑ Draw vertical grid ☑ Auto Adjust Min/Max

Concentration-Time Curves

Boreholes: 1 ☐, 2 ☐, 3 ☒, 4 ☐, 5 ☐, 6 ☐, 7 ☐, 8 ☐, 9 ☐, 10 ☐, 11 ☐
Graph Style: ● Linear ○ Semi-Log
X-Axis (Time): Min. time: 0; Max. time: 6.307E+08; Ticks: 10
Y-Axis: Min. value: 0; Max. value: 2.070331E-04; Ticks: 10
Data Types: ☑ Calculated ☑ Observation
Options: ☑ Draw horizontal grid ☑ Draw vertical grid ☑ Auto Adjust Min/Max

Concentration-Time Curves

Boreholes: 1 ☐, 2 ☐, 3 ☐, 4 ☒, 5 ☐, 6 ☐, 7 ☐, 8 ☐, 9 ☐, 10 ☐, 11 ☐
Graph Style: ● Linear ○ Semi-Log
X-Axis (Time): Min. time: 0; Max. time: 6.307E+08; Ticks: 10
Y-Axis: Min. value: -3.0815E-09; Max. value: 4.528239E-07; Ticks: 10
Data Types: ☑ Calculated ☑ Observation
Options: ☑ Draw horizontal grid ☑ Draw vertical grid ☑ Auto Adjust Min/Max

Concentration-Time Curves

Boreholes: 1 ☐, 2 ☐, 3 ☐, 4 ☐, 5 ☒, 6 ☐, 7 ☐, 8 ☐, 9 ☐, 10 ☐, 11 ☐
Graph Style: ● Linear ○ Semi-Log
X-Axis (Time): Min. time: 0; Max. time: 6.307E+08; Ticks: 10
Y-Axis: Min. value: -8.584927E-19; Max. value: 3.620939E-16; Ticks: 10
Data Types: ☑ Calculated ☑ Observation
Options: ☑ Draw horizontal grid ☑ Draw vertical grid ☑ Auto Adjust Min/Max

Concentration-Time Curves

Boreholes: 1 ☐, 2 ☐, 3 ☐, 4 ☐, 5 ☐, 6 ☒, 7 ☐, 8 ☐, 9 ☐, 10 ☐, 11 ☐
Graph Style: ● Linear ○ Semi-Log
X-Axis (Time): Min. time: 0; Max. time: 6.307E+08; Ticks: 10
Y-Axis: Min. value: 0; Max. value: 3.415358E-09; Ticks: 10
Data Types: ☑ Calculated ☑ Observation
Options: ☑ Draw horizontal grid ☑ Draw vertical grid ☑ Auto Adjust Min/Max

Fig. (5-12) Cs-137 concentration simulated after 20 years for observation wells

The contamination model was operated based on the dispersion and advection factors and neglected the effect of the chemical reaction. Leakage of contaminant to the second and third layers does not occur during Cs-137 transport model simulation before two years because the first layer of loam clay has low permeability.

The rate of pollution increases whenever increases the amount of leaking material increases, which may increase the amount of leaked material on the limit that has been used in the model as a result of the presence of polluting factors in the region. The increase of simulation time leads to increase the contaminated spread over a larger area and more depth.

According to this study, the movement of contaminants has been slow, but it is the highest in the third layer since this layer is medium sand and has high permeability. Since Al-Tuwaitha (Nuclear Research Center) is located near the Tigris river, therefore the risk of contamination may increase and reach consumption sites. The half-life of cesium is relatively long and there must be a permanent observation to control the spread of contamination that may occur.

In general, the shape of the plume is oval, but in this study it is closely a rectangular shape, which follows the direction of ground water flow. It results from diffusion and longitudinal dispersion coefficients, while the plume lateral spread is slight and depends on the transverse and vertical dispersion. The distance of the spread of Cs was approximately 690 m after 20 years with the direction of groundwater movement toward the Tigris river. The use of pumping well was considered helpful in reducing the spread of contamination.

Chapter Six

Conclusions and Recommendations

CHAPTER SIX

Conclusions and Recommendations

6.1 Conclusions

From the results obtained in this study, the following conclusions have been summarized below**:**

1. The results show that there is a good agreement between the observed and the calculated heads by using MODFLOW.
2. Groundwater flow direction was slow toward the Tigris river which influenced by soil type. The velocity of groundwater was 0.0015 m/day in the third layer, and in the first and the second layers, the velocity were 0.00000977 m/day and 0.00036 m/day respectively.
3. The changing in the horizontal hydraulic conductivity of the first, second and third layer by 50% leads to increase the hydraulic heads by 5% for the third layer and 1% for the first and the second layer, respectively.
4. The increase of water elevation of the Tigris river leads to an increase in the hydraulic heads aquifer of groundwater level for the first and the second scenarios.
5. The simulation results of the proposed pumping well lead to capture the flow lines of groundwater and change the movement direction. In addition lead to reduce the effect of the spread of the Cs-137 contaminant before reaching the river.
6. The results of transport model show that the vertical migration of contaminant does not occur before two years of simulation time and increases with time. While the direction of the horizontal migration occurs after ten years of simulation time with groundwater flow direction.

7. The Cs-137 concentration distribution shown in the aquifer for the study area during simulation MT3D model that it is not affected by the variation in longitudinal dispersion and diffusion coefficient values, but the variation in the distribution exists when the hydraulic conductivity values are changed into other limits.

6.2 Recommendations

The study recommendations may be taken into consideration for further studies.

1- Using another contaminant such as cobalt, heavy metals, uranium, and taking the chemical reaction into consideration in running the model.

2- Using transient simulations to show the change of aquifer levels with time.

3- Utilizing more parameters and changing boundary conditions by making the water surface elevation of the Diyala river as a boundary condition which located about 3.5 kilometers (*Km*) north of Nuclear Research Center.

4- Depending on the field data for other periods may be 2010-2018 to study and explain the influence on the aquifer.

5- Constructing a treatment station after determining the typical location for constructing it to reduce contamination in the study area before realising the pumping flow into the Tigris river.

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الخلاصة

توصِف الدراسة محاكاة حركة المياه الجوفية ونقل ملوث السيزيوم لنظام الطبقة الجوفية لمركز البحوث النووي لمنطقة التويثة الملوثة اشعاعيا نتيجة تعرضها للقصف واعمال التخريب والنهب في ٢٠٠٣، والواقعة جنوب محافظة بغداد بالقرب من نهر دجلة باستخدام برنامج Processing MODFLOW. استخدم MODFLOW موديل لتخمين حركة المياه الجوفية لمنطقة الدراسة وتأثير التغير بمنسوب نهر دجلة على الطبقة الجوفية بالإضافة لمعرفة مدى قدرة بئر الضخ المقترح في هذه الدراسة على تغير حركة المياه والتلوث في الحالة المستقرة، بينما استخدم نموذج النقل لمعرفة توزيع الملوث بالطبقة الجوفية وتغيره مع الزمن.

اعطت معايرة النموذج توافق جيد نسبيا بين المنسوب المحسوب والمقاس للإبار الست المختارة لهذه الدراسة. خلال عملية المعايرة وجد ان الشحنة الهيدروليكي لنظام الطبقة الجوفية ازدادت 5% حينما زيدت الايصالية الهيدروليكية الافقية 50% للطبقة الثالثة. العوامل التي استعملت كمساهمة في الموديل بعد المعايرة النهائية كانت 0.000002 , 0.00007 و 0.0003 م/ثا كقيم الايصالية الهيدروليكية الافقية, 0.1 , 0.26 و 0.32 كقيم المسامية الفعالة, و $1x10^{-9}$, $1x10^{-8}$, و $5x10^{-8}$ م^2/ ثا كقيم معامل الانتشار الجزئي للطبقة الاولى, الثانية والثالثة, على التوالي.

اشارت النتائج ان اي زيادة بمنسوب الماء لنهر دجلة تؤدي الى زيادة مناسيب الابار الموجودة بالمنطقة على فرض ان المتغيرات الاخرى المدخلة للنموذج ثابتة، علاوة على ان استخدام بئر الضخ ادى الى تقليل منسوب الماء الجوفي واعتراض حركة المياه الجوفية.

اظهرت نتائج نموذج نقل الملوث ان توزيع وانتشار عنصر السيزيوم يزداد مع الزمن وحركته مع حركة الماء الجوفي، كما تبين ان انتشار الملوث بالاتجاه الافقي قليل, و سرعة التسرب للطبقة الاولى, الثانية, والثالثة كانت 0.0357, 0,51, و1.76 م/سنة, على التوالي, وتأخذ الشكل الإهليلج نسبةً لمعامل الانتشار والتشتت. وان اطول مسافة انتقل فيها الملوث خلال ٢٠ سنة من المحاكاة حوالي ٦٩٠ م باتجاه بئر الضخ المتقاطع باتجاه الماء الجوفي لنهر دجلة. وكذلك تبين وجود ترابط مع المياه السطحية (نهر دجلة) والمياه الجوفية وطبيعة التربة حيث بتغير احد هذه العناصر قد يؤثر في العناصر الأخرى كثيرا.

وزارة التعليم العالي والبحث العلمي

جامعة الانبار

كلية الهندسة

قسم الهندسة المدنية

نموذج لمحاكات تلوث المياه الجوفية بالسيزيوم-137 في موقع التويثه

رسالة
مقدمة الى قسم الهندسة المدنية كلية الهندسة
في جامعة الانبار وهي جزء من متطلبات نيل
درجة الماجستير علوم
في
الهندسة المدنية

من قبل
رشا علي سعود الكبيسي
(بكالوريوس هندسة مدنية, 2012)

بأشراف

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